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Magnetic Fields of Solar Active Regions

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Abstract. After briefly summarizing the outstanding achievements and new tendencies witnessed in recent years in the studies of magnetic fields of solar active regions (ARs), we focus on the current understanding on flux appearance and disappearance. On flux appearance, the moving magnetic features (MMFs) stand still as a mystery in solar physics, although the emergence of magnetic flux in the bipolar form are fairly understood. However, the possibly sympathetic flux emergence of several ARs and the appearance of active longitudes or hot spots are poorly understood. The only confirmed model of flux disappearance is the observed flux cancellation. Detailed analysis of the alignments of transverse magnetic fields and the history of magnetic flux evolution suggest that flux cancellation is more likely to be the magnetic reconnection in the lower solar atmosphere. Magnetic and current helicity provide new diagnosis in understanding flux emergence and disappearance, and constrains the energy process in solar activity.

1. Introduction

The earliest sunspot record appeared in 28 B.C. in HanShu (Records of Five Elements Vol.27, p1507), while the instrument observations of sunspots started since the invention of telescope by Galileo around 1610. The first diagnosis of magnetic fields in sunspot by Hale (1908) marks the birth of modern solar physics and astrophysics. Since then, the studies of magnetic fields in ARs have occupies a central position in solar astronomy. Early key observations and concepts in this study are summarized in Table 1. By the author's limitation, the list, in any sense, could not be complete. However, one fact is clear that by 20 years ago solar astronomers had already prepared the necessary tools, discovered the basic facts and created key concepts for nowadays studies. Rapid progress in AR studies has been continuously made, which greatly influenced other branches of astrophysics. The Michelson Doppler Imager (MDI) on board of Solar and Heliospheric Observatory (SOHO) have realized round-the-clock observations of solar magnetic fields for the first time. The Soft X-ray Telescope on board of Yohkoh, Extreme ultraviolet Imaging Telescope (EIT) of SOHO, and the Transition Region and Coronal Explorer (TRACE) have revealed extremely rich structure and dynamics in active solar atmosphere. On the other hand, by reproducing the detailed observations, the 3-D magnetohydrodynamics (MHD) simulations have tested current understanding and explored new physics on solar magnetism.

2. Achievements and Tendencies

2.1. *Outstanding achievements*

The advent of new telescope design, adaptive optics, and advanced image processing techniques has led to very high spatial resolution in solar polarimetry (Berger, 2004). For the first time, 0.”16 resolution magnetograms have been obtained at Swedish (1 meter) Solar Telescope (Carlsson et al. this volume). At this spatial resolution, many

Year	Key development	Authors
1859	First observations of solar flare	Carrington, Hodgson
1908	Diagnosis of magnetic fields in sunspots	Hale
1919	Dynamo concept of Sun's magnetic fields	Larmor
1946	Early concept of magnetic reconnection	Giovanelli
1952	First magnetograph	Babcocks
1956	Theory of line transfer in magnetic fields	Unno
1958	Concept of neutral point and neutral lines	Sweet, Severny
1960	Early photospheric vector magnetograph	Stepanov
1960	Loop-loop interaction flare model	Gold & Hoyle
1965	Small-scale nature of magnetic fields	Sheeley et al.
1966	Early idea of the 'standard flare model'	Sturrock
1967	Identity of emerging flux regions	Bruzek
1971	First Stokes polarimeter	Cacciani & Fofi
1971	Observation of moving magnetic features	Vrabec
1971	First observations of coronal mass ejections	Tousey
1973	Observations of ephemeral active regions	Harvey & Martin
1973	Radio observation of magnetic fields	Gelfreikh et al.
1975	Early flux rope model	Piddington
1980	Space observation of magnetic fields	Henze et al.
1982	Seismology probe of sunspot	Thomas et al.
1984	Description of magnetic shear	Hagyard et al.
1985	Observations of magnetic flux cancellation	Livi, Wang & Martin

Table 1. Early History of AR Magnetic Field Studies

new phenomena, particularly, on the structure of sunspot penumbrae and lightbridge, magnetic elements have been discovered. Totally new terms have been created. At this stage, it is too early to evaluate whether or not the new observations will significantly improve the understanding on the Sun's magnetism and activity.

