Nonlinear Force-free Modeling of Flare-related Magnetic Field Changes at the Photosphere and Chromosphere

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Abstract

Rapid and stepwise changes of the magnetic field are often observed during flares but cannot be explained by models yet. Using a 45 minute sequence of Solar Dynamics Observatory/Helioseismic and Magnetic Imager 135 s fast-cadence vector magnetograms of the X1 flare on 2014 March 29 we construct, at each timestep, nonlinear force-free models for the coronal magnetic field. Observed flare-related changes in the line-of-sight magnetic field $B_{\text{LOS}}$ at the photosphere and chromosphere are compared with changes in the magnetic fields in the models. We find a moderate agreement at the photospheric layer (the basis for the models), but no agreement at chromospheric layers. The observed changes at the photosphere and chromosphere are surprisingly different, and are unlikely to be reproduced by a force-free model. The observed changes are likely to require a change in the magnitude of the field, not just in its direction.

Key words: Sun: chromosphere – Sun: flares – Sun: magnetic fields

1. Introduction

While photospheric magnetic field measurements are readily available, measurements at the solar chromosphere and in the corona are less common and less reliable. Often fields in these higher atmospheric layers are approximated by modeling, particularly by nonlinear force-free field (NLFFF) extrapolations. Our goal is to test the agreement of such extrapolations with chromospheric observations, particularly whether the models reproduce the magnetic field changes that are observed in the photosphere and in the chromosphere during a flare.

The equations of the NLFFF model may be written as

$$\nabla \cdot \mathbf{B} = 0,$$

(1)

and

$$\nabla \times \mathbf{B} = \alpha \mathbf{B},$$

(2)

where $\mathbf{B}$ is the magnetic field vector, and $\alpha$ is the force-free parameter. Equation (1) states the fundamental physical condition that the magnetic field must be divergence-free, while Equation (2) states our assumption that the Lorentz force in the corona is zero. NLFFF extrapolations use photospheric vector magnetogram data as boundary conditions to reconstruct the coronal magnetic field (e.g., Wiegelmann & Sakurai 2012). However, a given set of photospheric observations over-determine the force-free model. The data present two different choices for the boundary conditions, implying two possible solutions to the model. Hence additional choices must be made in the modeling, and the results depend to some extent on the specific choices made (e.g., DeRosa et al. 2015).

A flare is attributed to a change in the coronal magnetic field configuration, involving magnetic reconnection and leading to a release of energy. Free energy stored in the solar coronal field is converted, for example, into particle acceleration and heating of the solar atmosphere. Observations often show abrupt and permanent changes of photospheric magnetic fields during flares (e.g., Wang 1992; Wang et al. 1994; Cameron & Sammis 1999; Kosovichev & Zharkova 1999, 2001; Sudol & Harvey 2005; Petrie & Sudol 2010), but their mechanism is not yet fully understood. Photospheric magnetic fields preferentially change near the polarity inversion line, and the line-of-sight magnetic field is equally likely to increase or decrease (Castellanos Durán et al. 2018). Studies with vector magnetograms show that the horizontal field tends to increase close to the neutral line, in a direction parallel to the neutral line (e.g., Petrie 2012). In contrast, chromospheric magnetic field changes are more difficult to study because of the lack of continuous space-based chromospheric polarimetric observations and because of the more complex interpretation of chromospheric spectral lines. Kleint (2017) recently reported observations of chromospheric magnetic field changes during the X1 flare on 2014 March 29, which demonstrated a surprising disparity between the photosphere and the chromosphere. Changes in the magnetic field at the chromosphere were observed to occur over larger areas than at the photosphere; the changes were stronger, and in many cases their locations, signs, and timing did not coincide with those at the photosphere.

This leads to the question of whether NLFFF extrapolations are able to reproduce and explain photospheric and chromospheric magnetic field changes during flares. In this paper, we address this question, by examining again the data from the X1 flare SOL2014-03-29T17:48.

