Measurements of Coronal Magnetic Field Strengths in Solar Active Region Loops

David H. Brooks1,2, Harry P. Warren3, and Enrico Landi4
1 College of Science, George Mason University, 4400 University Drive, Fairfax, VA 22030, USA; dbbrooks.work@gmail.com
2 Hinode Team, ISAS/JAXA, 3-1-1 Yoshinodai, Chuo-ku, Saganahara, Kanagawa 252-5210, Japan
3 Space Science Division, Naval Research Laboratory, Washington, DC 20375, USA
4 Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA

Received 2021 May 7; revised 2021 June 14; accepted 2021 June 18; published 2021 July 6

Abstract

The characteristic electron densities, temperatures, and thermal distributions of 1 MK active region loops are now fairly well established, but their coronal magnetic field strengths remain undetermined. Here we present measurements from a sample of coronal loops observed by the Extreme-ultraviolet Imaging Spectrometer on Hinode. We use a recently developed diagnostic technique that involves atomic radiation modeling of the contribution of a magnetically induced transition to the Fe X 257.262 Å spectral line intensity. We find coronal magnetic field strengths in the range of 60–150 G. We discuss some aspects of these new results in the context of previous measurements using different spectropolarimetric techniques, and their influence on the derived Alfvén speeds and plasma β in coronal loops.

Unified Astronomy Thesaurus concepts: Solar physics (1476); Solar active region magnetic fields (1975)

1. Introduction

The magnetic field in the Sun’s corona is the primary driver of activity. To fully understand the processes that heat the solar corona, drive flares, and coronal mass ejections (CMEs), and form and accelerate the solar wind, we need to fully establish the coronal magnetic structure. Underpinning much of coronal physics research are models that extrapolate the photospheric magnetic field. We expect significant advances in our understanding of all aspects of coronal structure and dynamics would be made if we could reliably measure the actual topology and evolution of the coronal magnetic field.

Indirect measurements of coronal magnetic field strengths have been attempted through novel techniques such as coronal seismology (Nakariakov & Ofman 2001; Van Doorsselaere et al. 2008), or determining the geometric properties of a CME flux rope and leading shock (Gopalswamy et al. 2012). Attempts have also been made to infer the coronal magnetic field using nonlinear force-free field extrapolations (De Rosa et al. 2009; Malanushenko et al. 2009, 2012). These efforts highlight that direct measurements are difficult to make. Attempts have been made using Stokes V circular polarization measurements in a variety of spectral lines (Lin et al. 2000; Kuridze et al. 2019), microwave spectropolarimetry (Fleishman et al. 2020), and techniques that combine plasma density measurements with the phase speed of magnetohydrodynamic (MHD) waves (Yang et al. 2020). These studies have generally found coronal magnetic field strengths of a few G below 1.4 solar radii, and up to 50 G in active region loops. Higher field strengths of a few hundred G have been measured in flares and post-flare loops. The Daniel K. Inouye Solar Telescope (Rimmele et al. 2020) is now providing a new capability for measuring coronal magnetic fields.

Recently, a new direct measurement technique has been developed that does not depend on spectropolarimetry. The method relies on a magnetically induced transition (MIT) that contributes to the intensity of the Fe X 257.262 Å spectral line in the presence of an external magnetic field. Without any magnetic field, the line is formed as a combination of emission from an electric dipole (E1) transition from the 3s23p3d 4D5/2 level, and a magnetic quadrupole (M2) transition from the 3s23p43d 4D7/2 level, both down to the 3s23p5 P3/2 ground state. The Zeeman effect due to the magnetic field mixes the 4D5/2 and 4D7/2 levels, and opens a new pathway to the ground state. The idea was first proposed by Li et al. (2015) and discussed further by Li et al. (2016) and Judge et al. (2016). Si et al. (2020) and Landi et al. (2020) subsequently developed techniques to enable measurements using observations by the Hinode (Kosugi et al. 2007) Extreme-ultraviolet (EUV) Imaging Spectrometer (EIS; Culhane et al. 2007). The methods have been applied to EIS observations of the active region corona (Landi et al. 2020; Si et al. 2020), a C-class flare (Landi et al. 2021), and the footpoints of active region core loops (Brooks & Yardley 2021), but these developments now allow use of the large untapped resource that is the EIS post-launch database (14.5 yr at the time of writing).

