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On magnetic field “reconstruction”
(Research Note)

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ABSTRACT

Context. Solanki and colleagues have presented intriguing 3D “reconstructions” of magnetic fields from the vector polarimetry of the He I 1083 nm multiplet.
Aims. In this Research Note I re-examine the reconstruction technique used.
Methods. Using a simple dipole field, I examine the reconstruction technique as applied to the theoretical fields. I assume that the He line forms in two locations, (1) along the magnetic loops and (2) in a horizontal plane.
Results. The planar interpretation can account for all aspects of the data, but the loop interpretation has geometrical and physical problems.
Conclusions. The data by themselves are not sufficient to determine which picture is more applicable. Nevertheless I argue that the planar interpretation makes more physical sense and that the early reconstructions lead to spurious results. I suggest additional tests that might help constrain the problem further.

Key words. polarization – radiative transfer – techniques: polarimetric – Sun: chromosphere

1. Introduction

Measurement of magnetic fields in the solar chromosphere and corona is extremely difficult, yet the need for such measurements is pressing given the obvious dominance of magnetic energy in these regions of the Sun’s atmosphere. In recent years, Solanki and colleagues have pursued an interesting and important line of research using vector spectropolarimetry of the He I 1083 nm multiplet, formed near the coronal base (Solanki et al. 2003, 2006). A key element of their analyses is the assumption that the He line is formed along tubes of magnetic flux as the active region emerges through the chromosphere into the corona. The He line emission then forms in coronal-like loops. With this assumption a 3D magnetic field can be constructed which can be compared with extrapolations from deeper layers (Wiegelmann et al. 2005). Such work is of fundamental importance to understanding how the corona is energized as magnetic fields move from a high- to low β state from photosphere into the corona. For these and other reasons the original work of Solanki et al. (2003) has received considerable attention.

Here I re-examine the assumptions made in their field line “reconstruction” technique. I argue, using simple dipolar field models, that the data are subject to a different, more reasonable interpretation which does not permit one to reconstruct a 3D model empirically, as done by Solanki and colleagues. The different picture is inspired by time-series measurements of vector fields measured in the photosphere, showing that magnetic flux emerges as a 3D structure almost full of magnetic field (Lites et al. 1995, 1998; Okamoto et al. 2008). In such a model, He 1083 nm multiplet formation along a horizontal slab is arguably a more reasonable assumption than along the skin of the emerging region.

Before proceeding, it is useful to note that under “normal” solar conditions, the He I 1083 nm multiplet tends to form in a thin layer at the top of the chromosphere where ionizing EUV radiation (below 50.4 nm) can penetrate and recombination can populate the He I triplet system. Higher in the atmosphere the density is insufficient to produce significant line emission or absorption, in disk observations. Lower down, the EUV radiation cannot penetrate. Thus this line forms typically 2.4 Mm above the limb (Schmidt et al. 1994), with a broad distribution of heights owing to the corrugated nature of the chromosphere/corona interface, created by spicules, among other phenomena. However, the precise formation of the 1083 nm multiplet in the Sun remains a subject for debate (e.g. Centeno et al. 2008).

2. The “reconstruction” technique

From a set of disk spectropolarimetric measurements, magnetic and thermodynamic properties are derived from an inversion scheme. Ignoring the 180° azimuthal ambiguity, of no importance here, one has measurements of the vector magnetic field, line of sight velocities, and other parameters along a given place along the line of sight where the polarized radiation originates.

The central question here is, where is this place? Solanki and colleagues argue that this “formation height” follows some of the field lines, which can therefore be traced in 3D. The technique is then straightforward: choose a pixel near a footpoint, follow the field vector to a neighboring pixel. If the field in the new pixel points in the same direction, and its magnitude is smaller, assume that one traces a field line in 3D and proceed with the

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process until one of these conditions is no longer satisfied. The resulting structure is assumed to be a magnetic loop.

Solanki and colleagues provide the following support for this interpretation. First, the region observed is an emerging flux region so that the outer shell contains dense plasma out of force balance because pressure gradients cannot support the material lifted into the atmosphere. Second, the plasma flows are consistent with this picture – the tops of the reconstructed loops are blue-shifted but the legs are progressively more red-shifted as the footpoints are approached. This is exactly what is expected under conditions of flux emergence (e.g. Lites et al. 1998; Okamoto et al. 2008). Third, reasonable results are obtained.

3. A simple calculation

Consider a dipole magnetic field placed on a plane surface, with linear force-free fields extrapolated into the 3D overlying volume. Imagine that spectropolarimetry samples two different regions: (1) the “skin” of an emerging flux region associated with a fixed value of the associated vector potential; and (2) a horizontal cut through a surface a constant height h above the plane surface. Now examine the magnetic fields derived under both scenarios, by applying the “reconstruction” technique to each scenario. In scenario (1), the correct magnetic field configuration will be recovered. But it is clear that the magnetic fields measured in scenario (2) will also fulfil the conditions required for “reconstruction”: the field strength points from one pole towards the other and the field strength is concave upwards between the poles. This means that there are two physical scenarios which will produce qualitatively the same results.