We note that there are two basic limitations of NLFFF modeling for our purpose. First, the nonlinear force-free model does not accurately represent the photosphere–chromosphere transition region, because it excludes nonmagnetic forces. Second, the static NLFFF model cannot represent the dynamic fields present during the flare. To address the second problem, we construct a long sequence of NLFFF reconstructions starting before the flare and ending after. This sequence is used to identify permanent, flare-related changes in the NLFFF models.

2. Observations and Data Reduction

The X1 flare SOL20140329T17:48, the famous “best-observed” flare (e.g., Judge et al. 2014; Battaglia et al. 2015;
Kleint et al. 2015, 2016; Rubio da Costa et al. 2016) was observed by the ground-based Dunn Solar Telescope (DST) and most current solar spacecraft. Its location near disk center (heliocentric angle $\mu = 0.8$) in AR 12017 and the availability of spectroscopy and polarimetry in multiple wavelengths make it a well-suited target for studies.

For the observational comparison to NLFFF extrapolations, we used the data from Kleint (2017) who determined the permanent and stepwise magnetic field changes by fitting an arctan function (Petrie & Sudol 2010) to photospheric and chromospheric line-of-sight magnetic field data ($B_{\text{LOS}}$) after removing solar rotation by cross-correlation of each subsequent frame. For the photospheric changes, the data series hmi.M_45s_nrt from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO; Scherrer et al. 2012) was used with a fitting time range of 30 minutes (17:30-18:00 UT) and a cadence of 45 s. Additionally, as a cross-check, we carried out the same fitting on $B_{\text{LOS}}$ constructed from HMI High-Cadence Vector Magnetograms, which have a cadence of 135 s (Sun et al. 2017) and we used 21 data sets from 17:22 to 18:07 UT.

The chromospheric changes were derived from Interferometric Bidimensional Spectropolarimeter (IBIS) data from the DST (Cavallini 2006; Reardon & Cavallini 2008). The CaII 8542 Å spectral line was observed with two different observing programs: a cadence of 56 s and a Ca line scan time of 18 s before 17:48 UT and subsequently a cadence of 37 s and a Ca line scan time of 15.5 s, and the fit was performed on data from 16:45 to 18:23 UT. To convert the measured chromospheric polarization into $B_{\text{LOS}}$, only data with a sufficiently high polarization signal (max(V/I) $\geq 2\%$) were considered and the weak-field approximation was applied. A more detailed description of the data reduction and fitting process can be found in Kleint (2017).

NLFFF extrapolations require vector field data as input, which is only available in the photosphere. We used the HMI data series hmi.sharp_cea_720s and hmi.B_135s. The 720 s SHARP data contain only a part of the solar surface (usually one active region) and the magnetic field is retrieved by means of a Milne–Eddington inversion (using the VFISV code; Borrero et al. 2011). Because inversions contain a 180 degree ambiguity in the transverse magnetic field where $Q$ and $U$ cannot be uniquely assigned to a magnetic field direction, they are disambiguated in an additional step (e.g., Metcalf 1994).

The CEA in the data series stands for Lambert Cylindrical Equal-Area projection, which is a remapping of $B$ from azimuth, inclination, and field strength into $B_x$ (the radial component), $B_y$ (the westward component of the field), and $B_\theta$ (the southward component of the field; Sun 2013). The 135 s vector data are a new product by the HMI team (Sun et al. 2017). They are in HMI CCD coordinates and therefore we converted them to the CEA projection, which is suitable as input for the NLFFF code. We modified the routines bvec2cea.pro and get_bhzer.pro by Xudong Sun to replicate the output of the SHARP pipeline and verified our pipeline by comparing 135 and 720 s data from the same timestamp, which agreed well in all observables. Extrapolations were performed with both the 135 and 720 s data sets, to check whether the new 135 s data are comparable to the well-established 720 s data. In this paper, we present only the NLFFF extrapolations from the higher cadence data, but we found that the results are the same with the 720 s data.

