Emerging Flux Tube Geometry and Sunspot Proper Motions

Lidia van Driel-Gesztelyi

(1) Observatoire de Paris, DASOP, F-92195 Meudon Cedex, France
(2) Konkoly Observatory, Budapest, Pf. 67, H-1525, Hungary

Abstract. As sunspots appear at the intersection of rising flux tubes with the photosphere, the observed proper motions of a bipolar sunspot pair is a good indicator of the geometry of the underlying emerging flux tube. An emerging dipole caused by a simple symmetric potential flux tube should display a symmetric divergence of the two spots in diametrically opposite directions, while the proper motions of bipolar spot-pairs belonging to tilted or/and twisted (non-potential) emerging flux tubes are more complicated: asymmetric, not diametrically opposite and may follow a curved pattern. Observation of such motions may help to prove that emerging flux tubes are tilted and frequently twisted, in good agreement with predictions by recent simulation studies.

1. Introduction

Proper motion patterns in a complicated active region may look chaotic at first glance. To understand them we have to follow the evolution of the region, find the bipolar sunspot pairs which build up the magnetic structure, and study their motion first. When looking at the proper motion pattern of emerging simple bipoles we see a well-known divergence of opposite polarity spots. This divergence is rarely diametrically opposite and symmetric. Normally, preceding \( (p) \) spots move faster westward than their following \( (f) \) counterparts eastward. This asymmetry in sunspot proper motions was shown long ago, dating back to Carrington (1863) and Maunder (1919). The asymmetric proper motion biases the rotation rate of young sunspot groups to higher values, as it was pointed out by e.g. Balthasar & Wöhl (1980) and Ternullo, Zappala, & Zuccarello (1981). This fast rotation is decelerating with the age of the sunspot groups (Tuominen & Vitanen, 1987; Gesztelyi & Pap, 1987). Besides the asymmetry we find non-diametrically opposite and curved motion patterns which are most apparent in the earliest stage of the evolution of bipoles. Such irregularities were long attributed to the action of surface flows and/or co-rotation with deeper, faster rotating layers.

On the other hand, we know that sunspots appear at the intersection of magnetic flux tubes with the photosphere. What we actually observe as motion of sunspots is a series of successive cross-sections of the rising flux tube, therefore the geometry of the rising flux tube should strongly influence the motion pattern. Naturally, flux tubes do not emerge as rigid systems: strong buoyancy stretches,
deforms them while breaking through the photosphere, and drag forces of large-scale flows may act on the flux tubes. Nevertheless, we believe that the geometry of the rising flux tube can be deduced from the proper motion pattern.

In this paper we describe characteristic proper motions resulting from tilted and twisted (non-potential) flux tube geometry, review related observational results, and refer to relevant predictions by simulations.

2. Tilted Flux Tube Geometry

Assume a planar symmetric flux tube which is rising through the photosphere. The resulting bipolar spot pair should move in diametrically opposite directions and the divergent motion of the \((p)\) and \((f)\) spots should appear symmetric as well. Such symmetric diametrically opposite motions are very rare. The well-known fact that the preceding \((p)\) spots of bipoles move faster westward than the following \((f)\) spots move eastward can be related to a systematic eastward tilt (E-W inclination) of the emerging flux tubes as was proposed by van Driel-Gesztelyi & Petrovay (1990).

Petrovay et al. (1990) pointed out that a systematic inclination of the flux tubes should be accompanied by an asymmetry in the distribution of the magnetic fields in active regions (ARs) providing another method to diagnose the tilt. van Driel-Gesztelyi & Petrovay (1990) indeed discovered that in a statistical sense the magnetic inversion line lies somewhat closer to the \((f)\) spot than to the \((p)\) spot, what was expected in case of E-W inclined flux tube. For this study they used line-of-sight magnetic field maps of 95 bipolar sunspot groups published by Okayama and Tokyo Observatories for the years 1983-1987. Since the line-of-sight magnetograms are subjected to projection effects, therefore they are not ideal for such analysis.

Recently, Cauzzi, Moreno-Insertis & van Driel-Gesztyeli (1996) carried out a similar analysis of vectormagnetograms obtained with the Hawaii Stokes Polarimeter at Mees Observatory during the period of Oct. 1991–Jun. 1995. They computed \(B_z\) maps (along the solar verticals), which were free of projection effects and analysed the magnetic field distribution for 144 simple bipolar ARs using 612 magnetograms. Confirming the former results, they found a small, but significant asymmetry of the magnetic field distribution \(A = 0.54 \pm 0.03\) (an asymmetry greater than 0.5 indicates an eastward tilt of the flux tube). They also found that the asymmetry decreases with the age of the AR, and that the asymmetry of the magnetic field distribution increases with the total magnetic flux of the AR. The consistency of these results and expectations from theoretical simulations are discussed in the last section.

It is noteworthy that Howard (1991, 1993) from an analysis of Mt. Wilson magnetic field data also found an eastward tilt of flux tubes of sunspot groups.

3. Twisted Flux Tube Geometry

It has been a long-standing question what is the cause of more complex, non-diametrically opposite sunspot proper motions. Tanaka (1991), van Driel-Gesztelyi & Leka (1994), Leka et al. (1996) proposed that such can be caused by flux tubes emerging with an inherent twist. A major twist of the flux tube leads
to its deformation as it naturally develops a kink. A kinked flux tube is not a planar feature and its emergence may lead to the formation of bipoles with high axial tilt angles (Weart, 1972), and even reversed polarity ARs (Tanaka, 1991). Although Hα observations suggested that flux can emerge already twisted (e.g Kurokawa, 1987), it was still necessary to prove that.