The great success in infrared Stokes polarimetry from near-infrared to far-infrared lines has achieved unprecedented high sensitivity in magnetic field measurements (Mathew et al. 2003; Khomenko et al. 2003; Penn et al. 2004; Jennings et al.2002). For the first time, extremely high horizontal gradients in AR magnetic field, e.g., 5 G/km, were observed; intrinsic field strength of magnetic elements was obtained, and weak components of solar magnetism were identified. The diagnosis of magnetic fields in filament become possible and the direct measurements of coronal line-of-sight fields are promising by the infrared polarimetry (Lin, Penn & Khun 1998; Lin, Penn, & Tomczyk 2000). Future development of infrared polarimetry at high spacial resolution will enable solar astronomers get definitive ideas about the intrinsic field strength and basic physical scale in solar activity.

A physical understanding of AR magnetic fields can not be made without having the fundamental knowledge about sub-surface structure and dynamics. Important progress in diagnosis of sub-photospheric dynamics and thermodynamics of sunspots has been made by local helioseismology (Komm et al. 2004; Zhao & Kosovichev 2003, 2004; Zhao, Kosovichev, & Duvall, 2004; see also the review by Kosovichev, this volume). For a rapidly rotating sunspot, Zhao and Kosovichev (2003) found evidence of structural twists beneath the visible surface in the active region, indicating that magnetic twists seen at the photosphere also exist beneath the photosphere. These authors also presented evidence that opposite vortical flows might exist below 9 Mm. The vortical flows around this active region may build up a significant amount of magnetic helicity and energy to power solar eruptions.

After many decades of efforts, now we can fairly conclude that firm evidence of activity-associated magnetic changes are identified. Recently a few types of the definitive and rather universal magnetic changes associated with flare occurrence are identified by Big Bear and Huairou Solar Observatories, US National Solar Observatory and a few other institutes (Deng et al. 2001; Zhang et al. 2001; Kurokawa et al. 2002; Qiu et al. 2004; Spirock et al, 2002; Wang et al. 2002a,b, 2004). Rapid flux emergence and sudden flux disappearance in the course of flares are confirmed by high cadence and resolution observations. A new discovery of Sudden decay of sunspot penumbrae is found to be universal for δ-sunspot producing flares (Wang et al. 2004). It was recognized that the flare transients first observed in 1980's might be produced by the nonthermal beam impacted on the atmosphere in regions of strong magnetic fields (Kosovichev & Zharkova 2001; Qiu & Gary 2003).

2.2. *New tendencies*

A new type of approached emerged and became mature, which we refer to as *Observational MHD Approaches*. Typical examples of this type of studies are found in Isobe et al.(2002), Qiu et al. (2002, 2004). Started from the well-accepted MHD theoretical results and based on high cadence and high resolution observations, these authors have extracted some basic plasma parameters in activity for better physical understanding. As a good example, Qiu et al.(2004) inferred the magnetic reconnection rate in terms of the reconnection electric field E_{rec} inside the reconnecting current sheet (RCS) and the rate of magnetic flux convected into the diffusion region by measuring the magnetic flux swept through by flare ribbons. Their results clearly indicated that the physical link between the evolution of flares and CMEs was magnetic reconnection, and a stronger reconnection electric field was associated with a greater mass acceleration. The *observed MHD approach* is promising not only in confirming the established theories, but also in testing if new physics needed for observations.

In addition to the careful case studies, a tendency in vector magnetogram analysis appeared – a *Synthesized Analysis of Vector Magnetograms toward the models of flare/CME prediction*. Studies to extract as much information as possible from the time-sequence of vector magnetograms related to the occurrence of solar energetic events were made by Falconer, Moore, & Gary (2002, 2003), and Leka & Barnes (2003a,b). So far, the following perspectives are considered by the above and other authors: 1) distribution of magnetic flux density, 2) total flux and flux imbalance (see Shi & Wang, 1994) in ARs, 3) length and morphology of magnetic neutral line, 4) field inclination, 5) gradients of B, B_h, B_z, 6) vertical Current J_z, 7) twist parameter – α, 8) helicity density – rate and pattern, 8) shear angles, 9) free magnetic energy (Wang et al. 1996).