Active region loops formed near 1–2 MK are of great interest because of their intriguing properties. These loops persist longer than expected cooling times, are overdense compared to static equilibrium theory (Aschwanden et al. 2000; Winebarger et al. 2003), have narrow, but not quite isothermal, temperature distributions (Warren et al. 2008), and are close to being spatially resolved (Brooks et al. 2012). An extensive review of their properties can be found in Reale (2014). The coronal magnetic field strengths in these loops, however, are currently not known accurately.

When measuring their properties, it is critical to account for line-of-sight contributions from background/foreground emission (Del Zanna & Mason 2003). This line-of-sight superposition is even more difficult to deal with in off-limb measurements, such as would be made with ground telescopes, because of the longer path lengths. The EIS capability to measure magnetic field strengths in coronal loops observed on disk allows us to deal meaningfully with this problem.

Here we measure the coronal magnetic field strength in a sample of active region loops formed near 1 MK. We extract co-spatial background-subtracted intensities for 17 loop segments that are prominent in Fe X and Fe XI emission lines. We then determine their magnetic field strengths. Note that the
loops that are bright in Fe X and Fe XI are usually high-lying structures toward the active region boundary, so there is some overlap with what the community would usually call “fan” loops as well as “warm” loops.

2. Observations and Data Analysis

Hinode/EIS records EUV spectra in two wavelength intervals covering 171–211 Å and 245–291 Å with a spectral resolution of 23 mA and there are four slit options (1″, 2″, 40″, and 266″). The data we use were reduced and processed using the standard procedure eis_prep from the SolarSoftware IDL library (Freeland & Handy 1998)—current as of 2021 April. The calibration software treats instrumental issues such as the effects of contaminated pixels and cosmic-ray strikes. It also converts the raw data to physical units (erg cm⁻² s⁻¹ steradian⁻¹) for analysis. We use the artificial neural network model of Kamio et al. (2010) to correct positional offsets between the two EIS charge-coupled devices (CCDs), and the spectral drift due to orbital thermal effects.

We measure the coronal magnetic field strength using a technique that extracts the excess emission in the Fe X 257.262 Å spectral line due to the production of the MIT by the coronal magnetic field. A method to utilize this line was first investigated by Si et al. (2020). Their technique relied on using the Fe X 174.532 Å spectral line ratioed with Fe X 257.262 Å, although unfortunately this ratio is only weakly sensitive to the magnetic field strength (about 15% over 1–1000 G). The Fe X 174.532 Å line is also rather weak itself. Therefore, Landi et al. (2020) further developed this technique, by estimating the contributions of the E1 and M2 transitions to the Fe X 257.262 Å line, using the much stronger Fe X 184.536 Å spectral line. When the magnetic field strength does not exceed ~200 G, the MIT intensity can be retrieved by removing the E1 and M2 contributions determined by the intensity ratios with the Fe X 184.536 Å line under the assumption of zero magnetic field; therefore, the branching ratio between the MIT and M2 transitions can be determined. This ratio has a much stronger dependence on the magnetic field strength, and can be determined from

\[
\frac{I_{\text{MIT}}}{I_{\text{M2}}} = \frac{I_{257} - (r(E1M2/184) \times I_{184})}{r(M2/184) \times I_{184}}
\]  

(1)

where \(I_{257}\) and \(I_{184}\) are the measured intensities of Fe X 257.262 Å and Fe X 184.536 Å, respectively, \(r(E1M2/184)\) is the ratio of the theoretical magnetic field-free E1 + M2 contribution to Fe X 257.262 Å to the Fe X 184.536 Å intensity, \(r(M2/184)\) is the ratio of the theoretical magnetic field-free M2 contribution to Fe X 257.262 Å to the Fe X 184.536 Å intensity, \(I_{\text{MIT}}\) is the inferred MIT contribution to the intensity of Fe X 257.262 Å (upper line in the equation), and \(I_{\text{M2}}\) is the inferred intensity of the M2 transition (lower line in the equation). The theoretical calculations were made using the CHIANTI v.10 database (Del Zanna et al. 2021).

