NEW AND OLD MAGNETIC FLUXES AT THE BEGINNING OF SOLAR CYCLE 23

E. E. Benevolenskaya¹, J. T. Hoeksema², A.G. Kosovichev², P.H. Scherrer²

¹Pulkovo Astronomical Observatory, St. Petersburg, 196140, Russia
²W.W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085

ABSTRACT

The 11-year cycle of solar activity follows Hale's law by reversing the magnetic polarity of leading and following sunspots in bipolar regions during the minima of activity. In the 1996-97 solar minimum, most solar activity emerged in narrow longitudinal zones - 'active longitudes' but over a range in latitude. Investigating the distribution of solar magnetic flux, we have found that the Hale sunspot polarity reversal first occurred in these active zones. We have estimated the rotation rates of the magnetic flux in the active zones before and after the polarity reversal. Comparing these rotation rates with the internal rotation inferred by helioseismology, we suggest that both 'old' and 'new' magnetic fluxes were probably generated in a low-latitude zone near the base of the solar convection zone. The reversal of active region polarity observed in certain longitudes at the beginning of a new solar cycle suggests that the phenomenon of active longitudes may give fundamental information about the mechanism of the solar cycle. The non-random distribution of old-cycle and new-cycle fluxes presents a challenge for dynamo theories, most of which assume a uniform longitudinal distribution of solar magnetic fields.

Key words: solar magnetic field, solar cycle, interior.

1. ACTIVE LONGITUDES

Solar magnetic fields and complex of solar activity are distributed on the Sun non-uniformly. Complexes of solar activity are zones of field concentration 20°–60° wide that during subsequent rotations tend to reappear at constant longitude or drift slightly eastward or westward (Gaizauskas et al. 1983). These active zones may persist for 20–40 consecutive rotations and are called 'Magnetic Active Longitudes' (Bumba and Howard 1969). Each complex of solar activity rotates around the Sun at a steady rate. The period is often close to the 27.28 day Carrington rotation period. Using the WSO synoptic maps of the line-of-sight component of magnetic field, $B_\parallel$, we constructed distributions of the relative magnetic flux, covering the period from Carrington rotation number 1909 (CR 1909) until CR 1940. The relative magnetic flux ($F_R$) is defined as the ratio of the absolute values of $B_\parallel$ component averaged in nine longitudinal zones 40° wide and the $B_\parallel$ component averaged for the whole Carrington rotation (CR):

$$F_R(\mu, l_i, t) = B_\parallel(\mu, l_i, t)/\frac{1}{9}\sum_{i=1}^{9} B_\parallel(\mu, l_i, t)$$

(1)

where $\mu = \cos \theta$ is colatitude, $l_i$ are longitudes ($i = 1, \ldots, 9$); $t$ is time in periods of the Carrington rotation. The relative fluxes were calculated separately for the Northern and Southern hemispheres.

Using the relative magnetic flux we have estimated the relative activity in each of the 9 longitudinal zones and compared with the others for a given Carrington rotation. Figure 1a and Figure 2a show that the distributions of the relative magnetic flux in Northern and Southern hemispheres are non-uniform in both longitude and time. Figures 1b and 2b show the flux averaged for the whole period of investigation, also in Northern and Southern hemispheres separately. It is clearly seen a zone at 120°–160° longitude with supressed activity in both hemispheres, and two zones, at 240°–320° in Northern hemisphere and 240°–280° in Southern hemisphere, of enhanced...
activity. The existence of these zones could be a consequence of relatively stable non-axisymmetrical modes of the solar magnetic field.

2. SOHO/MDI DATA

Using SOHO/MDI magnetograph and coronal SOHO/EIT data we focus our investigation on active complex activity living longer than 2 rotations and on the period when the "old" magnetic flux was replaced by "new" magnetic flux. Early it was founded that the "old" magnetic flux was replaced by the "new" magnetic flux in fixed longitudinal zones (Benevolenskaya et al., 1998).