In last a few years, very hot studies of magnetic and current helicity in ARs have been carried out in following the pioneer work of Berger & Field (1984). These studies mostly concentrate on the helicity determination (DeVore 2000; Chae 2001; Démoulin & Berger 2003; Pevtsov, Maleev, & Longcope, 2003), relationship between activity and helicity (Moon et al.2002; Zhang 2002), CME helicity source (DeVore 2000; Démoulin et al. 2002; Green et al. 2002; Nindos & Zhang 2002; Nindos, Zhang, & Zhang 2003), origin and cyclic changes of helicity (Benevolenskaya 2000; Berger & Ruzmaikin 2000; Magara & Longcope 2003; Bao & Zhang 1998; Bao, Sakurai, & Suematsu, Y. 2003; Choudhury 2004 in this volume; Sokoloff 2004 in this volume), and helicity patterns (Kusano et al. 2004; Wang, Zhou, & Zhang 2004). An early estimation (Wang, 1996) that for a rapidly growing AR, the total magnetic helicity was $10^{43} Mx^2$, and the rate of helicity evolution

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was $10^{39} Mx^2 s^{-1}$ seems to be confirmed by later investigations. The key questions to be considered are what has been constrained by helicity on the magnetic field generation, what can we learned from helicity on the energy release process in solar activity.

3. Explorer New Physics on Flux Appearance and Disappearance

3.1. *Flux Appearance*

3.1.1. *Emerging flux regions*

Emerging flux regions (EFRs) are elementary building blocks of AR magnetic fields. Manifesting the subsurface structure and dynamics, they present the surface signature of solar dynamo. EFRs and their interaction with pre-existing AR fields are always found in activity-prolific ARs. Understanding EFRs means understanding the essential physics of solar activity.

An isolated EFR has been well understood as the expanding topmost portions of a twisted Ω-shaped flux tube by buoyancy instability (Shibata et al. 1989). The 3-D MHD simulations made by Fan (2001) reproduced the fundamental characteristics of observed EFRs, including the flux distribution, transverse field alignment, and the shear motion of magnetic footpoints. Maraga & Longcope (2003), Fan & Gibson (2004) further demonstrated the transport of magnetic energy and helicity to corona by EFRs, and the formation of X-ray sigmoid structure related.

A flare-productive AR, particularly, a δ-sunspot group often has complicated flux emergence. A phenomenological model of flux emergence in δ-sunspots was first proposed by Tanaka (1991). He adopted the emergence of kinked and/or knotted flux ropes to interpret the successive flux appearance in δ-sunspot groups. This idea was further developed by Kurokawa and his co-workers (see Kurokawa et al. 2004). On the other hand, the non-linear development of kink instability of a twisted flux rope in high β plasma has been studies by 3-D MHD simulations (Linton et al. 1999; Fan et al. 1999). The simulations predicted several features required by Tanaka model, e.g., the sharp bending of flux rope and the compact bipole with magnetic orientation inverse to the Hale's polarity law.

It is noticed that the simulations predict that the writhing helicity of the rope and the twisting helicity of the filed lines have the same sign. A statistics of more than 80 flare-productive ARs in this solar cycle by Tian & Liu (2003) confirmed this prediction. Another test can be made by mapping current helicity for a complicated AR. If we assume that the given AR represented the successive emergence of a kink-instable flux rope, we would speculate that the twisting sense, i.e., the current helicity at each cross-section of the rope with the photosphere should generally have the same sign. This is, indeed, the case for AR 10486, a CME-prolific AR. We seem to have basically correct understanding about δ-sunspots. However, for AR 10486 we find profound opposite helicity patches in contrast to the predominant helicity of the AR. Moreover, the flare/CME activity initiated at the site of opposite helicities. We do not have a clear physical picture why this should happen and what it means.

Sometimes, indications of sympathetic flux emergence in several locations of the Sun are seen. Interesting example was the flux emergence of NOAA 10489, 10490, 10491, and 10492 together with NOAA 10488 in a quasi co-temporal way in the late October of 2003. Note, these ARs were not on the same hemisphere. We do not have any ideas about the sympathetic flux emergence.

