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Time-Latitudinal Dynamics of Magnetic Fields and the Green Corona Over Three Solar Cycles

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Abstract Time-latitudinal distributions of the solar-surface magnetic fields and the green corona (530.3 nm, Fe XIV) intensities in the period 1975 – 2004 are analyzed. Meridional migration maps show that time-varying components consist of both the poleward and equatorward belts over a solar cycle. The green-corona maps are, for the first time, directly compared with magnetic flux charts, yielding a good association between the green corona and magnetic fields; this is most reliably seen at high latitudes.

1. Introduction

Time-latitudinal distributions and/or meridional migration of the green-corona intensities have been studied for several decades (*e.g.*, Trellis, 1954; Waldmeier, 1981 (and references therein); Leroy and Noens, 1983; Bumba, Rušin, and Rybanský, 1990, Altrock 1997, 2004, Minarovjech, Rybanský, and Rušin, 1998). The main results obtained can be summarized as follows (see Figure 2):

i There is a splitting of the green-corona intensities occurring at heliographic latitudes around 45° at or around the cycle minima. These branches, in the northern and southern hemispheres, show a poleward migration with a velocity of several meters per second. These meridional migrations, known also under the names "poleward migration branches," "rush-to-poles," or "polar branches," decay in the close vicinity of the poles around cycle maxima.

ii There is a second separation in the green corona that occurs three to four years after the appearance of the first poleward migration branch and at the heliographic latitudes of 30 – 40°. The second branch is sometimes strong and sometimes ephemeral. Sometimes it

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begins not three to four years after the first branch but almost at the same time (1945 – 1946). It sometimes lasts three to four years (1945 – 1950) and sometimes one to two years (1958 – 1960). Sometimes the first branch does not exist (prior to 1998). Sometimes the second branch does not evolve into the main branch near 70°, but the main branch splits off from the second branch (1992). The green-corona extended cycle bears a strong similarity, in its duration, to the torsional oscillation pattern suggested by Howard and LaBonte (1980); see also Wilson *et al.* (1988).

The observations of high-latitude meridional migration of the green corona and prominences (not discussed in this paper) gained further acceptance with the discovery of meridional migrations by the SOHO spacecraft and/or ground-based telescopes with a sufficiently high spatial and temporal resolution (*e.g.*, Ulrich *et al.*, 1988; Hathaway, 1996; Giles, 2000; Beck, Gizon, and Duvall, 2002). For example, Makarov and Sivaraman (1983, 1989) studied poleward migrations of the magnetic neutral line and the reversal of the polar fields on the Sun for the period 1904 – 1983. They used the Hα (656.3 nm) filaments and K_{232} spectroheliograms acquired at the Kodaikanal Observatory. The poleward drift velocity of the neutral line was found to vary from 4.2 to 29 m s^{-1}. More recently, McIntosh (2003) created synoptic charts where he combined observations of filaments (prominences observed against the solar disk), active regions, and coronal holes with the associated magnetic-field patterns and discovered good agreement between large-scale circulations of all three structures.

Meridional migrations of the green corona have to be taken into account when modeling solar surface and sub-photospheric layers for the Sun as a star. The green-corona intensities are also very intimately connected with the distribution of solar local magnetic flux and mimic its development over a solar cycle (*e.g.*, Rušin and Rybanský, 2002, and references therein). The present paper is, to our knowledge, the first work where the meridional migrations of both photospheric magnetic field and the green corona are analyzed together and compared with each other, not only for low and middle latitudes, but also, and especially, for high-latitude regions.

2. Description of the Data and Reduction Techniques

In our work we focused on the period from 1975 to 2004 and made use of the following data (sources): (a) magnetic-field synoptic charts as provided by NSO/Kitt Peak for Carrington rotations 1625 to 2006 (years 1975 – 2003), downloadable from ftp://nsokp.nso.edu/kpvt/synoptic/mag/, and (b) the magnetic data from the SOHO/MDI to cover, in particular, the final part of the period under study, accessible at http://soi.stanford.edu/magnetic/index6.html. The computed SOHO/MDI and NSO/Kitt Peak magnetic-field averages for CR 1909 to 2006 were used for the purpose of rescaling the SOHO/MDI averaged data for CR 2007 using the least-squares method. Both kinds of maps were transformed into a 180 $\times$360 data array for each CR file with the subsequent averaging of these arrays across longitude. To facilitate the analysis, the sine latitudes of both maps were interpolated into a linear latitude range from -90 to $+90°$. The resulting map represents the longitude-averaged radial components of magnetic fields as a two-dimensional 414 $\times$180 array (Figure 1). The gray scale in the top panel runs from -40 G (darkest areas) to $+40$ G (lightest areas) (as we did not find values that, when averaged, would fall outside of this range) with a resolution of 256 levels; in the bottom panel, the magnetic fields are given in absolute values with darkest/lightest areas representing weakest ($\approx$0 G)/strongest ($|B| \approx 40$ G) fields; *the darkest areas at high latitudes represent the boundaries* ("*neutral lines*") *between opposite polarities of averaged magnetic fields*. The green-corona intensities were inferred from the homogeneous coronal data