This method corresponds to the weak magnetic field technique discussed by Landi et al. (2020), and is valid for magnetic field strengths below ~200 G. For higher field strengths, the population of the \(^{1}D_{3/2}\) level becomes sensitive to the magnetic field, so that the M2 intensity can not be directly estimated through zero-field ratios with the Fe X 184.536 Å line, and another method involving the ratio of the total M2 + MIT intensity to the Fe X 184.536 Å intensity is preferred. For all the fine details of these techniques we refer to the papers cited above and in Section 1.

Note that to compute the theoretical ratios we also have to measure the electron density. We used the Fe XI 182.167/ (188.299+188.216) density-sensitive ratio suggested by Landi et al. (2020). One consequence is that we have to ensure that the loops we select are the same when observed in Fe X or XI. This is a condition that limits our selection. The Fe XI lines, however, are stronger than the Fe X density-sensitive ratios that involve the weak Fe X 174.532 Å line.

For this analysis, we focus on large field-of-view (FOV) scans of two active regions taken in 2007 May and December. EIS generally downloads only a subset of all possible spectral lines in each observation. This is because of limitations on the downlink telemetry. Prior to early 2008, however, the X-band transmission system was fully functional, so larger volumes of data could be generated. This means that 2007 is a rich period for data mining of observations with extended wavelength coverage. This is helpful for finding EIS observations that contain the critical Fe X 257.262 Å line. Furthermore, perhaps the biggest uncertainty in applying the EIS magnetic field strength measuring technique is the fact that it relies on spectral lines that fall on different detectors, and therefore depends on the detector cross-calibration. This is known to have evolved over time, but there is not yet a consensus on the best correction method (see Del Zanna 2013; Warren et al. 2014).

By using observations taken early in the mission, we avoid the need to consider the time-dependence of the calibration.

Figure 1 shows an example Fe X 184.536 Å raster image of AR 10978 taken on 2007 December 12. For this observation, the 1″ slit was used to scan an FOV of 460″ × 384″ and the exposure time at each slit position was 40 s. We were able to collect a sample of 14 loops from observations of this active region as it crossed the disk from 2007 December 10 to 18—but see the discussion below. To supplement the sample, we added three more loops from AR 10953 and 10956 that were observed on 2007 May 1 and 19. The raster used for those observations was an early version of the same one, with the same exposure time but a slightly smaller FOV of 330″ × 304″.

A critical component of reliable loop intensity measurements is an adequate background removal technique. Background/foreground emission is known to contribute significantly along the line of sight (Klimchuk et al. 1992; Del Zanna & Mason 2003; Aschwanden & Nightingale 2005; Reale 2014; Brooks 2019), and can distort the measured properties. Here we use a well-established technique introduced by Aschwanden et al. (2008), that we have developed and made use of in several previous studies (Warren et al. 2008; Brooks et al. 2012, 2013). We select a loop segment that is clearly visible in Fe X 184.536 Å spectral images. An example is shown in the top-right panel of Figure 1. The Fe X 184.536 Å spectral image is formed by fitting a single Gaussian to the intensity profile at each pixel. We used a single Gaussian for all the spectral lines analyzed in this study. We extract cross-loop intensity profiles perpendicular to the loop axis and at several positions within the selected segment (boxed region). These are resampled to a higher resolution (sub-pixel) scale. We then average these profiles along the loop axis.

Examples of the cross-loop averaged intensity profiles are shown in the bottom row of Figure 1 for all the lines needed for the magnetic field measurements. The histograms show the data (resampled back to the EIS pixel scale). We subtract the
loop co-spatial background emission by visually selecting two background positions and fitting a first-order polynomial between them. This is the dashed line in the plots of Figure 1. The background positions were selected using the Fe X 184.536 Å profile and the same pixels were used for all the lines. After background subtraction, we fit a Gaussian function to the remaining profile and the area of the Gaussian is the loop intensity.

