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FINAL TECHNICAL REPORT

MAGNETIC HELICITY AND THE SOLAR DYNAMO

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1 OVERALL OBJECTIVES OF THIS RESEARCH

The objective of this investigation is to open a new window into the solar dynamo, convection, and magnetic reconnection through measurement of the helicity density of magnetic fields in the photosphere and tracing of large-scale patterns of magnetic helicity in the corona.

2 RESEARCH RESULTS

2.1 Theory

With MSU mathematics professor Isaac Klapper, Longcope studied the dynamics of a thin twisted flux tube, which is relevant to our research on helicity. A set of dynamical equations were derived for a slender tube of isolated magnetic flux generalizing a model due to Spruit. The tube as assumed to consist of field lines which twist about the tube's axis at some rate q. The equations describe the evolution of the axis and the evolution of the twist. They include the interaction between twist and motions of the axis described as writhing. Through this interaction the motion of the axis can introduce twist into a previously untwisted tube. The twist so introduced will have a sign opposite to the local handedness of the axial curve. This may be important for the generation of current in emerging active regions. Tubes with sufficiently large twist are subject to an instability which distorts the axis into a helix of pitch similar to the tubes field lines. Such an instability might be responsible for observed morphology in δ-spots on the Sun.

Magnetic reconnection is believed to play a fundamental role in many types of coronal activity such as flaring and transient loop brightenings. Reconnection occurs when flux is transferred between neighboring coronal flux systems. A single flux system consists of coronal magnetic field lines originating in a common pair of photospheric features, (i.e. flux tubes). Changing the flux in such a system requires a substantial electric field in the corona, parallel to a magnetic field line in at least one place. Such an electric field is not consistent with the highly conductive nature of the hot corona.

Longcope developed a model for the evolution of a complexly structured coronal magnetic field driven by motion of photospheric flux tubes. Barring reconnection, motion of photospheric flux tubes leads to the development of three dimensional current sheets (current ribbons) along particular field lines called separators. A separator is a field line which lies at the boundaries of four distinct flux systems simultaneously. The amount of current in a given ribbon is an increasing function of flux tube displacement. The presence of current implies free magnetic field energy, and reconnection must occur eventually if the separator current and stored energy are not to grow indefinitely. When it occurs, reconnection adjusts the fluxes in each system to temporarily obviate the need for current ribbons, thereby liberating the stored free energy. Such instances of reconnection occur sporadically during a typical evolutionary scenario. The frequency of these events, and the energy released, is consistent with transient brightenings observed by Yohkoh.

With Dr. A. V. R. Silva from BBSO, Longcope applied his coronal modelling methods to an observed flare. Observations of a flare on Jan. 7, 1992 were interpreted using a topological model of the magnetic field. Previous observations showed this flare to have complex structure, and involve at least two loops. The topological model confirms this structure and predicts energy storage an subsequent release along separator magnetic field lines. These are found to correspond to the observed locations of soft X-ray emission. The magnitude of stored energy compares favorably to that inferred from observations. The model explains the flare as an impulsive transfer of 3×10^{20} Mx of flux from an emerging bipole into the surrounding active region field.

2.2 Observation and Data Analysis

Using X-ray images, $H\alpha$ images, and vector magnetograms, Pevtsov, Canfield, and Zirin studied the evolution of the coronal structure and magnetic field of NOAA AR 7154 from 5 – 12 May, 1992. A two-ribbon 4B/M7.4 flare was observed on 8 May, 15:13 – 19:16 UT. An interesting feature of the region was a long twisted X-ray structure, which formed shortly before the flare and disappeared after it, being replaced by a system of unsheared post-flare loops. Neither the X-ray nor $H\alpha$ morphology nor the photospheric magnetic field showed any indication of gradual buildup of nonpotential energy prior to the flare. Rather, the long structure appears to result from the reconnection of two shorter ones just tens of minutes before the flare.

From the vector magnetograms and X-ray morphology, we measurezd the helicity density of the magnetic field using the force-free field parameter α. The long structure retained the same helicity density as the two shorter structures, but its greater length implies a higher coronal twist. We show that the measured length and α value combine to imply a twist that exceeds the threshold for the MHD kink instability in a simple flux tube.

Pevtsov and Canfield used Mees Solar Observatory vector magnetograms and Yohkoh Soft X-Ray Telescope images to study the role of magnetic chirality in the trans-equatorial reconnection of active regions. They concluded that active regions reconnect preferentially with others of the same sign of twist (right or left handed). We explain this result with a simple model of the closure of their current systems.

The magnetic helicity of flux tubes can be separated into twist and writhe. If flux magnetic flux bundles rise in Ω-shaped loops through the convection zone, they acquire writhe through the effect of the Coriolis force on flows within them. The tilt of active regions with respect to the equator is an observable manifestation of writhe, at photospheric levels. If magnetic helicity is conserved, we should expect rising flux bundles to acquire equal and opposite twist and writhe.

Using a dataset of Mees Solar Observatory vector magnetograms for about 100 active regions, Pevtsov and Canfield measured both the tilt and twist of their magnetic fields, at large scales. This dataset clearly shows two well-known phenomena, Joy's law and the hemispheric dependence of twist. However, twist and tilt are not related as expected above. We therefore conclude that the twist seen in active regions is the consequence of a deep-seated phenomenon, presumably that of the solar dynamo itself.

Using photospheric vector magnetograms from the Haleakala Stokes Polarimeter and coronal X-ray images from the Yohkoh Soft X-Ray Telescope, Pevtsov, Canfield, and McClymont (University of Hawaii) inferred values of the force-free field parameter α at both photospheric and coronal levels within 140 active regions. We determine the value of α for a linear force-free field that best fits each magnetogram in a least-squares sense. We average values from all available magnetograms to obtain a single mean photospheric α value $< \alpha_p >$ for each active region. From the SXT images we estimate α in the corona by determining $(\pi/L)\ \sin\ \gamma$ for individual loops, where γ is the observed shear angle of X-ray loops of length L. We then average these values to obtain a single coronal α value, $< \alpha_c >$, for each active region.

In active regions whose photospheric α map is predominantly of one sign, we find that the values of $< \alpha_p >$ and $< \alpha_c >$ are well correlated. Only for active regions in which both signs of α are well represented, for which our analysis method breaks down, are the values of $< \alpha_p >$ and $< \alpha_c >$ poorly correlated. The former correlation implies that coronal electric currents typically extend down to at least the photosphere. However, other studies imply subphotospheric origin of the currents, and even current systems, that are observed in the photosphere. We therefore conclude that the currents responsible for sinuous coronal structures are of subphotospheric origin.

3 PUBLICATIONS

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