3. NLFFF Extrapolations

We used the NLFFF code CFIT, which solves the NLFFF equations using the Grad–Rubin method (Wheatland 2007). The NLFFF equations are replaced by linear equations, which are solved iteratively (by “Grad–Rubin iteration”). The linear equations represent updates at a given iteration to the magnetic field in the computational volume and the electric current density in the volume. If the iteration sequence converges, the result is a solution to the NLFFF model (Equations (1) and (2)).

The CFIT code works in a Cartesian geometry. The SHARP data are treated as field values on a Cartesian grid with $B_x = B_{\rho\varphi}$, $B_y = -B_{\rho\varphi}$, and $B_z = B_\rho$, which corresponds to the lower boundary of the computational domain. The boundary conditions for the problem are the values of $B_z$ and the values of the force-free parameter $\alpha$ over one polarity of the field in the boundary (either the region where $B_z > 0$ or the region where $B_z < 0$; Wheatland 2007). Values of $\alpha$ are obtained using $\alpha = \mu_0 J_z/B_z$, where $J_z$ is the local vertical component of the current density, which can be estimated from the values of $B_z$ and $B_\rho$ using finite differences. Hence the vector magnetogram data provide values of $\alpha$ over both polarities; they overspecify the problem. Two solutions can be constructed—the P and the N solutions—corresponding to the choice of values of $\alpha$ on either the positive or negative polarity. In practice, the two solutions may be quite different, because the vector magnetogram boundary data are inconsistent with the model (e.g., De Rosa et al. 2009).

For the active region of interest here (AR 12017 on 2014 March 29), we find that the P and the N solutions are significantly different. Figure 1 illustrates the problem. The middle panel shows the P solution obtained by CFIT for AR 12017 at 17:36 UT on 2014 March 29, and the right panel shows the P solution. Chosen field lines for the two solutions are shown, superposed on an aligned AIA image. The P solution features a filament seen in the AIA image. However, this structure is absent in the N solution. This is because the photospheric positive polarity field has regions with high values of $\alpha$, which do not have counterparts in the negative polarity field. As a consequence of the force-free assumption, $\alpha$ is a constant along any field line in the NLFFF P solution, so the $\alpha$ values at the conjugate footpoint (in the negative polarity) will not match the vector magnetogram values of $\alpha$. The origin of the discrepancy is that the photospheric field is forced, and hence inconsistent with the force-free model.

The energies of the two solutions are also different. We can define the free energy as the difference between total energy $E$ of the model field and the energy $E_0$ of the potential component of the model field. The free energy of the P solution of AR 12017, 2014 March 29 for 17:36 UT is $2.9 \times 10^{31}$ erg (corresponding to $E/E_0 = 1.08$), and the free energy of the N solution at the same time is $9.0 \times 10^{29}$ erg ($E/E_0 = 1.02$). Wheatland & Régnier (2009) proposed the “self-consistency procedure” to address this problem. In this procedure, the P and N solutions are calculated, and then the different boundary
values of $\alpha$ from the two solutions are averaged, subject to the uncertainties in the values. This provides a new set of boundary values of $\alpha$, from which new P and N solutions can be calculated (using also the common boundary values on $B_z$). The new solutions will again be different, but should be closer to agreement. This procedure is repeated (“cycled”) until the P and N solutions agree. The final result is a single, self-consistent force-free solution (Wheatland & Régnier 2009).

We apply CFIT, with self-consistency implemented, to the 2014 March 29, 17:15–18:09 UT, 135 s cadence vector magnetogram data from AR 12017. We rebin the data by a factor of 2 to speed up calculations, so that our volume is $346 \times 277 \times 115$ pixels in size, with each pixel being 1.005 arcsec. In addition, on the boundary data we censor vertical currents with low signal-to-noise, i.e., we set $\alpha = 0$ at points with $\text{SNR}(J_z) < 1$, and we also set $\alpha = 0$ at points with $|B_y| < 0.05 \times \max(|B_z|)$. The number of self-consistency cycles required for CFIT to converge varies between each vector magnetogram boundary data set, but is usually 6–10 cycles.

