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Are the photospheric sunspots magnetically force-free in nature?

Sanjiv Kumar Tiwari

Udaipur Solar Observatory, Physical Research Laboratory, Dewali, Bari Road, Udaipur - 313 001, India.
email: `stiwari@prl.res.in`

Abstract. In a force-free magnetic field, there is no interaction of field and the plasma in the surrounding atmosphere i.e., electric currents are aligned with the magnetic field, giving rise to zero Lorentz force. The computation of many magnetic parameters like magnetic energy, gradient of twist of sunspot magnetic fields (computed from the force-free parameter α), including any kind of extrapolations heavily hinge on the force-free approximation of the photospheric magnetic fields. The force-free magnetic behaviour of the photospheric sunspot fields has been examined by Metcalf *et al.* (1995) and Moon *et al.* (2002) ending with inconsistent results. Metcalf *et al.* (1995) concluded that the photospheric magnetic fields are far from the force-free nature whereas Moon *et al.* (2002) found the that the photospheric magnetic fields are not so far from the force-free nature as conventionally regarded. The accurate photospheric vector field measurements with high resolution are needed to examine the force-free nature of sunspots. We use high resolution vector magnetograms obtained from the Solar Optical Telescope/Spectro-Polarimeter (SOT/SP) aboard Hinode to inspect the force-free behaviour of the photospheric sunspot magnetic fields. Both the necessary and sufficient conditions for force-freeness are examined by checking global as well as as local nature of sunspot magnetic fields. We find that the sunspot magnetic fields are very close to the force-free approximation, although they are not completely force-free on the photosphere.

Keywords. Sun: atmosphere, Sun: force-free fields, Sun: magnetic fields, Sun: sunspots

1. Introduction

A force-free magnetic field does physically mean a zero Lorentz force (Chandrasekhar 1961; Parker 1979; Low 1982a) i.e., $(\nabla \times \mathbf{B}) \times \mathbf{B} = \mathbf{0}$. This equation can be rewritten as

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \tag{1.1}$$

The z component of above condition allows us to compute the distribution of α on the photosphere (z = 0)

$$\alpha = \left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right] / B_z \tag{1.2}$$

Three cases may arise: (i) $\alpha = 0$ everywhere, i.e., no electric current in the atmosphere resulting in a potential field (Schmidt (1964); Semel (1967); Sakurai (1989); Régnier & Priest (2007) (ii) $\alpha =$ constant everywhere, i.e., linear force-free state (Nakagawa & Raadu 1972; Gary 1989; van Ballegooijen & Cranmer 2010, etc) which is not always valid and (iii) α varies spatially, i.e., nonlinear force-free magnetic field (Sakurai 1979; Low 1982b; Amari *et al.* 2006; Wiegelmann 2004; Schrijver *et al.* 2008; De Rosa *et al.* 2009; Mackay & van Ballegooijen 2009), this is the most common state expected (Low 1985). However, high resolution vector magnetograms are required to confirm this. In earlier works, perhaps the poor resolution of data obscured the conclusions about the validity of linear/non-linear force-free approximations. In the present work, we check the validity of linear/nonlinear assumptions along with examining the force-freeness over sunspot magnetic fields using high spatial resolution photospheric vector magnetograms obtained from Solar Optical Telescope/Spectro-Polarimeter onboard Hinode. The effect of polarimetric noise present in the data obtained from SOT/SP does not affect much in derivation of the magnetic field parameters (Tiwari *et al.* 2009a; Gosain *et al.* 2010).

2. Necessary and sufficient conditions

Necessary condition. Under the assumption that the magnetic field above the plane z = 0 (photosphere) falls off enough as z goes to infinity, the net Lorentz force in the volume z > 0 is just the Maxwell stress integrated over the plane z = 0 (Aly, 1984; Low, 1985). Thus the components of the net Lorentz force at the plane z = 0 can be expressed by the surface integrals as follows:

$$F_x = -\frac{1}{4\pi}\int B_x B_y dxdy; F_y = -\frac{1}{4\pi}\int B_y B_z dxdy; F_z = -\frac{1}{8\pi}\int B_z^2 - B_x^2 - B_y^2 dxdy \quad (2.1)$$

where F_x, F_y and F_z represent the components of the net Lorentz force. According to Low (1985) the necessary conditions for any magnetic field to be force-free are that

$$|F_x| << |F_p|; \quad |F_y| << |F_p|; \quad |F_z| << |F_p| \quad (2.2)$$

where F_p is force due to the distribution of magnetic pressure on z = 0, as given by,

$$F_p = -\frac{1}{8\pi}\int B_z^2 + B_x^2 + B_y^2 dxdy \quad (2.3)$$

It was discussed by Metcalf *et al.* (1995) that the magnetic field is force-free if the aforementioned ratios are less or equal to 0.1. It is to be noted that the conditions 2.2 are only necessary conditions for the fields to be force-free. The reason for this is that some information is lost in the surface integration in Equations 2.1.