Karen Harvey and Cornelia Zwaan (1993) investigated emergence of the active regions and found that the basically all regions emerged with a bipolar structure. The complexity of the magnetic fields of active regions was created only by the emergence of new bipolar active regions within existing active regions. Bipolar sunspot groups are "Ω-loops" structure of the toroidal magnetic field that erupted through the solar surface. The toroidal $B_\phi$ component is called positive when its direction is westward and the leading sunspot of a bipolar region is negative. During the cycle 22 the polarity of preceding sunspots was positive in the southern hemisphere ($B_\phi < 0$) and was negative in the northern hemisphere where $B_\phi > 0$. Sunspot polarities in the new cycle 23, which began in 1996 September, are reversed according to Hale's law (Hale et al. 1919). We call the magnetic flux observed in cycle 22 "old" if $B_\phi > 0$ in the northern hemisphere or $B_\phi < 0$ in the southern hemisphere. We call the magnetic flux "new" if the sign of $B_\phi$ component is reversed.

The two major zones of the "old" flux occurred at longitudes 160°–220° and 240°–300°. They drifted slowly westward. In this zones the old-cycle flux was

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**Figure 2.** a) Distribution of the relative magnetic flux. The grayscale shows magnetic flux in the range from 0 to 2. (b) Averaged magnetic flux in the beginning of the cycle 23 using WSO data for Southern hemisphere.

**Figure 3.** Synoptic maps of the solar magnetic field for Carrington Rotations 1911 to 1934 derived from the SOHO/MDI magnetograms, during the activity minimum between Cycles 22 and 23. Values of the line-of-sight component of the magnetic field are represented in light and dark colors for positive and negative polarities, respectively. The grayscale shows magnetic field in the range from −10 to 10 G.
Figure 4. Rotation rate inside the Sun determined by helioseismology (Schou et al. 1998) as a function of radius at three latitudes, 0°, 15°, 30° (solid curves with light gray areas indicating 1σ-error estimates). The horizontal shaded areas show the rotation rates of the old magnetic flux in the latitude range 1°—5°, and the new magnetic flux in the range 28°—32°. The horizontal solid line shows the Carrington rotation rate, 456.03 nHz (sidereal period 25.38 days). The vertical dotted line shows the lower boundary of the solar convection zone. R is the solar radius.

replaced by the new-cycle flux. After CR 1923 all significant bipolar regions were of the new cycle and through CR 1934 the number of sunspots substantially increased and covered latitudinal zones 10°—40° wide in both hemispheres (Figure 3).

3. ROTATION OF THE ACTIVE ZONES

We have determined the sidereal rotation rate of 4°-wide latitudinal zones near the equator (the ‘old’ flux zone) and at 30° (where the ‘new’ flux appeared) using the data for the current cycle. The rotation rate of magnetic flux was determined separately for the northern and southern hemispheres. To measure the rotation rate we cross-correlated the magnetic fields measured for subsequent rotations in the latitudinal zones, then averaged the cross-correlation functions separately for each zone for 10 rotations before CR 1922 and 10 rotations after CR 1923, and, finally, determined the location of the maxima of the averaged cross-correlation functions by fitting a Gaussian. We have also applied this procedure to the individual longitudinal active zones using several different averaging periods and obtained similar results. The rotation rate of the equatorial zones in both hemispheres ranged between 461.2 and 462.3 nHz, with a mean value of 461.8 nHz and 1σ-error estimate 0.5 nHz (corresponding sidereal period 25.06±0.03 days).

This value is close to the rotation rate of recurrent sunspots in this zone, 462.1 nHz (25.05 days), determined by Newton and Nunn (1951). For the 30° zones, the rotation rates in the northern and southern hemispheres were slightly different: 446.6 ± 1.7 nHz (25.92 ± 0.10 days) and 444.8 ± 1.6 nHz (26.02 ± 0.10 days) respectively. Both these values are higher than the recurrent sunspot rotation rate of 440.6 nHz (26.27 days) at 30° latitude.

