New dynamo pattern revealed by solar helical magnetic fields

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ABSTRACT
Previously unobservable mirror asymmetry of the solar magnetic field – a key ingredient of the dynamo mechanism which is believed to drive the 11-year activity cycle – has now been measured. This was achieved through systematic monitoring of solar active regions carried out for more than 20 years at observatories in Mees, Huairou, and Mitaka. In this paper we report on detailed analysis of vector magnetic field data, obtained at Huairou Solar Observing Station in China. Electric current helicity (the product of current and magnetic field component in the same direction) was estimated from the data and a latitude-time plot of solar helicity during the last two solar cycles has been produced. We find that like sunspots helicity patterns propagate equatorwards but unlike sunspot polarity helicity in each solar hemisphere does not change sign from cycle to cycle - confirming the theory. There are, however, two significant time-latitudinal domains in each cycle when the sign does briefly invert. Our findings shed new light on stellar and planetary dynamos and has yet to be included in the theory.

Key words: Sun: activity – Sun: magnetic fields – Sun: dynamo.

1 INTRODUCTION

"Whirling storms in the earth’s atmosphere, whether cyclones or tornadoes follow a well-known law which is said to have no exceptions: the direction of whirl in the Northern hemisphere is left-handed or anti-clockwise, while in the Southern hemisphere it is right-handed or clockwise" (Hale et al. 1919). Eruptive phenomena in the solar atmosphere are much more powerful than typhoons in the Earth’s atmosphere, and strong helical magnetic fields in regions where eruptive phenomena occur store huge amounts of magnetic energy. American astronomer G.E. Hale was the first to discover the magnetic fields of sunspots and to analyse their helical magnetic configurations. He recognized a similarity with the above-cited polarity rule now known as Hale’s polarity rule for sunspots: the sign of magnetic field is antisymmetric over the solar equator and changes with every 11-year cycle. Recent observations of helical structures in the magnetic fields of solar active regions at the photospheric level encourage us to generalise Hale’s law for the time-latitudinal distribution of the magnetic field helicity, which plays a key role in the mechanism of magnetic field generation operating in the solar interior.

In 1955, Parker suggested a dynamo mechanism in the solar interior based on the combined action of differential rotation and cyclonic convective vortices (Parker 1955) as a viable way to generate magnetic fields capable of driving the activity cycle. We are able to quantify the differential rotation from the motion of large-scale magnetic fields at the solar surface and from helioseismology in the solar convection zone. However, because of the opacity of the solar atmosphere, knowledge of the action of convective vortices can only be obtained from available observations of helical magnetic fields. According to mean field dynamo theory, the electromotive force $\mathbf{E}$ averaged over convective eddies has a component parallel to the magnetic field, $\mathbf{E} = \alpha \mathbf{B} + ...$, where the pseudoscalar $\alpha$ is related to kinetic and electric current helicities $\alpha \sim < \mathbf{V} \cdot \nabla \times \mathbf{V}> + <\mathbf{B} \cdot \nabla \times \mathbf{B}>$. The determination of the kinetic helicity in the solar atmosphere is difficult, while the twist of magnetic fields, can be...
estimated from photospheric vector magnetograms of solar active regions (Seeber 1990; Abramenko et al. 1996; Zhang 2006). The formation of twisted magnetic fields inside the Sun is a fundamental topic for solar dynamo models (Kleiner et al. 2003; Choudhuri et al. 2004; Sokoloff et al. 2006; Zhang et al. 2006); however, for alternative interpretations see (Tanaka 1991; Zhang 1995). The achievement presented in this Report is analysis of vector magnetograms of solar active regions, obtained as a result of systematic monitoring for about 20 years at several solar observatories, such as at Mees in Hawaii, Huairou in Beijing, Mitaka in Tokyo, and also Marshall Space Flight Center in Huntsville. The information on mean electric current helicity and twist comes from vector magnetograms in the form $H_{Cz} = (\mathbf{B} \cdot \nabla \times \mathbf{B})_z$ or \(\alpha_{ff} = (\mathbf{B} \cdot \nabla \times \mathbf{B})_z / B_z^2\), where the former is a part of the current helicity density, and the latter keeps the same sign as the former one, being a factor of the force-free magnetic field. These two quantities reflect different helical characteristics of magnetic fields (see, e.g., Sokoloff et al. 2008; Kuzanyan et al. 2000 Zhang et al. 2002 for details) and, therefore, we consider both of them.

Obtaining values of these helical parameters averaged over an active region we may expect that they reflect the handedness of the solar magnetic field. We found that active regions in the northern (southern) solar hemisphere possess statistically mainly left (right) handedness (Seeber 1990; Pevtsov et al. 1994, 1995; Bao & Zhang 1998) which is persistent over the noisy nature of the signal. Although we admit that the comparison of observational results obtained at different instruments and their interpretation performed by various research groups is not a straightforward issue (Pevtsov et al. 1994; Bao & Zhang, 1998; Hagino & Sakurai, 2004), on average, about 57-66% of solar active regions follow this, so called, the hemispheric helicity rule (Pevtsov et al. 1995; Bao & Zhang 1998; Hagino & Sakurai 2004; Bao, Ai & Zhang 2000; Pevtsov, Canfield & Latushko 2001; Abramenko et al. 1997).