Sufficient condition. In a force-free case the tension force will balance the gradient of magnetic pressure demanding for zero Lorentz force. We can split up the Lorentz force ($F = (1/c)J \times B$) in two terms as,

$$\mathbf{F} = \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{4\pi} - \frac{\nabla(\mathbf{B}\cdot\mathbf{B})}{8\pi} \quad (2.4)$$

The first term in the right hand side in the above equation is the tension force ($\mathbf{T}$). The second term represents the gradient of the magnetic pressure i.e., the force due to magnetic pressure ($\mathbf{F_p}$). The vertical component of the tension force term can be simplified to,

$$T_z = \frac{1}{4\pi}\left[B_x\frac{\partial B_z}{\partial x} + B_y\frac{\partial B_z}{\partial y} - B_z\left(\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y}\right)\right] \quad (2.5)$$

where, the last component has been drawn from the condition $\nabla \cdot \mathbf{B} = 0$. The usefulness of the tension force has not found much attention earlier in the literature but for few studies (Venkatakrishnan 1990; Venkatakrishnan *et al.* 1993; Venkatakrishnan & Tiwari 2010). Recently Venkatakrishnan & Tiwari (2010) pointed out the utility of tension force as a diagnostic of dynamical equilibrium of sunspots. It was found (Venkatakrishnan & Tiwari 2010) that the magnitude of vertical tension force attains values comparable to the force of gravity at several places over the sunspots meaning that the non-magnetic forces will not be able to balance this tension force. Only gradient of the magnetic pressure can match this force resulting into the force-free configurations. This serves as a sufficient

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condition for verifying the force-freeness of the sunspot magnetic fields. A detailed work is under preparation.

3. Data and analysis

We have used the high resolution vector magnetograms obtained from the Solar Optical Telescope/Spectro-polarimeter (SOT/SP: Tsuneta *et al.* (2008); Suematsu *et al.* (2008); Ichimoto *et al.* (2008); Shimizu *et al.* (2008)) onboard Hinode (Kosugi *et al.* (2007)). The data has been prepared as done successfully in Tiwari *et al.* (2009b, 2010); Venkatakrishnan & Tiwari (2009, 2010); Gosain *et al.* (2009, 2010)).

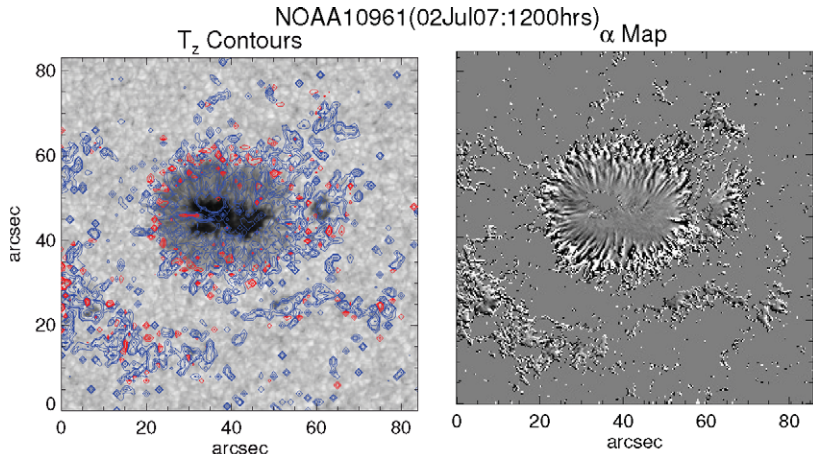

Figure 1. Left panel: Vertical tension force distribution of a sunspot NOAA AR 10961 over its continuum map. Blue (red) colors show negative (positive) contours of $\pm 0.4, \pm 1.2, \pm 4, \pm 12$ millidynes/cm^3. Right panel: Alpha map of the same active region.

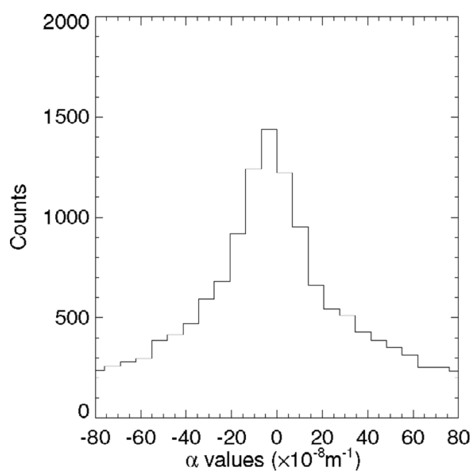

Figure 2. Histogram of the α values of NOAA AR 10961 observed on July 12, 2007 at 1200UT, as an example. We can see even in this simple sunspot, the alpha has a wide range of its distribution.

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4. Results and Discussion

We conclude the following: 1. the sunspot magnetic fields are not far from the force-free nature as has been suspected for long time. 2. The non-linear force-free approximation is closer to validity in all sunspots, either it is a simple active region or a complex one.

It is well known that all extrapolation techniques rely on the photospheric vector field measurements and also on its force-free approximation. Coronal magnetic field reconstruction by extrapolations of photospheric magnetic fields under non-linear modeling have shown satisfactory results by roughly matching with the coronal observations McClymont & Mikic (1994); Wiegelmann *et al.* (2005); Schrijver *et al.* (2006). These results then also support our conclusion that the sunspot magnetic fields are close to non-linear force-free approximation. Greater details will be given in a forthcoming regular paper.

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