Figure 4 compares these measurements with the internal rotation rate inferred by helioseismology (Schou et al., 1998). It appears that the rotation rate of the old flux is close to the equatorial rotation rate of plasma in the lower convection zone and in the upper part of the convection zone. However, the old flux rotates faster than the averaged rotation rate in the tachocline - the region of the steep radial gradient of solar rotation at the bottom of the convection zone, where the magnetic flux is probably generated (e.g., Golub et al., 1981; Parker, 1993). The rotation rate of the new flux at 30° latitude matches the internal rotation at the same latitude only in a narrow zone of fast rotation in the upper part of the convection zone, approximately at 0.91—0.98 solar radii; it is significantly lower than the rotation rate in the bulk of convection zone including the tachocline.

4. CORONAL SOHO/EIT DATA

The Fe XII (195 Å) EUV coronal images are mainly dominated by closed field regions of the quiet Sun. All the hottest active region loops are visible in this wavelength. Eruptions of the “new” and “old” magnetic flux and reconnections among them are clearly seen in low corona. The compassion between the MDI and EIT images provides more detailed picture of the process of reversal of magnetic field in active longitudes. For the investigated longitudinal zone 160°—220° the “old” magnetic flux was replaced by the “new” magnetic flux during the CR 1921 and CR 1922. In CR 2192 we see co-existence of “new”-cycle region in Southern hemisphere (active region B) and “old”-cycle (active region A) region in Northern hemisphere (Figure 5 a). Both active regions have formed an extended longitudinal “Ω” - loops structure seen in the EIT images (left panel). The emergence of the “new”-cycle region (C) inside the “old”-cycle region can be clearly seen in Figure 5 b. The evolution of the “new”-cycle active region is represented in Figures 5c and 5d.

On the East side of the longitudinal complex activity after emergence of active region (C) a coronal hole is formed. Looking at the whole sequence of such images we can conclude, that the formation of the coronal hole is related to opening “Ω-loops” magnetic structures starting from the mid latitudes and continuing in both poleward directions closely to longitudinal complex activity in a wave-like process. By comparing with Figures 1 and 2 we conclude that the coronal hole was formed in a low-activity longitudinal zone at 120°—160°.

When the active region could be seen at the west limb we can see the loops connecting the active regions of the “old”-cycle and “new” cycle (Figure 6). It is possible that these interconnecting loops appeared as a result reconnection between “old”-cycle and “new”-cycle magnetic fluxes. However, we cannot rule out that the magnetic connection between the “old” and “new” fluxes existed in the interior prior the emergence of the “new” flux. The emergence of the “new” magnetic flux region inside the “old”-cycle region and the connection between them leads to the idea that solar corona play a very important role in evolution photospheric magnetic field, and in formation of longitudinal extended active structures.

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Figure 5. The EIT (195 A) images (left panels) and its corresponding MDI magnetograms (right panels) showing the emergence of an active region (C) of the new cycle at the same longitude which contains a decaying active region (A) of the "old" cycle. Coronal hole (D) was formed after the emergence of region (C).
Figure 6. The SOHO/EIT (195 Å) full-disk image of April, 15, 1997, showing the loops connecting the active regions of the "old" and "new" magnetic flux on the West limb.
5. CONCLUSIONS

1. Emergence the "new" flux and its reconnection with the magnetic field of the "old"-cycle complex activity resulted in an extended longitudinal structure of activity.

2. The new flux, which appears near 30\degree latitude, rotates faster than the mean convection zone rotation rate at that latitude. It matches the subsurface 30\degree rotation only in a fairly narrow zone from 0.91-0.98 R. If the new flux was generated by a dynamo-process at the base of the convection zone than it is likely that the dynamo operates at low latitudes, below 15\degree.

3. This extended longitudinal magnetic structure produced a very long coronal hole connecting the polar regions. It was initially formed at mid latitudes and then extended to the poles in wave-like process.

4. The regions of the new and old cycles were connected in the corona via large-scale loops. Further investigation should show whether the interconnected loops result from magnetic reconnection in the corona, or some kind of magnetic connection between the "new" and "old" fluxes already existed when the "new" flux emerged from the interior.

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