We want to compare the field values in the NLFFF models with the photospheric (HMI) and chromospheric (IBIS) observations. To do this, we construct line-of-sight photospheric magnetograms from the NLFFF solution data cubes by taking the vector field values at the lower boundary and constructing the line-of-sight field component for the given viewing direction. For the chromospheric comparison, it is necessary to identify an appropriate height in the model. Figure 2 shows line-of-sight magnetograms constructed from the NLFFF extrapolation based on data at time 17:44:15 UT. The magnetograms are shown for the first few height steps in the model, where height 0 is the photospheric boundary and where each step corresponds to 0.725 Mm. The Ca II 8542 Å line forms in the low chromosphere from about 0.5 Mm (line wing) to $\approx 1.5$ Mm (core). By comparing with the observed Ca II 8542 Å magnetograms, we determined the first height step to match the observations most closely.

4. Results

4.1. Comparison of Magnetograms

First we compare the photospheric and chromospheric line-of-sight magnetograms from the available data and from the extrapolations. Figure 3 shows the photospheric magnetograms in the top row with the colors scaled between $-1500$ and $1500$ G. Values below and above these limits are indicated in black and white, respectively. The 45 s data, while qualitatively similar, underestimate the field strength, a known effect of the HMI pipeline (Hoeksema et al. 2014). The photospheric NLFFF data show more weak internetwork field than the original HMI data. To understand this discrepancy, we note that this active region was observed slightly off disk center ($\mu = 0.8$) and therefore the line-of-sight field $B_{\text{LOS}}$ is a mixture of the values of $B_x$, $B_y$, and $B_z$ at the lower boundary in the NLFFF model. The boundary conditions for the NLFFF model are $B_z$ and $\alpha = J_z/B_z$ at the photosphere. The Grad–Rubin method preserves $B_x$ at the photosphere, but changes the values of $\alpha$, which means $B_x$ and $B_z$ at the photosphere change. This is
the origin of the differences between the HMI line-of-sight magnetogram and the one constructed from the model. The bottom row shows the chromospheric IBIS data, whose FOV (indicated by the black rectangle) is limited by the telescope, and the first height step from the extrapolation. The weak field is invisible in IBIS because low polarization signals were excluded from the analysis. The agreement between magnetograms from observations and extrapolations is generally good.

4.2. Comparison of Magnetic Field Changes

Figure 4 shows the stepwise magnetic field changes in the photospheric observations and models. The top row shows the magnetic field changes (according to the color bar) at different spatial locations across the photosphere. To construct the panels in the top row, we verified the arctan fits for every pixel yielding steps above 80 G manually and excluded all data points below 80 G. The HMI 45 s data are shown on the left of the top row (from Kleint 2017), the HMI 135 s data are in the middle, and the changes at the base of the NLFFF models are on the right. Five locations are also identified by boxes and numbers in each panel in the top row. The middle and bottom rows of the figure show the temporal variation of the field (in both the HMI 135 s and NLFFF photospheric data) for nine pixels at the location of each numbered box. The panels in the middle and bottom rows of Figure 4 also show the arctan fits used to determine the size of the change in field in each case.

The field changes seen in the HMI 45 s and 135 s data in the top row of Figure 4 agree well, at least qualitatively, although the size of the changes is larger in the 135 s data due to the previously mentioned underestimation of the field strength in the 45 s data. The photospheric NLFFF changes match the changes in the HMI data near the neutral line, which went through the eastern sunspot. For example, box 0 shows a similar evolution of $B_{\text{LOS}}$, only with a constant offset between observations and model. However, there are also locations where the HMI and NLFFF data disagree, for example, boxes 2 and 5, where the NLFFF model shows a field change that was not observed on the Sun. In order to generate a coronal field that is force-free and self-consistent, the NLFFF reconstruction process necessarily changes the horizontal magnetic field strengths at the photospheric boundary (while keeping the vertical magnetic field strength unchanged). The LOS magnetic field strengths of the NLFFF model are therefore different from those given by the magnetogram data, and the model field can show features and changes that are not observed in the data. The specific reasons for the discrepancies are difficult to identify.