We also obtain a measure of the electron temperature for each loop. Because 1 MK active region loops typically have narrow temperature distributions (Warren et al. 2008), it is useful to assume a Gaussian emission measure function and find the fit that best reproduces the background-subtracted intensities to localize the peak (we are not concerned here with the shape of the distribution). We then take the temperature of the peak of the emission measure distribution as the temperature of the loop segment. To do this, we add background-subtracted intensities from spectral lines of MgV–VII, SiVII, SiIX, and FeVIII–XVI ions, which cover a wide and adequate range of temperatures ($\log(T/K) = 0.3$–2.8 MK). The co-spatial background was subtracted using the same method as for FeX. Recall that we ensured that each loop observed in FeX was also observed in Fe XI to use the density diagnostic ratio. To do this, we only included examples where the cross-field intensity profiles were highly correlated ($r > 0.8$) with the FeX cross-field intensity profile. We apply the same criteria here for the emission measure analysis, and include a 22% uncertainty to account for the intensity calibration error (Lang et al. 2006).

The cross-field intensity profile for a particular spectral line was not correlated with the FeX cross-field intensity profile, we assume that the emission does not come from the same loop and set the observed intensity to zero. In these cases we take the error as 20% of the background intensity. We also use the electron density we previously calculated to compute the theoretical contribution functions needed for the emission measure measurements.

Having obtained measurements of the loop temperature, electron density, and coronal magnetic field strength, we are also able to compute several plasma quantities for comparisons with theoretical models. We therefore calculated the coronal Alfvén speed, $v_A$, sound speed, $c_s$, and ratio of plasma pressure to magnetic pressure, $\beta$, as follows:

$$v_A = \frac{B}{\sqrt{4\pi \mu m_p n}}; \quad c_s = \sqrt{\frac{\gamma P}{m_p n}}; \quad \beta = \frac{8\pi P}{B^2}$$

where $\mu$ is the permeability of free space, $m_p$ is the proton mass, $n$ is the electron density, $\gamma$ is the ratio of specific heats, $P$ is the plasma pressure, and $B$ is the magnetic field strength.

3. Results and Discussion

We summarize the results of our analysis in Table 1 and Figure 2. The table gives the date of each loop measurement, and the time when the EIS slit was scanning over the position of the selected loop segment. The electron density was calculated using the FeXI ratio, and the temperature was...
All dates are in 2007. Electron densities are shown in brackets.