Figure 1 illustrates quantitatively the two scenarios, for the case of a potential field. Point magnetic poles were placed at positions −0.5 and +0.5 of equal and opposite magnetic flux. The figure shows properties of the field in the vertical plane passing through both poles. The upper panel shows some field lines, the middle and lower panels magnetic field strengths and inclinations (arctan B_h/B_v where h, v refer to “horizontal” and “vertical” respectively) as if they were observed from vertically above. Two lines (solid and dotted) show field strengths derived if the measurements sampled planes at geometric heights 0.04 and 0.08 above the lower plane, the others show field strengths as found by following individual field lines upwards to the symmetry point at $x = 0$. (For geometric comparison, the emerging flux region analyzed by Solanki et al. 2003 has footpoints separated by 30 Mm, and the height of formation of the He I 1080.3 nm line in quiet regions is 2.4 Mm, or 0.08 times the footpoint separation.)

The differences in the plotted magnetic properties appear, at a first inspection, to be quite different for cases (1) and (2). Away from the magnetic source, the field strengths are smaller and inclinations smaller for case (1), as expected geometrically. However, this is a highly ideal and artifical calculation. Among other difficulties, in reality the chromosphere is stratified so that the magnetic properties along loops very near the footpoint ($x = -0.5$) will not contribute to the formation of the He I 1083 nm multiplet, because they will lie below the typical formation height of 2.4 Mm of the line. Also the footpoint is here treated as a point source, artificially enhancing field strengths near the source. Thus, one must regard the computed magnetic properties within, say $\delta x \approx 0.05$ of the footpoint to be inaccessible to observations of chromospheric features. Taking this into account, I argue that *the variation of field strength and inclination with distance between the footpoints, for the bulk of the “loop” length, are qualitatively similar in*

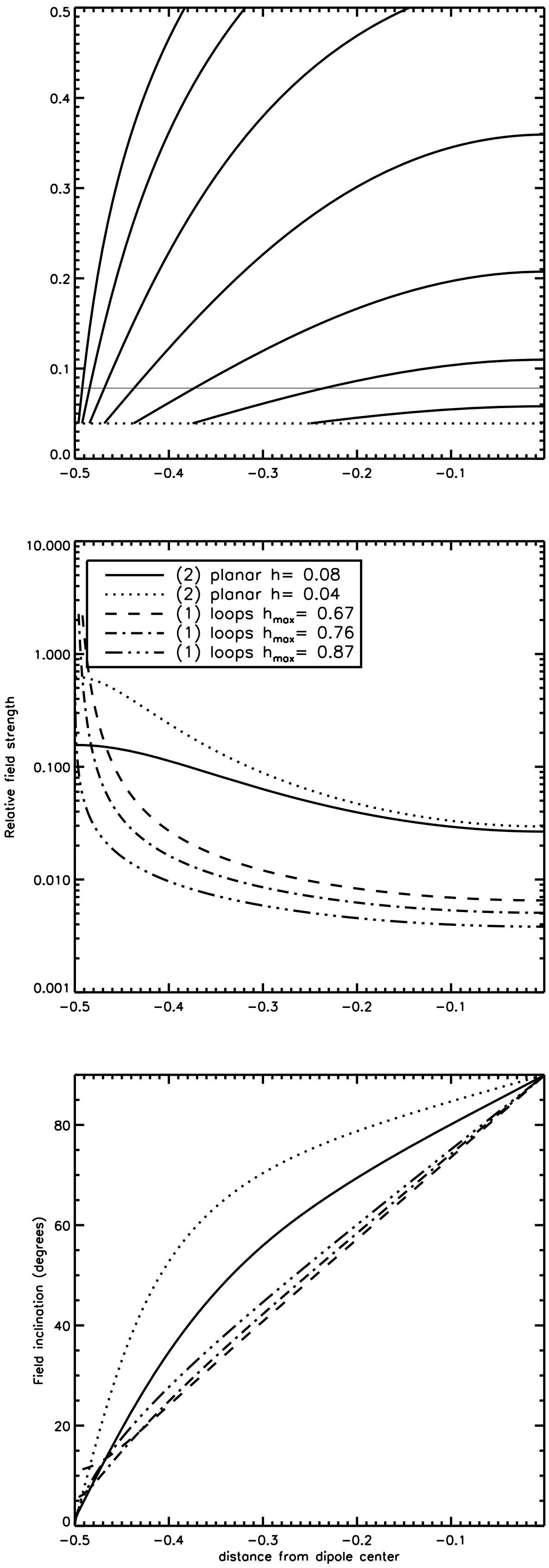

Fig. 1. A potential field calculated from a simple dipole with poles at (−0.5, +0.5) is shown (*top*), in the vertical plane containing the dipoles. *The middle panel* plots field strengths through the intersections of this plane with horizontal planes (solid and dotted lines) and with field lines (others). *The lower panel* shows the field inclination (arctan B_h/B_v where h, v refer to horizontal and vertical respectively).

both cases. Quantitatively, the plotted differences between the two cases simply reflect that fact the loops must extend higher where the field is weaker.