The comparison of chromospheric changes is shown in Figure 5. The left panel in the top row shows the photospheric changes in the HMI 45 s data and is identical to the corresponding panel in the previous figure. The middle panel in the top row shows the changes derived from IBIS observations, and the right panel shows the changes at height.
The poor match between model and observations is obvious. The model shows a broad region with a decrease in the line-of-sight field over the neutral line around [530, 265]″, which is only similar to the observations near box 1. The observations show a prominent region with a line-of-sight field increase centered around box 0 that is not reproduced by the NLFFF models.

To try to understand the observed (and NLFFF model) changes in relation to the model coronal magnetic field, we have overlaid field lines for the NLFFF solutions at three times on the diagrams showing the locations and magnitudes of permanent field changes. Figure 4 presents the results. The three columns correspond to three times: before (17:35:15 UT), during (17:46:30 UT), and after (17:55:30 UT) the flare. The first and second rows from the top show the changes in the NLFFF model and observations at the chromosphere. The third and fourth rows show the changes in the photosphere, in the same order. The field changes are shown in red when positive and blue when negative.

Figure 4 illustrates that most of the changes, in the models and observations, occur around a set of low-lying loops in the models, which run along the neutral line. The observed chromospheric changes are predominantly associated with the footpoints of the loops, whereas the observed photospheric changes include a broad region of decreased line-of-sight field, which is centered around [510, 270]″ and crosses the neutral line. This region underlies a set of very low loops in the models. The changes in the model at the photosphere do not reproduce this feature. The figure illustrates again the point made by Kleint (2017), that the observed photospheric and chromospheric changes are very different. The observed changes have a complex relation with the model field lines. The observed changes at the chromosphere appear to include cases where the line-of-sight field increases at one footpoint and decreases at the other, and cases where the field increases at both footpoints.

In principle, a change in the line-of-sight field seen at the footpoints of coronal loops might be produced by a change in the orientation of the loops. If a field line at a positive footpoint tips toward the observer, the observed \( B_{\text{LOS}} \) increases, and if it tips away, the observed \( B_{\text{LOS}} \) decreases. We can estimate the implied change in angle as follows. If the magnetic field is at an angle \( \theta_0 \) to the line of sight and the angle changes by \( \Delta \theta \) without changing the magnitude \( B \) of the field, then the change in the line-of-sight field is

\[
\Delta B_{\text{LOS}} = B \cos(\theta_0 + \Delta \theta) - B \cos \theta_0 = B(\cos \theta_0 \cos \Delta \theta - \sin \theta_0 \sin \Delta \theta - \cos \theta_0). \tag{3}
\]

Averaging over all possible angles \( \theta_0 \) gives

\[
\langle \Delta B_{\text{LOS}} \rangle = -\frac{2B}{\pi} \sin \Delta \theta. \tag{4}
\]
Taking $\langle \Delta B_{\text{LOS}} \rangle \approx 200$ Gauss and $B_{\text{LOS}} \approx 1000$ Gauss gives the change in angle $|\theta| = \sin^{-1}\left(\frac{\langle \Delta B_{\text{LOS}} \rangle}{B}\right) = 18^\circ$.

Figure 7 illustrates the extent to which field lines in the NLFFF solutions change in direction. Each panel in the figure shows the NLFFF model field lines before (17:35:15 UT) and after (17:55:30 UT) the flare as yellow and black curves, respectively. The field lines are overlaid on images of $\Delta B_{\text{LOS}}$, for the observations (top row) and for the models (bottom row). The left column shows the changes at the photosphere, and the right column shows the changes at the chromosphere. The figure shows clearly that the changes in orientation of the magnetic field lines between the before and after solutions are generally small. The changes in the line-of-sight field in the model involve changes in the magnitude of the field. To the extent that the changes in the model fields at the photosphere reproduce the changes in the HMI observations, this suggests that the observed field changes also involve a change in the magnitude of the field. However, as discussed, the modeled changes in the field at the chromosphere are quite different to those obtained from the IBIS observations.