Table 1

| No. | Date | Time | T | $I_{A44}$ | $I_{A57}$ | E1M2/184 | M2/184 | MIT/M2 | B | $v_A$ | $c_s$ | $\beta$ |
|-----|------|------|---|-----------|-----------|-----------|--------|-------|---|------|------|------|
| 01  | 05/01| 02:57| 9.3| 6.1       | 750 ± 160 | 530 ± 120 | 0.64    | 0.35  | 0.21 ± 0.11 | 120 ± 28 | 5800 | 200 | 1.2(–3) |
| 02  | 05/01| 02:01| 9.2| 6.0       | 670 ± 150 | 490 ± 110 | 0.70    | 0.41  | 0.10 ± 0.05 | 81 ± 18  | 4500 | 190 | 1.7(–3) |
| 03  | 03/19| 13:16| 9.2| 6.0       | 5500 ± 1200 | 4600 ± 1000 | 0.71    | 0.43  | 0.27 ± 0.14 | 140 ± 36 | 7800 | 180 | 5.5(–4) |
| 04  | 12/10| 03:20| 9.3| 6.1       | 590 ± 130 | 420 ± 93  | 0.66    | 0.36  | 0.15 ± 0.08 | 100 ± 23 | 5100 | 200 | 1.5(–3) |
| 05  | 12/10| 03:28| 9.4| 5.9       | 2200 ± 490 | 1400 ± 300 | 0.60    | 0.29  | 0.07 ± 0.03 | 65 ± 13  | 2800 | 160 | 3.2(–3) |
| 06  | 12/12| 15:08| 8.9| 6.1       | 320 ± 70  | 300 ± 66  | 0.82    | 0.55  | 0.22 ± 0.11 | 120 ± 29 | 9400 | 210 | 4.9(–4) |
| 07  | 12/12| 14:48| 9.1| 6.0       | 510 ± 110 | 380 ± 84  | 0.72    | 0.43  | 0.06 ± 0.03 | 60 ± 12  | 3500 | 170 | 2.4(–3) |
| 08  | 12/12| 14:47| 9.4| 6.1       | 650 ± 140 | 460 ± 100 | 0.60    | 0.30  | 0.31 ± 0.16 | 150 ± 39 | 6400 | 210 | 1.0(–3) |
| 09  | 12/12| 14:40| 9.2| 6.2       | 310 ± 68  | 260 ± 56  | 0.71    | 0.42  | 0.28 ± 0.14 | 140 ± 36 | 7800 | 230 | 8.6(–4) |
| 10  | 12/12| 12:58| 8.8| 5.9       | 1000 ± 220 | 960 ± 210 | 0.88    | 0.62  | 0.11 ± 0.05 | 84 ± 19  | 7400 | 170 | 4.9(–4) |
| 11  | 12/13| 16:08| 9.1| 6.1       | 440 ± 97  | 380 ± 83  | 0.74    | 0.46  | 0.25 ± 0.13 | 130 ± 32 | 8000 | 200 | 6.0(–4) |
| 12  | 12/13| 15:36| 9.1| 6.2       | 790 ± 170 | 650 ± 140 | 0.76    | 0.47  | 0.15 ± 0.08 | 100 ± 23 | 6500 | 220 | 1.1(–3) |
| 13  | 12/13| 15:53| 9.8| 5.9       | 1000 ± 230 | 590 ± 130 | 0.45    | 0.13  | 0.99 ± 0.50 | 260 ± 94 | 6800 | 160 | 5.2(–4) |
| 14  | 12/15| 20:06| 9.2| 6.2       | 870 ± 190 | 720 ± 160 | 0.70    | 0.41  | 0.31 ± 0.16 | 150 ± 39 | 8200 | 230 | 8.0(–4) |
| 15  | 12/15| 20:12| 9.5| 6.1       | 720 ± 160 | 460 ± 100 | 0.58    | 0.27  | 0.20 ± 0.10 | 120 ± 28 | 4700 | 220 | 2.0(–3) |
| 16  | 12/15| 20:08| 9.3| 6.1       | 1100 ± 250 | 760 ± 170 | 0.63    | 0.33  | 0.13 ± 0.07 | 95 ± 22  | 4400 | 220 | 2.3(–3) |
| 17  | 12/18| 02:07| 8.9| 6.2       | 700 ± 160 | 630 ± 140 | 0.81    | 0.54  | 0.15 ± 0.07 | 100 ± 23 | 7400 | 230 | 9.1(–4) |

Note. All dates are in 2007. Electron densities ($n$) and temperatures ($T$) are base-10 logarithms in units of cm$^{-3}$ and K. $I_{A44}$ and $I_{A57}$ are the Fe X 184.536 Å and Fe X 257.262 Å intensities, respectively, and are in units of erg cm$^{-2}$ s$^{-1}$ steradian$^{-1}$. E1M2/184 is the modeled contribution of the E1 and M2 transitions to $I_{A44}$ normalized by $I_{A44}$, M2/184 is the modeled contribution of the M2 transition to $I_{A57}$ normalized by $I_{A57}$, MIT/M2 is the MIT to M2 intensity ratio calculated from Equation (1). Coronal magnetic field strengths ($B$) are in units of Gauss. Alfvén ($v_A$) and sound ($c_s$) speeds are in units of km s$^{-1}$. The exponents of the plasma beta ($\beta$) are shown in brackets.

Figure 2. Measurements of the loop segment magnetic field strength (blue dots) overlaid on the theoretical curve of the MIT/M2 intensity ratio as a function of field strength.

