Highlights of Astronomy, Vol. 13
International Astronomical Union, 2003
O. Engvold, ed.

Magnetic Helicity in Sigmoids, Coronal Mass Ejections and Magnetic Clouds

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Abstract. Sigmoids, coronal mass ejections (CMEs) and magnetic clouds (MCs) all show signatures of twisted and writhing magnetic fields. CMEs are often associated with MCs, whose fields are regularly mapped with sensitive magnetometers. These measurements reveal that MC fields are helical, and each MC carries magnetic helicity away from the sun. It is more difficult to determine the magnetic helicity of the corresponding features on the sun. This presentation surveys recent work on helicity in solar features, focusing especially on the interpretation of sigmoids, which are S-shaped, bright features seen in images from the Yohkoh soft X-ray telescope. Several lines of evidence indicate that sigmoids are twisted and writhing flux ropes that erupt as components of CMEs. CMEs may be initiated by MHD-instable flux ropes. The fact that the ejected flux ropes carry off a large amount of positive helicity from the south and negative helicity from the north each solar cycle implies an equal, compensating flow of helicity through the sun's equatorial plane.

1. Introduction

Since it was suggested that interplanetary MCs (Burlaga et al. 1982) systematically carry magnetic helicity away from the sun (Rust 1994; Bieber & Rust 1995), many authors have studied solar phenomena in search of the origins of this helicity flow. The role of magnetic helicity in producing CMEs, from which the MCs evolve, is one of the most intriguing new challenges in solar physics. An appealing picture would have the magnetic helicity generated in or at the base of the convection zone, from which it buoys upward and bursts through the photosphere into the corona. There, it accumulates and forms 'sigmoids' (Rust & Kumar 1996). Sigmoids are S-shaped, bright features that are best seen in images from the Yohkoh soft X-ray telescope. These features presage CMEs (Canfield, Hudson, & McKenzie 1999), and the eruption of a sigmoid often signals the onset of a CME. CMEs from the northern hemisphere predominantly carry off negative helicity while those from the southern hemisphere carry off positive helicity. Equal amounts, $\sim 10^{46}$ Mx^2 of helicity are carried off from each hemisphere in the course of each solar cycle. This escape of helicity may be necessary to the successful functioning of the solar dynamo (Brandenburg, Bigazzi, & Subramanian 2001). Studies of the flow of helicity through the photosphere and corona and into interplanetary space may thus provide important clues to understanding how the solar dynamo works.

The picture just described is not universally accepted, and there are many disputed and unresolved issues. The build-up of helicity in CMEs has been attributed alternatively to (1) the effects of surface differential rotation on the footpoints of coronal loops (DeVore 2000); (2) a systematic effect of the Coriolis force on rising flux tubes (the alpha effect), producing CMEs that simultaneously liberate small-scale twist and large-scale writhe of opposite sign (Blackman & Brandenburg 2003); and (3) a statistical effect on flux tubes due to turbulence and Coriolis forces (the sigma effect) (Longcope, Fisher, & Pevtsov 1998). In addition, there are numerous interpretations of sigmoids: the X-ray emitting plasma of sigmoids may outline writhing flux rope axes, current sheets, or force-free fieldlines. Similarly, the role of helicity escape in the dynamo is not clear: (1) the helicity seen at the sun's surface may be associated with the small-scale or large-scale component of the classical alpha-omega dynamo (Brandenburg & Dobler 2001); helicity may flow globally as described above and by Berger & Ruzmaikin (2000); or (3) no net helicity is released in either hemisphere, the writhe helicity of the flux ropes being equal and opposite to the twist helicity in each flux rope. See Berger (1999) for a tutorial on magnetic helicity.

In this paper, I discuss various interpretations of the origin of helicity, the helicity budget of CME-producing active regions (ARs), and the interpretation of sigmoids, which is an area of much current research; sigmoids are indeed a crucial element in understanding the link between helicity generation in the sun and CMEs .

2. Generation of Magnetic Helicity

Differential rotation at the sun's surface can transfer helicity to coronal magnetic loops. DeVore (2000) found that the effect of differential rotation on 1000 idealized ARs would produce the amount of helicity ejected from the sun each solar cycle by an estimated 5000 CMEs. However, several recent studies (e.g., Démoulin et al. 2002; Pevtsov, Maleev, & Longcope 2003) of helicity generation in ARs whose CME production rate is known from LASCO observations showed that differential rotation could not impart enough helicity to account for the CMEs, assuming that each CME carries off a net helicity of $\sim 2 \times 10^{42}$ Mx^2. The helicity loss rate depends on two important assumptions: that most CMEs include a flux rope-like structure that evolves into the well-documented flux rope structure of a MC, and that magnetic helicity is conserved as the event propagates from sun to Earth. No one has ever directly measured the magnetic helicity of a CME, but recently, Bleybel et al. (2002) used non-linear force-free field reconstructions based on a series of vector magnetograms to show that the magnetic helicity in an AR decreased by 0.7×10^{42} Mx^2 after a CME. This quantity is consistent with CME helicity estimates.