Serious challenges have been raised by the presence of active longitudes of solar activity known since the late of 1930's. As the active longitudes in the northern and southern hemispheres are different, Bai (2003) suggested to adopt the term of *hot spots*. He found a

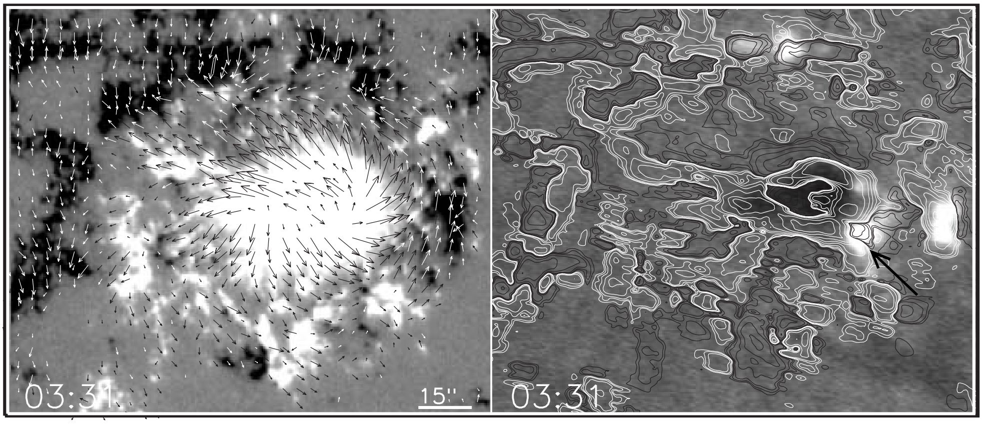

Figure 1. Left: Huairou vector magnetograms at 03:31 UT. The line-of-sight magnetogram is scaled from -300 to 300 G in order to show MMFs more clearly, and the transverse field is represented by arrow with length proportional to the field strength; Right: Hβ filtergram showing the early flaring sites. The brightest flaring patch is indicated by an arrow. Superposed on the Hβ image are the contours of current helicity with levels of $\pm$0.5, 1, 5, 10, 20, 40, 60 A^2m^{-3}.

double-hot-spot system with rotation period of 28.2 days during Solar Cycle 23. Current dynamo theories have not confronted this long-lasting problem in solar physics.

3.1.2. *Moving magnetic features*

Moving magnetic features (MMFs) are an intriguing property of sunspots (Harvey & Harvey, 1973). However, the nature of MMFs are not known clearly by solar community. They certainly do not represent the sunspot decay, since even the new emerging ARs have MMFs, and the total magnetic flux of MMFs emanated from a sunspot are comparable to the total flux of their parent sunspot. The MDI observations with high resolution mode greatly facilitate the MMF studies (Yurchyshyn et al. 2001a,b,c; Zhang, Solanki, & Wang 2003). Zhang, Solanki, & Wang proposed that the MMFs were part of U-loops emanating from the sunspot canopy. This idea partially comes from the polarity distribution of MMF pairs: the opposite polarity component (referring to that of sunspot) located in the near site of the sunspot. More recently, Zhang et al. (2004 submitted to *A&A*) further identified that the opposite polarity in a MMF pair coincided with downdraft patch in the Dopplergrams. The new revelation suggests that Evershed flow continues over the edge of sunspot, and then down and up through the U-loop of MMFs.

On the other hand, puzzling correlations of homologous CMEs and MMFs in NOAA 9236 were reported by Zhang & Wang (2002); repeated flares were observed in NOAA 8996, in which instead of EFRs only MMFs were clearly identified (Pohjolainen 2003). If the MMFs really have close correlation with flare/CME activity we may anticipate that MMFs are current-carrying or have non-potential magnetic nature. An examination was made for NOAA 8375 for which high quality Huairou vector magnetograms are available. Figure 1 illustrates that most MMFs in the sunspot moat had negative helicity which is opposite to the dominant helicity sign of the sunspot. This is indicative that MMFs seem to not represent part of sunspot fields. Thus, there is an obvious inconsistency when trying to understand the nature of MMFs. MMFs stand still as a mystery in solar physics.

Flux source of opposite polarity	From different bipoles or origins
Inflow velocity of magnetic flux	0.3 - 0.5 kws^{-1}
Rate of mutual flux disappearance	On quiet Sun – $10^{18} Mxh^{-1}$
	In ARs – $10^{19} Mxh^{-1}$
Alignment of transverse fields	Clear discontinuity and shear

Table 2. Properties of Magnetic Flux Cancellation

3.2. *Flux Disappearance*

The only confirmed mode of flux disappearance is the magnetic flux cancellation which was first described as the mutual flux disappearance in closely-spaced magnetic fields of opposite polarity (Livi, Wang, & Martin, 1985; Martin, Livi, & Wang, 1985). The description was based on the measurements with line-of-sight magnetograms. The first analysis of vector magnetic fields in flux cancellation was made by Wang & Shi (1993). Observed properties of flux cancellation are summarized in Table 2. While active searching for evidence of magnetic reconnection in the corona has been making for many years without definitive success, in the photosphere careful measurements of magnetic changes which meet the scenario of magnetic reconnection are already available.