The mean electron density for the loops in our sample is log ($n_e$/cm$^{-3}$) = 9.2, which is typical for “warm” 1–2 MK active region loops. The actual mean temperature of the loops is 1.2 MK. The mean magnetic field strength is ~110 G, with the sample of loops falling in the range of 60–150 G. These values are plotted as blue dots in Figure 2. In one exceptional case the field strength is rather high: 260 G. As discussed in Section 2, we used the weak field approximation for this study. This is valid for field strengths up to ~200 G whereupon the strong field approximation should be used (Landi et al. 2020). Adopting the strong field approximation, the value is within a few percent for this loop. This is an encouraging sign that the two methods work consistently.

Alfvén speeds fall in the range of ~2800–9400 km s$^{-1}$, which is much larger than the local coronal sound speeds (~160–230 km s$^{-1}$). The mean plasma beta for this loop sample is ~0.001.

We did not find any obvious relationship between our measured coronal loop magnetic field strengths and the magnitude of the photospheric magnetic flux of the active regions in this survey. We performed some preliminary checks, however, to investigate whether we could uncover any obvious correlations with other properties of the loops. Excluding the loop segment where the measured field strength was too high for the weak field approximation to be valid, we found a strong correlation ($r = 0.66$) with the measured temperature, such that higher magnetic field strengths lead to higher loop temperatures. We show this relationship in Figure 3. This could be influenced by the location where the measurements were made around the loop, although our sample does cover quite a wide range of loop properties from cooler, denser cases to hotter, more tenuous ones. We also found that a relationship can be established with the loop pressure that extends to the loop segment with the highest field strength (shown in Figure 4). This segment also has the highest density and lowest temperature, which act to offset each other and allow the loop

...
to follow the same trend as the others and the correlation between the parameters is also strong ($r = 0.68$). Our initial survey has been limited by the need to select a sample from data taken early in the mission when calibration degradation was minimal. Ongoing progress in improving the EIS calibration will allow a wider study to take advantage of more extensive data (including flare data) in the future. This should help to clarify these relationships further.

Landi et al. (2020) estimated the uncertainty in their measurements to be on the order of 70%—driven by multiple factors such as the cross-calibration between the short- and long-wavelength detectors, the density diagnostic ratio, atomic physics parameters, and also the accuracy of the energy separation between the $^4\text{D}_5/2$ and $^4\text{D}_3/2$ levels. This includes an estimate of the contribution from the radiometric calibration and sensitivity degradation over time. As discussed, we chose observations from early in the mission to minimize the impact of the time-dependence of the calibration. Based on the Warren et al. (2014) model, sensitivity loss is minimal ($<10\%$) for the data sets that we use, so this contribution is reduced from 50% to 24%. This propagates through to produce an uncertainty in $I_{\text{MIT}}/I_{\text{IM}}$ of 51%. We adopt this value in Table 1. Furthermore, the conversion from $I_{\text{MIT}}/I_{\text{IM}}$ to B is not linear (see Figure 2).

To assess the impact of the uncertainties on this conversion, for each loop, we performed a 10,000 run Monte-Carlo simulation where we randomly perturbed the $I_{\text{MIT}}/I_{\text{IM}}$ value within a uniform distribution covering the range defined by the 51% uncertainty. We then take the standard deviation of the magnetic field strength distribution, with the estimated $\sim20\%$ uncertainty in the $^4\text{D}_5/2$ and $^4\text{D}_3/2$ energy separation added in quadrature, as our evaluation of the uncertainty in B. These range from 20%–36% and are added in Table 1.

These uncertainties raise an important issue. The measurements are difficult and the methodology that we use requires good data in several aspects. For example, while background subtraction has proven to be necessary for accurately determining loop properties, if the loop is embedded close to other distinct loops—such as in the fans—then the overlap of emission along the line of sight could be overestimated. This is clearly not the case for the isolated loop in Figure 1, but it highlights that the loops need to be reasonably prominent above the background emission to make the measurement. When the measured field was negative we discarded the loop under investigation. This can happen if the modeled E1+M2 transition contribution to Fe X 257.262 Å is relatively high, or if the $I_{257}/I_{184}$ ratio is relatively low (see Equation (1)). In these cases the $I_{\text{MIT}}/I_{\text{IM}}$ ratio becomes negative and the magnetic field strength is too low to be measured even by the weak field technique. We also discarded any loops with field strengths lower than the measurable limit of the method ($\sim50\,$G, Landi et al. 2020) To be clear, this is a general problem in spectroscopic analysis and not necessarily specific to the magnetic field measurements: we also discarded loops where the measured density was negative. However, it may lead to a selection effect toward loops with strong enough field strength in our sample. The lowest field strength that we were able to measure was 60 G. To gain some insight into this problem, we recorded the reason we rejected each loop from our analysis. In the end, we discarded a comparable number of loop segments from further analysis for this reason. This is why we finally added more loops from ARs 10953 and 10956.