5. Discussion and Conclusions

Our findings can be summarized as follows:

1. Using an NLFFF model, we compared synthetic and observed line-of-sight magnetogram data to examine how well the model reproduces changes in the observed field strength at both photospheric and chromospheric heights over a $>40$ minutes period around the time of an X1-class flare. The models are constructed from HMI photospheric vector field data, but the model $B_{\text{LOS}}$ is not identical to the photospheric observations because of how the NLFFF solutions are obtained. While there is generally good agreement between the model and observed magnetograms at both heights, there are significant differences in the locations and magnitudes of changes in $B_{\text{LOS}}$.

2. The photospheric changes of the line-of-sight field $B_{\text{LOS}}$ in the observations and NLFFF models match relatively well, especially near the neutral line.

3. The chromospheric changes in $B_{\text{LOS}}$ in the NLFFF models and the observations do not agree. The observations show changes concentrated along the footpoints of loops that span the neutral line, while the NLFFF models indicate broader changes closer to the neutral line. The changes also do not match in sign.

4. The changes at the photosphere in the models (and to the extent that the models reproduce the data, the observations) are unlikely to be produced by a change in the orientation of the field alone. They involve changes in the magnitude of the field.

It is important to consider the influence of observational factors on the results. The observed chromospheric field changes appear to coincide with loop footpoints on either side of the neutral line, whereas the changes in the models are predominantly along the neutral line. This may be in part due to a reduced visibility of the Ca II 8542 Å line at the locations over the neutral line, where the field is nearly perpendicular to the line of sight. The influence of field configurations on the visibility might be tested by additional observations of flares.
with different locations on the disk, and also by forward modeling of the expected changes. Additionally, we are only considering a constant height in the model. During flares, the opacity of the atmosphere may change and we may be seeing different heights in the Ca II 8542 Å line. While we believe that this influence is not major because we fit a long time range of the observations and the intensity returns to preflare values during this time, we cannot fully exclude an influence. But it is known from simulations that the surface with an optical depth $\tau = 1$ is corrugated even in nonflare cases, which means that our approximation of a constant height is not entirely accurate, but cannot be too far off because the observed and modeled magnetograms agree relatively well.

Another observational factor is the method of determining the changes in the field associated with the flare. In principle, some of the inferred changes might be due to flux emergence or diffusion during the observing interval. However, in general, these are slower processes and they are not expected to show clear jumps in $B_{\text{LOS}}$ exactly at the flare time. This possibility was tested by performing the same arctan-fitting on data without any flares (the same region observed a few hours before and after this flare). The result was that no “jumps” larger than 150 G were detected, and the number of small $B_{\text{LOS}}$ changes was an order of magnitude lower than in the current sample. This provides confidence that most of the changes in this analysis are directly related to the flare.

The observed changes in the line-of-sight field at the photosphere and the chromosphere (Kleint 2017) are very different. There is general agreement between the observed and model field changes at the photosphere, but discrepancy between the observed and model changes at the chromosphere. The likely explanation is that the model behavior at the chromosphere follows the photospheric data, and the NLFFF model excludes physics needed to reproduce the chromospheric changes. It is known that the magnetic connection between the photosphere and chromosphere is complex. The high-resolution chromospheric movie of the flare shows a very complex small-scale (subarcsecond) structure with changing loops, which do not seem to be reproduced by this global lower-resolution NLFFF model and this could be a major contributor.
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In summary, for the purpose of reproducing the observed changes, however, these forces may be too slow to generate the large, stepwise changes observed on the flare timescale. The dynamic process most likely requires nonzero Lorentz forces.

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