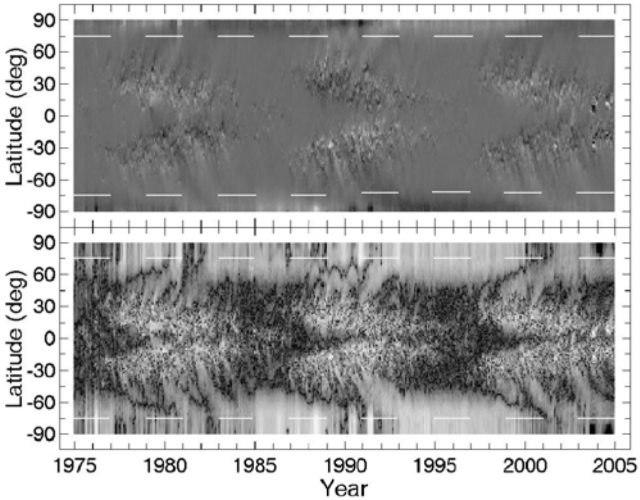

Figure 1 Longitudinally-averaged meridional migration for magnetic fields based on the original data (top) and the data after our processing (bottom). In the upper figure, the white/dark areas correspond to positive/negative polarities of the azimuthally averaged magnetic flux (adopting the same terminology as used by NSO/Kitt Peak). In the bottom figure, the white/dark areas represent high/low strengths of the absolute values of the averaged magnetic fields (see description in Section 2). The dashed lines correspond to 75°, above which the values of the magnetic field may be unreliable, because they are radial values inferred from a longitudinal magnetograph.

set (HDS) as proposed by Rybanský (1975), currently available for the period 1939 – 2004 (Rybanský *et al.*, 2005). The HDS data were converted to the Lomnický – Štít photometric scale for the entire period of observations. Here, the number of local intensity maxima is shown. Darkness in this figure is proportional to the number of bright regions in the green corona at a given latitude. The nature of these intensity maxima is not discussed here.

3. Analysis and Emerging Patterns

The original distribution of the longitudinally averaged magnetic flux is shown in Figure 1 (*upper panel*). Apparent "flows" are visible moving in both directions, *i.e.*, to the poles as well as to the equator. The beginning of the longitudinally-averaged magnetic-field "butterfly diagram" begins shortly after the solar minimum and at latitudes of around 30 – 40°. The "butterfly" pattern moves as a whole to the equator, with individual strips of different polarities (branches) moving from it to the poles at different heliographic latitudes. We note that this pattern is relatively wide, being about 30°. However, we were unable to find in it any migration branches similar to those visible in the green-corona distributions (see Figure 2).

To get a deeper insight into this apparent discrepancy, we decided to prepare a new synoptic chart – "the processed longitudinally averaged magnetic flux" – as shown in the lower part of Figure 1; one can easily see from this figure that the boundaries ("branches") between the opposite polarities of the magnetic field split off the "longitudinally averaged magnetic-field butterfly" pattern at mid-latitudes and migrate from there toward the poles. The existence of these so-called meridional migrations of magnetic fields follow from the generally accepted theory of solar magnetism as discussed by Topka *et al.* (1982). According to this theory,

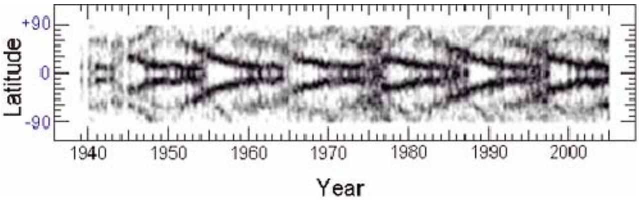

Figure 2 A time-latitudinal distribution of the green corona's local intensity maxima (Rušin *et al.*, 2007). Every local intensity maximum is represented by a single dot, so the more maxima located in a given area, the darker the area appears in the plot. That is, the darkness does *not* say anything about the *values* of the intensities of these maxima.

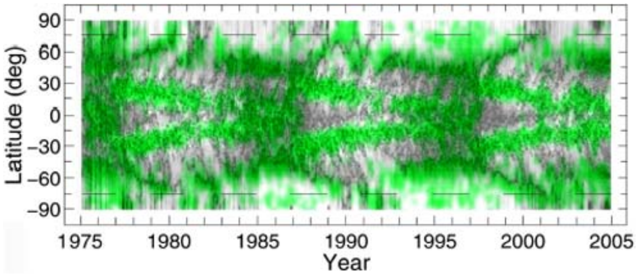

Figure 3 Meridional migrations for the magnetic fields from the bottom of Figure 1 (gray color scale) and the green corona (green color). Here, by "green corona" we mean local maxima of the green-corona intensities, as in Figure 2. The "green part" of this figure is a colored portion of Figure 2, appropriately rescaled and adjusted. The dashed lines correspond to 75° latitude (see discussion in Figure 1 caption).

poleward-transported magnetic regions flow toward poles, gradually disappearing at high-latitude regions or even closer to the poles around cycle maxima, when the change of the global magnetic field is observed (*e.g.*, McIntosh, 2003).