Our magnetic field strength measurements are higher than reported previously in off-limb observations of the corona obtained from ground telescopes. Yang et al. (2020), for example, measured values of 1–4 G at heights ranging from 1.05–1.35 solar radii. We mentioned earlier that the path integration length along the line of sight at the limb results in a larger contribution from the background/foreground emission. It could be that our field strengths are higher because we remove the co-spatial background around the loop. To test this explanation, we re-computed the field strengths for the loops in our sample retaining the background emission. In this case our field strengths are indeed lower, with a median value of 19 G. The reason is that while the background emission may have comparable levels of magnetically insensitive E1 and M2 intensity, it likely has a lower magnetic field strength. This leads to the magnetic signature of the loop being diluted, and appearing to be a structure with a lower magnetic field. This result also gives an indication of the effect of overestimating the background. Because of the limitations in the sensitivity of the technique just discussed, however, many of the field strength measurements become negative. It would be better to
gather a dedicated sample focused on this particular measurement before drawing a definitive conclusion.

We mentioned selection effects and that this is a general problem in spectroscopic analysis and not specific to our magnetic field measurements. coronal seismology techniques, for example, require loop waves/oscillations to make the measurement. This also suggests that there could be real physical reasons for our higher field strengths. Perhaps a lower confining field strength, and potentially less field line braiding, leads to a higher prevalence of loop oscillations.

Given that our magnetic field strengths are higher, and considering that $v_A$ depends linearly on $B$, it is not surprising that our calculated Alfvén speeds are fairly high. Similarly, because $\beta$ depends on the inverse square of $B$, it is also not surprising that the plasma beta for the loops in this sample is small. Our values correspond to approximately the low- to middle-corona in the plasma $\beta$ model of Gary (2001) i.e., below $\sim 100 \text{Mm}$. This might anyway be reasonable as the measurements are made using Fe X.

It will be interesting to compare actual EIS loop field strength measurements with magnetic extrapolations from the photosphere. Landi et al. (2020) compared EIS off-limb measurements with the radial decrease of magnetic field strength obtained from a potential field source surface extrapolation. They found that the measured field falls more slowly—due to a combination of the likely presence of non-potential fields and the weakness of the Fe X spectral lines high off-limb. Comparisons with individual loops are more challenging. Typically the observed intensities scale to some power of $B/B_{\text{loop}}$ where $B$ is the average magnetic field strength along the loop and $L$ is the loop length. Ugarte-Urra et al. (2019), for example, found that Fe X intensities in active region loops scale as $(B/L)^{1/2}$. For the longer, cooler loops in our sample we would expect lower heating rates unless the field is very strong. The mean field strength in the extrapolations in Ugarte-Urra et al. (2019), however, is about a factor of two higher than we measure here.

The data and software needed to reproduce Figure 1 for all the loops is freely available (Brooks & Yardley 2021; 10.5281/zenodo.5044817). The work of D.H.B. and H.P.W. was funded by the NASA Hinode program. The work of E.L. is funded by NASA grants 80NSSC18K1208, 80NSSC20K0185 and NSF grant AGS-1408789. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway). CHIANTI is a collaborative project involving George Mason University, the University of Michigan (USA), University of Cambridge (UK) and NASA Goddard Space Flight Center (USA).