Up to now, the best-documented example of twisted flux emergence was published by Leka et al. (1996), who presented a careful analysis of flux emergence in AR 7260 between Aug. 16-20, 1992, utilising multiwavelength data including, among others, Hawaii Stokes and IVM vector magnetograms, Hα ± 10 Å, MCCD data and soft X-ray and continuum (G-band) images from the Yohkoh/SXT.

Leka et al. (1996) showed that (i) the Hα and X-ray structures associated with well-observed bipoles did not agree with potential-field extrapolations of magnetograms; (ii) proper motions of the bipoles were not diametrically opposite and followed curved patterns implying that the geometry of the emerging flux tube was not planar; (iii) the new bipoles were co-spatial with significant vertical currents already at a very early stage; (iv) the morphology, proper motion and measured currents of the bipoles were all consistent implying the same sense of twist (v) the new flux emerged in the trailing region of a big pre-existing sunspot, which possessed the same sense of twist as the new flux (vi) the increase of currents, as the new flux emerged, was not consistent with their generation by photospheric motions, i.e. their calculations showed that the observed motions were insufficient to create the observed strong currents during the time available. Therefore they concluded that emerging magnetic flux can appear at the solar surface carrying electric current. The consistency of the sense of twist deduced from the sunspot proper motions and other, very different observations described above, gives further encouragement for reducing the geometry of flux tubes from sunspot motions.

4. Discussion and Conclusions

Simulations of the buoyant rise of flux tubes throughout the convection zone clearly show the appearance of an eastward tilt (Moreno-Insertis, Caligari & Schüssler (1994); Caligari, Moreno-Insertis & Schüssler (1995); Caligari, Schüssler & Moreno-Insertis (1997)). It has been shown that as a consequence of Coriolis force, conservation of angular momentum leads to a retardation of the rising loop, with respect to its anchored feet resulting in an eastward tilt. Furthermore, simulations predict a larger asymmetry during the first few days of an emerging AR, in good agreement with the scenario deduced from proper motions.

Besides the several points where observations and simulations agree, there appears to be a controversy concerning the dependence of the rotational rate on the size (taken as a proxy for flux) of the sunspots. Howard, Gilman & Gilman (1984) and Howard (1987) using the wealth of Mt. Wilson data found that big sunspots, even when young, rotate about 2% slower than small sunspots of the same age. A similar result was found by Dezső & Kovács (1987) in a smaller, but carefully measured and identified sample. While Caligari, Moreno-Insertis & Schüssler (1995) and Caligari, Schüssler, & Moreno-Insertis (1997) deduced
from their model computation that small ARs are less asymmetric and should show slower proper motion than large bipolar regions. On the other hand, Cauzzi, Moreno-Insertis & van Driel-Gesztesy (1996) found that the magnetic field distribution, which was used as a proxy for E-W inclination, increases with the total magnetic flux of the AR, which was consistent with the simulations of Moreno-Insertis, Caligari & Schüssler (1994); Caligari, Moreno-Insertis & Schüssler (1995); Caligari, Schüssler & Moreno-Insertis (1997).

Unfortunately there is no statistical proper motion study using recent data, for which vector magnetograms would be available. Therefore, it is very probable but still to be proven that the greater the asymmetry in proper motions the greater the asymmetry in magnetic field distribution, implying that the greater the E-W inclination of the emerging flux tube is. To answer this question, using Debrecen proper motion data an analysis is on the way of the asymmetry of proper motions for the 144 simple bipolar ARs studied by Cauzzi, Moreno-Insertis & van Driel-Gesztesy, (1996), (Cauzzi et al. 1997).

Theoretical arguments have been raised in favour of the possibility of flux emerging in non-potential magnetic configuration from consideration of available energy for flaring (McClymont & Fisher, 1989; Melrose, 1992). Schüssler (1979) as well as Longcope, Fisher & Arendt (1996) showed that non-twisted flux can not even surface, since untwisted flux tubes tend to split as they rise, while Moreno-Insertis & Emonet (1996) showed that twisted flux tubes do not split. It was shown above that at least in one well-documented case twisted flux emergence was indeed observed and the observed proper motions clearly showed a non-diametrically opposite curved motion pattern.

Recently, Linton, Longcope & Fisher (1996) started to develop a model to examine the extent of deformation of current-carrying sub-photospheric flux tubes. They found that an observable deformation occurs only for strongly twisted flux tubes \( qR \geq 1 \) where \( q \approx \alpha/4\pi \) and \( R \) is the radius of the flux tube. The bipole analysed by Leka et al (1996) were twisted in this sense with \( 0.5 \geq qR \geq 1.2 \). It is possible that in most of ARs the twist is not strong enough to deform the shape of the emerging flux tubes considerably, therefore it stays unobserved in sunspot proper motion patterns. Whether this is true or not, should be further investigated in a statistical sample. Data of Debrecen Heliographic Results combined with relevant vector magnetograms could form a suitable data base for that.

This is a case when "observations meet theory", although we can not say that they agree on all details. Also, there is a lot of observational work to be done. Proper motion patterns, magnetic field distribution and non-potentiality should be investigated on statistical samples, which will be very time-consuming, but certainly very useful in promoting our understanding of the flux emergence process.

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References