4. Discussion

To get 3D information one must obtain data, such as in a CT scanner, probing three dimensions, or data must be augmented with credible assumptions. Unfortunately stereoscopic data of the kind needed are not available nor will they be for the forseeable future. The assumption made by Solanki and colleages, making their 3D "reconstruction" of magnetic field possible, is that the spectral feature is formed along field lines in an emerging flux region. Unfortunately, my simple example reveals another equally or perhaps more plausible explanation of these data in terms of spectral formation near a given height in the atmosphere. The problem is akin to studying an onion: in case (1), one samples the onion's skin. In the other case one samples a surface after slicing it parallel to the axis of symmetry. In the solar context, case (1) would apply to magnetic field measurements of coronal loops, shown to be 3D loops by stereoscopy (Aschwanden et al. 1999). Case (2) applies to measurements of photospheric magnetic features, formed near a given surface of a certain column mass. The difference is an interpretive one: the magnetic field measured in both cases is part of the same 3D structure. But it is important because further physical interpretation requires knowledge of the 3D geometry. I claim that one cannot easily tell the difference between these two cases, as applied to He I 1083 nm, by remote sensing the solar atmosphere without stereoscopy.

To support this claim further, consider the particular case examined by Solanki et al. (2003). They found field strengths of a few hundred G near the footpoints, and 50 G or so between them. The middle panel of Fig. 1 shows that both cases (1) and (2) might account for such variations, taking into account the unobservability of the source region ($x = -0.5$). The variations in computed field strength for case (1) seems uncomfortably larger than the observed variation, in case (2) the opposite might be true. Solanki et al. note that the observed Doppler shifts- upflow in the middle of the dipole and downflows near the footpoints-support their picture. But this behavior is also expected in the planar picture, for the same reasons, namely that material drains from the emerged flux under the force of gravity in the absence of supporting pressure gradients. One might be tempted to try to discriminate between the two cases using the inclinations of the magnetic field, since for the calculations shown here the behavior is somewhat different: in case (1) the field inclination is almost linear in x, in (2) it has a significant negative curvature. It is interesting that Fig. 2 of Solanki et al. (2003) shows a roughly linear increase of inclination as a function of position between the footpoints, supporting perhaps case (1). However, this support is weak because other potential fields were analyzed, with extended sources, for which qualitatively different results were obtained.

Emerging flux carries with it dense plasma which, if it persists long enough to produce sufficient helium in the triplet system, will be observable in the 1083 nm multiplet. This is the basic assumption underlying the reconstruction technique. The visibility of the 1083 nm multiplet in the shells of emerged flux depends essentially on time scales. Using the measured dimensions and Doppler velocities of the system studied by Solanki et al. (2003), we deduce the following: the rise time of the system $t \sim 1 \times 10^4$ km/2 km s^{-1} $\sim 5 \times 10^3$ s or 80 min. The loop drainage time is $t_d \sim 10^4$ km/10 km s^{-1} or about 17 min. (Downflow velocities are more commonly on the order of 40 km s^{-1}, Lites et al. 1998.) Thus, this loop is most likely emptied of cool material unless it is captured in the initial rise phase. Given that the loop heights already reached 10^4 km as analyzed by Solanki and colleagues, it is probable that these are indeed mostly drained. Cool loops are routinely observed at the limb in Hα as surges, for example, and have been observed in UV active region data in lines from ions such as O VI since SKYLAB (Foukal 1975). Such loops are almost always dynamic, short-lived entities. It would be important to clarify relationships between surges, cool UV active region loops and the He I data analyzed by Solanki and colleagues in future limb observations.

Finally, I note that the region observed has the local vertical was inclined at 39° to the line of sight. Thus, if indeed these are loops, it is interesting that they must have been near the plane containing the loop footpoints and the observatory, otherwise the loop images images would have appeared significantly curved, with field azimuths varying accordingly. But neither feature is evident in the data of Solanki and colleagues. This fortuitous coincidence is not an issue for the planar interpretation. Conversely, significant curvature might favor the loop interpretation.

5. Conclusions

I conclude that the planar interpretation has as much, if not more, in support of it than the loop reconstruction interpretation. The consequences of the different interpretations are obvious, because the magnetic field measurements in the two pictures refer to quite different places on the Sun. As Solanki and colleagues emphasize, the discovery of a current sheet within the corona is an important step in attempting to identify sources of coronal dynamics and heating. Placing the current sheet at the top of the chromosphere, implied by the planar interpretation, means that we have yet to detect a genuine coronal current sheet, observationally.

To decide where the line formation occurs, one might examine the field divergence in the 3D loop interpretation, although this involves the differentiation of noisy data. Another possibility is to examine similar solar features farther from disk center, including the limb, to see if loop reconstructions have the expected curvature when observed obliquely.

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