ORCID iDs

David H. Brooks @ https://orcid.org/0000-0002-2189-9313
Harry P. Warren @ https://orcid.org/0000-0001-6102-6851
Enrico Landi @ https://orcid.org/0000-0002-9325-9884

References

Aschwanden, M. J., & Nightingale, R. W. 2005, ApJ, 633, 499
Aschwanden, M. J., Nightingale, R. W., & Alexander, D. 2000, ApJ, 541, 1059
Aschwanden, M. J., Nitta, N. V., Wuelsor, J.-P., & Lemen, J. R. 2008, ApJ, 680, 1477
Brooks, D. H. 2019, ApJ, 873, 26
Brooks, D. H., Warren, H. P., & Ugarte-Urra, I. 2012, ApJL, 755, L33
Brooks, D. H., Warren, H. P., & Winebarger, A. R. 2013, ApJL, 772, L19
Brooks, D. H., & Yardley, S. L. 2021, SciA, 7, eabf0068
Culhane, J. L., Harra, L. K., James, A. M., et al. 2007, SoPh, 243, 19
De Rosa, M. L., Schrijver, C. J., Barnes, G., et al. 2009, ApJ, 696, 1780
Del Zanna, G. 2013, A&A, 555, A47
Del Zanna, G., Dere, K. P., Young, P. R., & Landi, E. 2021, ApJ, 909, 138
Del Zanna, G., & Mason, H. E. 2003, A&A, 406, 1089
Feilshman, G. D., Gary, D. E., Chen, B., et al. 2020, Sci, 367, 278
Freeland, S. L., & Handly, B. N. 1998, SoPh, 182, 497
Gary, G. A. 2001, SoPh, 203, 71
Gopalswamy, N., Nitta, N., Akiyama, S., Mikela, P., & Yashiro, S. 2012, ApJ, 744, 72
Judge, P. G., Hutton, R., Li, W., & Brage, T. 2016, ApJ, 833, 185
Kamio, S., Harra, H., Watanabe, T., Fredvik, T., & Hamsten, V. H. 2010, SoPh, 266, 209
Klimchuk, J. A., Lemen, J. R., Feldman, U., Tsuneta, S., & Uchida, Y. 1992, PASJ, 44, L181
Kosugi, T., Matsuzaki, K., Sakao, T., et al. 2007, SoPh, 243, 3
Kuridze, D., Mathioudakis, M., Morgan, H., et al. 2019, ApJ, 874, 126
Landi, E., Hutton, R., Brage, T., & Li, W. 2020, ApJ, 904, 87
Landi, E., Li, W., Brage, T., & Hutton, R. 2021, ApJ, 913, 1
Lang, J., Kent, B. J., Paustian, W., et al. 2006, ApCh, 45, 8689
Li, W., Grumer, J., Yang, Y., et al. 2015, ApJ, 807, 69
Li, W., Yang, Y., Tu, B., et al. 2016, ApJ, 826, 219
Lin, H., Penn, M. J., & Tomczyk, S. 2000, ApJL, 541, L83
Malanushenko, A., Longcope, D. W., & McKenzie, D. E. 2009, ApJ, 707, 1044
Malanushenko, A., Schrijver, C. J., DeRosa, M. L., Wheatland, M. S., & Gilchrist, S. A. 2012, ApJ, 756, 153
Morgan, H., & Druckmüller, M. 2014, SoPh, 289, 2945
Nakariakov, V. M., & Ofman, L. 2001, A&A, 372, L53
Reale, F. 2014, LRSP, 11, 4
Rimmele, T. R., Warner, M., Keil, S. L., et al. 2020, SoPh, 295, 172
Si, R., Brage, T., Li, W., et al. 2020, ApJL, 898, L34
Ugarte-Urra, I., Crump, N. A., Warren, H. P., & Wiegelmann, T. 2019, ApJ, 877, 129
Van Doorsselaere, T., Nakariakov, V. M., Young, P. R., & Verwichte, E. 2008, A&A, 487, L17
Warren, H. P., Ugarte-Urra, I., Doschek, G. A., Brooks, D. H., & Williams, D. R. 2008, ApJL, 686, L131
Warren, H. P., Ugarte-Urra, I., & Landi, E. 2014, ApJS, 213, 11
Winebarger, A. R., Warren, H. P., & Mariska, J. T. 2003, ApJ, 587, 439
Yang, Z., Bethge, C., Tian, H., et al. 2020, Sci, 369, 694