Wang and Shi (1993) presented the first evidence of magnetic reconnection in the lower atmosphere by the detailed changes of vector magnetic fields in flux cancellation. They demonstrated that whenever there was new emerging flux there was always magnetic reconnection among the new and pre-existing flux. They particularly exemplified in details how a sub-photospheric reconnection, associated with an EFR emerged in an unipolar flux region, resulted in the peculiar appearance of the EFR which showed only the local flux growth and reduction of the same polarity but enhanced bundle of transverse fields connecting the patches of growing and reducing flux. This scenario has been further confirmed by vector field changes in NOAA 9661 (Wang et al. 2002b).

By calculating the electric conductivity in the partially-ionized plasma of the lower atmosphere, Wang (1993) further argued that the Sweet-Parker scheme of reconnection would be enough to account for the observed flux cancellation. Further theoretical arguments for lower atmosphere reconnection were given by Litvinenko (1999), Sturrock (1999), and Ji, Song, & Li (2001).

Generally speaking, magnetic reconnection in the lower atmosphere has not been drawn enough attention in solar community. It is mostly because the slowness of this reconnection which can not match the rapid magnetic energy release in flares. However, the fact that the slow reconnection in the lower atmosphere takes place continuous for hours to days in everywhere when new and old flux systems interact makes this reconnection be extremely important in the magnetism of solar activity. It continuously changes the magnetic connectivity of the overall field, thus, closely couples the photosphere and corona. This seems why almost all types of solar activity, including the CME initiation (Zhang et al. 2001, Zhang, Wang, & Nitta 2001), are associated with the slow reconnection in the lower atmosphere.

In searching for helicity source of CMEs, Wang, Zhou, & Zhang (2004) studies 9 CME-prolific ARs. Unexpectedly, instead of confirming the helicity charging picture, they identified evidence that the new emerging flux often brings up the helicity with sign opposite to the dominant helicity of the ARs. The flare/CME initiated where there is slow reconnection between opposite helicity EFR and AR fields. Since the EFR has opposite helicity sign, it is speculated to present an independent flux system which is

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not topology connected with the AR flux where it emerged. Then the finding supports a paradigm that interaction of topology-independent flux systems is a key ingredient in flare/CME magnetism. It is consistent with the 3D MHD simulation by Linton et al. (2001) and the model by Kusano et al. (2004) that solar flares were triggered by magnetic reconnection which converted oppositely-sheared field into the sheared-free field. It is further argued that counter-helicity interaction causes the largest amount of magnetic energy to release, while co-helicity interaction results in the highest final energy state of the flux system. Therefore the magnetic helicity does constrain the amount of free energy released in flare/CMEs.

4. Two General Remarks

Almost a century elapsed since Hale (1908). Solar astronomers have discovered too many spectacular phenomena, accumulated too many important concepts for general astrophysics. Although unprecedentedly rich observations from space are available, the breakthrough progress in understanding the electromagnetic interaction on the Sun and in the Universe is still waiting for extremely hard and bitter efforts. At this critical time of solar research, the following two general remarks seem to be worthy of further considerations.

We should try very hard to narrow, at least, not widen the gaps between the theories and observations. Diagnosis of sub-photospheric structure and dynamics is still the key to understand the AR fields. Without the detailed knowledge about the vector magnetic fields in the photosphere, the coronal heating and activity can not be properly understood.

We should try very hard to explorer new physics. Following E.N. Parker, when the mathematics becomes too much complicated in the study, it seems the time to stop to find new physics, while when the observations get into too many details, it seems the time to stop to think what physics we are working on. To extract new physical elements in seemingly ugly observations and to understand the lacunae of well-known theories are essential for making new progress.

Solar research will have great contributions to general astrophysics, particularly on understanding cosmical electromagnetic interaction, and benefits the society by laying down the foundation for space weather enterprise.

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