2 METHODS

The observational data used in our analysis were obtained at several observatories in Mees, Mitaka and Huairou. The magnetographic instrument at Huairou Solar Observing station is based on the FeI 53324.19 Å spectral line and determines the magnetic field values at the photospheric level. The data are obtained from a CCD camera with 512 × 512 pixels over the whole magnetogram, whose total size is comparable with the size of an active region. Because of the observational technique, the line-of-sight field component \(B_z\) is determined with a much higher precision than the transverse components \((B_x, B_y)\), where \(x, y, z\) are local Cartesian coordinates connected with a point on the solar surface, and the \(z\)-axis is normal to the surface. For details see, e.g. (Abramenko et al. 1996). A measure of mirror asymmetry of magnetic fields is the electric current helicity \(H_{Cz} = (\mathbf{B} \cdot \nabla) j_z\), where \(j = \nabla \times \mathbf{B}\) is the electric current and \(B\) is the (small-scale) magnetic field. Because \(\nabla \times \mathbf{B}\) is calculated from the surface magnetic field distribution, we are able to determine only the vertical electric current component \(j_z = (\nabla \times \mathbf{B})_z\).

Therefore, the observable quantity averaged over an active region is \(< H_{Cz} >= (\mathbf{B} \cdot \nabla \times \mathbf{B})_z = < j_z >\), see (Abramenko et al. 1996; Pevtsov et al. 1995; Bao et al. 2000).

In the framework of the hypothesis of local homogeneity and isotropy this value is 1/3 of the current helicity \(H_C\). In the solar atmosphere conductivity is relatively small and the magnetic field can be locally described as force-free. We consider the force-free factor as another proxy for the mirror asymmetry of the magnetic field which has the meaning of twist. The twist can be determined as \(\alpha_{ff} = (\mathbf{B} \cdot \nabla \times \mathbf{B}) / B_z^2\). The observational equivalent of the quantity averaged over an active region is the ratio \(\alpha_{av} = < j_z > / B_z\). The magnetic field value at each pixel of a magnetogram plays a role of a weighting factor in averages of twist and current helicity over individual magnetograms. Note, that both the electric current and magnetic field highly fluctuate in.

Figure 1. The main part of active region NOAA 6619 taken at Huairou Solar Observing Station on May 11, 1991, at 03:26 UT. Top: the photospheric vector magnetogram taken. Positive/negative values of longitudinal components of the magnetic field are shaded white/black. The transverse magnetic field is shown by blue arrows; the magnitude of the field is proportional to the length of the arrows. Bottom: the contours of electric current helicity are plotted over the filtergram of this active region; positive (negative) values are shown by red (green) contours corresponding to 0.01, 0.05, 0.1, 0.5 G^2 m\(^{-1}\), respectively. The average values of current helicity and twist are $-8.7 \times 10^{-3}$ G^2 m\(^{-1}\) and $-3.2 \times 10^{-8}$ m\(^{-1}\), the standard deviations 0.08 G^2 m\(^{-1}\) and 1.1 $\times 10^{-6}$ m\(^{-1}\), respectively. One can see that the quantities are highly fluctuating. The field of view is 2.6’ × 1.8’.
space (over the individual magnetogram). One can see that
the average of the product and the average of the ratio of
these quantities may differ a lot and, in general, not have
the same sign. Note that the signal of current helicity can
be detected from solar vector magnetograms with relatively
high accuracy rather than one for twist. So, given their dif-
terent physical meanings, we consider them as two separate
characteristics of mirror asymmetry of magnetic field.

As an example, the photospheric vector field in a typ-
cal delta-type solar active region NOAA 6619 is shown in
Fig. 1. One can see that the longitudinal and transverse
components of the sunspot magnetic field twist clockwise
in the sunspots of the active region (cf. Zhang 2006).

3 RESULTS

Fig. 2 shows the distribution of the average helical char-
acteristics of the magnetic field in solar active regions in
the form of butterfly diagrams (latitude-time) for 1988-2005
(which covers the most of 22nd and 23rd solar cycles). These
results are inferred from photospheric vector magnetograms
recorded at Huairou Solar Observing Station after statistical
reduction of the influence of magneto-optical (or Faraday)
effects in the measurements of magnetic field (Su & Zhang
2004; Gao et al. 2008). This longest available systematic
dataset covering the period of two solar cycles comprises
6205 vector magnetograms of 984 solar active regions (most
of the large solar active regions of both solar cycles). Of
these, 431 active regions belong to the 22nd solar cycle and
553 to the 23rd one. We have limited the latitudes of active
regions to ±55° and most of them are below 35°. The hel-
icity values of the active regions have been averaged over
latitude by intervals of 7° of solar latitude, and over over-
lapping two-year periods of time (i.e., 1988-1989, 1989-1990, ..., 
2004-2005). By this way of averaging we were able to group
at least 30 data points in order to make error bars (computed
as 95% confidence intervals) reasonably small. In this sam-
ping we find that 66% (63%) of active regions have negative
(positive) mean current helicity in the northern (southern)
hemisphere over the 22nd solar cycle and 58% (57%) in the
23rd solar cycle.