Comparison between the absolute values of magnetic-field intensities and the green-corona local maxima is shown in Figure 3. Although in some cycles it is quite difficult to trace all of the overlaps between the pronounced values of the processed magnetic fields and the intensity maxima of the green corona, there is often a good association between the two quantities. The time-varying components of the green corona's meridional migration in the polar branch are located just around the neutral lines or shifted from them a bit closer to the poles, so that they seem to reach the poles sooner than the associated neutral lines themselves or the prominences associated with them (McIntosh, 2003); this can, however, be a mere artifact resulting from both the effect of projection and/or the effect of discrete steps of patrol observations with a lag of 5° in positional angle. The green-corona local intensity maxima decay around the poles at the same time as the corresponding magnetic flows. The onset of the green-corona principal zone, whose duration is about 17−18 years, and its splitting may be connected with the magnetic neutral line between about 30 and 60°. However, its time-latitudinal distribution is not as clear as for the polar green-corona zone. The most serious problem is the discontinuity in the distributions of the green corona at higher heliographic latitudes owing to low intensities in these regions. It is, however, worth stressing that although in cycles 18, 19, and 21 the second polar branch is well pronounced, in other cycles under study this is not the case, as is particularly evident from the right-hand part of Figure 3.

Measurements of the strength of magnetic fields, in particular the radial component, are extremely difficult to make near the limb of the Sun and are often disregarded as purely artificial; in the case of the creation of synoptic charts this problem is most pronounced near the poles (above 75° latitude). However, measurements of intensities of the green corona are obtained all over the solar limb and their reliability is not sensitive to latitude. Because of the well-established link between the intensity of the green corona and the magnetic-field strength (Rušin and Rybanský, 2002), it is reasonable to assume that at least some correlations between the two quantities seen in our data in Figure 3 above 75° might be real.

As a final note, it is worth mentioning the existence of isolated local intensity maxima of the green corona in the polar regions that are apparently not coupled with local magnetic fields (see Figure 3). They could simply be artifacts of the processing of the data resulting from the low intensity values during minima of solar activity, or they could have a real physical meaning, being connected with the existence of polar plumes, usually observed during minima in the white-light eclipse corona (*e.g.*, Pasachoff *et al.*, 2006), or high-latitude streamers extending in front of or behind the limb. This question is, however, out of the scope of this paper.

4. Results and Discussion

The time-varying component of the green corona and its meridional migration correlate well with the magnetic-field distributions and their flows. Such a direct correlation between the two features of solar activity at different parts of the solar atmosphere is experimentally confirmed, to our knowledge, for the first time. Waldmeier (1981), using green-corona and prominence data, showed that the polar prominence zone (branch) follows the coronal zone at a latitude difference of 10°. Therefore, the prominence zone studied by him reached the pole about one year after the coronal zone. By employing the present data, there seems to be a negligible latitude difference between the two zones. We suppose that the neutral magnetic line in polar regions is fairly well represented by the distribution of prominences.

Rušin and Rybanský (2002) have found that although the intensity of the green corona in the middle and low heliographic latitudes depends on the absolute values of the magnetic-field strength, for the polar region the opposite seems to be true. How, then, can we account for the observed coincidence between the enhanced intensities of the green corona above and/or in the proximity of the neutral line? The following scenario lends itself as a most plausible one. The active regions in middle and low latitudes are characterized by magnetic fields that are not only much stronger than those in polar regions, but they are also strongly entangled. Hence, as there is no clear-cut distinction between different active regions, it is difficult to see the boundaries between the regions with enhanced intensities of the green corona and "empty" space along the line of sight. In contrast, the latitudes above 40° are characterized by weak local magnetic fields and the green corona. Moreover, as pointed out by McIntosh (2003), these latitudes mostly feature regions of unipolar magnetic fields, which is an empirical indicator that the intensity of the green corona must be, on average, much less than that over the zone of sunspots. The only places with enhanced intensities thus appear to be those that are at the junctions of large cells of magnetic fields of opposite polarities, or the regions of so-called polar plumes, which can be observed in both white-light and EUV/XUV emissions by SOHO (DeForest *et al.*, 1997). The observed "gaps" in the intensities of the green corona at high latitudes can also be ascribed to inaccuracies and difficulties in their measurements. We note that green-corona intensities do not depend on magnetic-field polarity.

The large-scale circulation at the solar surface has its response in the green corona. Magnetic fields define the local intensity maxima in the green corona. Our findings simply lend support to the idea that a direct physical coupling between the photospheric magnetic fields and the green corona, discovered in the middle and low heliographic latitudes long ago, applies well also to polar regions.

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