Longcope, Fisher & Pevtsov (1998) proposed that solar AR helicity is produced by the combined effects of the Coriolis force and convective turbulence on rising flux tubes. Their mechanism would seem to produce no net helicity in the corona because the writhe helicity imparted in the flux tube is equal and opposite to the induced twist helicity, under the assumption of helicity conservation. Their so-called sigma mechanism accounts very nicely for the statistical spread of AR twist helicities. If they can keep the writhe helicity from canceling out the twist helicity as the fields emerge into the corona, then the mechanism may be the correct one. According to Berger & Ruzmaikin (2000), however, an emerging flux rope should quickly untwist and unkink if its net helicity is zero.

Like the sigma effect, the classical alpha effect of dynamo theory produces no net helicity in the fields reaching the corona, as pointed out by Blackman & Brandenburg (2003), who proposed that sigmoids in the southern hemisphere, for example, are writhed in the left-handed sense and twisted equally in the right-handed sense. However, relaxation in the corona should proceed at the Alfvén speed, which is generally 300 - 1000 km/s.

3. Interpretation of Sigmoids

Rust and Kumar (1996) interpreted sigmoids as writhing flux ropes, that is, as twisted magnetic fields in which at least one turn of twist helicity has been converted in an $m = 1$ kink instability into writhe of the axis. In their picture, the twist and writhe have the same sign, and twist can accumulate either by transfer from beneath the photosphere or by reconnections with similarly twisted flux ropes. $H\alpha$ filaments sometimes also take on a sigmoidal shape, and their fields might be explained by the same mechanism (Sakurai 1976). On the other hand, Pevtsov, Canfield, & McClymont (1997) showed that linear force-free fields computed from photospheric magnetograms in 140 ARs can nicely fit the corresponding sigmoids. More recently, Low and Berger (2003) proposed that sigmoids trace-out a family of field lines that is in contact with the photosphere near a polarity inversion line in the photospheric fields. Their model is in general agreement with the empirical description of sigmoids offered by Moore et al. (2001). From the observations and the model one gains the impression that a sigmoid is illuminated in soft X-rays because of heating by currents near a so-called bald patch (Titov, Priest, & Demoulin 1993) and that this patch corresponds to the bright waist sometimes seen in sigmoids. The waist is where the field lines writhe downward, so that a sigmoid with positive writhe looks from above like an S. This interpretation is consistent with the findings of Pevtsov, Canfield, & McClymont and others, that positive helical fields associate with S-shaped sigmoids and negative fields associate with Z-shaped sigmoids. Low and Berger also conclude that sigmoids' twist and writhe have the same sign. This implies that the helicity in sigmoids is predominantly positive in the southern hemisphere, because S-sigmoids predominate there, and negative in the north. $H\alpha$ filaments have the same hemispheric distribution, that is, those which positive helical fields fit best predominate in the south, etc. Ruzmaikin, Martin, & Hu (2003) found three MCs with remnants of solar filaments, as revealed by higher density plasma at 1 AU. They showed in each case that the flux rope threading the filament remnants had the same chirality as the flux rope of the surrounding MCs.

4. Conclusions

Recent work tends to confirm that there is an accumulation of magnetic helicity in sigmoids and that this helicity is carried into interplanetary space by CMEs and filament eruptions. This has an important implication for understanding CME onset, suggesting that it could be due to an MHD instability caused by an excess of helicity in the fields. The MHD kink instability might become nonlinear in certain instances (Baty et al. 1998) and start a CME. This idea can be tested in part by measurements of the flow of helicity into the corona. New techniques (e.g. Chae 2001; Kusano et al. 2002; Bleybel et al. 2002) should enable better comparisons of helicity flow with CME rates. A second implication is that since helicity (mostly right-handed in the southern hemisphere and left-handed in the northern hemisphere) is carried off by CMEs, there must be a compensating flow of helicity through the solar equatorial plane, as pointed out by Berger and Ruzmaikin (2000). Positive helicity must flow from north to south, and taking this into account may lead to an explanation of how the activity cycle in the south keeps in phase with that in the north.

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https://doi.org/10.1017/S1539299600015203 Published online by Cambridge University Press