We note a remarkable similarity between the wings plotted
for the different tracers (helicity and twist) in Fig. 2. The
analysis of the data for individual tracers shows some simi-
larity between these tracers (Sokoloff et al. 2008; Kuzanyan
et al. 2000) as well as between the data obtained at different
observatories (Huairou, Mitaka and Mees) (Hagino & Saku-
rai 2005; Pevtsov et al. 2008; Xu et al. 2007). However, some
discrepancy reflects the noisy nature of the mirror asymme-
try, also obtained in direct numerical simulations (Branden-
b urg & Sokoloff 2002; Otmianowska-Mazur et al. 2006).

The message which we infer from this butterfly diagram is as follows:

(i) Electric current helicity and twist follow the propa-
gation of the magnetic activity dynamo waves recorded by
sunspots. This demonstrates that the mirror asymmetry is
closely related to the dynamo process. Traditionally, helical
motions were considered as necessary for breaking mirror
symmetry in dynamos. However, the symmetry can also be
broken by random motions (Pevtsov & Longcope, 2007).

(ii) The helicity and twist oscillate with 11-year period
like sunspots rather than 22-year period as magnetic fields
do. This is strikingly important for the theory, as both quan-
tities are not exactly quadratic in magnetic field. Here we
would like to note that the average amplitude of helicity
does not show any significant dependence on the phase of
solar cycle. In generating the magnetic field, dynamo flows
constantly twist and shear the seed magnetic field. As this
magnetic field becomes more twisted, it exerts stronger re-
fistance to further twist. The twist accumulated in a dy-
namo region may slow-down the dynamo action. This effect
is known in dynamo theory as quenching.

(iii) The helicity and twist patterns are in general anti-
symmetric with respect to the solar equator. This result con-

![Figure 2. Top: the distribution of the averaged twist $\alpha_T$; and bottom: electric current helicity $H_{C4}$ of solar active regions in the 22nd and 23rd solar cycles. Superimposed, the underlying coloured “butterfly diagram” shows how sunspot density varies with latitude over the solar cycle. Vertical axis gives the latitude and the horizontal gives the time in years. The circle sizes give the magnitude of the displayed quantity. The bars to the right of the circles show the level of error bars computed as 99% confidence intervals, scaled to the same units as the circles. 72 out of 88 groups for current helicity (82%) as well as 67 out of 88 groups for twist (74%) have the error bars lower than the signal level.](image-url)
firms the hemispheric rule obtained in studies of 11-year observational data sets (Kleeorin et al. 2003; Pevtsov et al. 1994, 1995; Bao & Zhang 1998).

(iv) The helicity pattern is more complicated than Hale’s polarity law for sunspots. Our results revealed specific latitudes and times on the butterfly diagram where the hemispheric helicity law is inverted. So, we found areas of the “wrong” sign at the end of the butterfly wings. This is a challenge for dynamo theory. We can interpret this phenomenon as penetration of the activity wave from one hemisphere into the other “wrong” hemisphere. An analogous pattern can be recognized in sunspot data at the end of the Maunder minimum (Sokoloff 2004). The other domain of the “wrong” helicity sign located just at the beginning of the wing has been predicted (Choudhuri et al. 2004) as a result of additional twisting of the magnetic tubes arising to form a sunspot group.

(v) The average amplitude of the helicity does not show any significant dependence on the phase of solar cycle. In generating the magnetic field, dynamo flows constantly twist and shear the seed magnetic field. As the magnetic field becomes more twisted, it exerts stronger resistance to further twist. Too much twist accumulated in a dynamo region may slow-down the dynamo action, the effect is known in dynamo theory as quenching. The lack of a systematic change in the amplitude of helicity of the solar magnetic field over the course of the solar cycle suggests that helicity is continuously removed from the dynamo region.

(vi) There is an approximately two year time lag between the sunspots and current helicity and twist patterns: the helicity and twist patterns come after the sunspot pattern. Moreover, the maximum value of helicity, at the surface at least, seems to occur near the edges of the butterfly diagram of sunspots. This is an unexpected result which poses another challenge for dynamo theory. The theory predicts (Parker 1955) a lag of the opposite sign (helicity and twist pattern) should appear some 2.7 year before the sunspot pattern. Conventional dynamo models, however, ignore the fact that helicity needs time to follow the magnetic field.

4 CONCLUSIONS

Let us summarize the results. The mirror asymmetry of magnetic fields at the solar surface is related with the magnetic field generation inside the Sun. It evolves with solar cycle, in particular, it has domains of the “wrong” helicity sign at the beginning and end of the wings (see Fig. 2). A quantitative description of the phenomenon remains for further theoretical studies.

Our results bring up a new type of characteristic of hydromagnetic dynamos and pose a challenge for the theory of stellar and planetary magnetic fields.

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