A Diagnostic of Coronal Elemental Behavior during the Inverse FIP Effect in Solar Flares

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Abstract

The solar corona shows a distinctive pattern of elemental abundances that is different from that of the photosphere. Low first ionization potential (FIP) elements are enhanced by factors of several. A similar effect is seen in the atmospheres of some solar-like stars, while late-type M stars show an inverse FIP effect. This inverse effect was recently detected on the Sun during solar flares, potentially allowing a very detailed look at the spatial and temporal behavior that is not possible from stellar observations. A key question for interpreting these measurements is whether both effects act solely on low-FIP elements (a true inverse effect predicted by some models), or whether the inverse FIP effect arises because high-FIP elements are enhanced. Here we develop a new diagnostic that can discriminate between the two scenarios, based on modeling of the radiated power loss, and apply the models to a numerical hydrodynamic simulation of coronal loop cooling. We show that when low-/high-FIP elements are depleted/enhanced, there is a significant difference in the cooling lifetime of loops that is greatest at lower temperatures. We apply this diagnostic to a post X1.8 flare loop arcade and inverse FIP region, and show that for this event, low-FIP elements are depleted. We discuss the results in the context of stellar observations, and models of the FIP and inverse FIP effect. We also provide the radiated power-loss functions for the two inverse FIP effect scenarios in machine readable form to facilitate further modeling.

Key words: stars: abundances – stars: coronae – Sun: abundances – Sun: corona – Sun: flares – Sun: UV radiation

Supporting material: data behind figure

1. Introduction

Despite the early UV and X-ray spectroscopic work of Pottasch (1963), it was not until the mid-1980s that it was recognized that the elemental composition of the solar photosphere is different from that of the corona and slow speed solar wind (Meyer 1985). Elements with a low first ionization potential (FIP), below around ∼10 eV, are enhanced in the corona and slow wind by factors of 2–4 compared to their photospheric values (Feldman 1992). This abundance anomaly is known as the FIP effect and is likely related to the coronal heating mechanism itself. A large body of work also now exists exploring coronal abundance anomalies in evolving active regions and different features within them (Sheeley 1995; Widing 1997; Widing & Feldman 2001; Testa et al. 2011; Warren et al. 2012; Baker et al. 2013, 2015; Del Zanna 2013b; Del Zanna & Mason 2014) and also as an identification diagnostic for sources of the solar wind (Ko et al. 2006; Brooks & Warren 2011, 2012; Brooks et al. 2015; Guennou et al. 2015; Lee et al. 2015). Schmelz et al. (2012) give a recent review of our state of knowledge of solar coronal abundances.

The effect also appears to be present in stellar coronae (Drake et al. 1997; and see Feldman & Laming 2000; Testa 2010; Testa et al. 2015 for reviews). In fact, stellar coronae show an interesting pattern. Stars of a similar spectral type to the Sun show a solar-like FIP effect, transitioning through no obvious effect around spectral type K5, to an inverse FIP effect in M-type stars (Wood & Linsky 2010; Wood et al. 2012). As noted by Laming (2015), stars of later spectral type likely have a greater preponderance of large starspots with a strong umbral and penumbral field. So greater flaring activity, for example, could be consistent with the absence of the FIP effect in early skeptical work on abundance variations in solar flares (Feldman & Widing 1990; Phillips et al. 1994), which are now potentially understood as consistent with the idea that the FIP effect does not operate when material is rapidly ejected from below the photosphere as in flares (Warren 2014), impulsive heating events (Warren et al. 2016), and coronal jets (Lee et al. 2015; but see Sterling et al. 2015).

Solar and stellar observations have complimentary advantages that we can use to move toward the goal of understanding how their atmospheres are heated, and how the mechanisms that produce processes such as the FIP effect are generated. Stellar observations enable us to explore a larger parameter space of stellar properties such as activity, rotation, spectral type, etc. (Wood & Linsky 2010), whereas solar observations allow much more detailed analysis of specific features and scenarios. It is from stellar observations that we now know an inverse FIP effect can happen, and that it occurs in later spectral types with stronger magnetic fields, but high-spatial and temporal resolution observations are not possible.

Such observations were also not possible for the Sun until recently, when Doschek et al. (2015) discovered several instances of abundance anomalies occurring near strong sunspot magnetic fields during solar flares. They found unexpectedly high Ar XIV 194.396 Å and 187.964 Å line intensities relative to Ca XIV 193.874 Å. These lines are formed in similar temperature conditions so the observed ratios were unusual. Their measurements are the first detection of the inverse FIP effect on the Sun, and the first observations of an inverse FIP region with high-spatial and temporal resolution. Doschek & Warren (2016) subsequently identified several further events. With the discovery of these events, we can bring

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the power of spatial and temporal resolution to bear on understanding the inverse FIP effect.

An important question, that is difficult to answer from stellar observations, is whether the inverse FIP effect is caused by an enhancement of high-FIP elements (HFE) or a depletion of low-FIP elements (LFD). This is significant for several reasons. A promising model to explain the FIP and inverse FIP effects has been developed by Laming (2004, 2012) based on the ponderomotive force acting on Alfvén waves in coronal loops. In this model, the FIP or inverse FIP effect arises from the direction of propagation of the waves. Waves with a coronal origin—perhaps excited by nanoflares—cause the usual FIP effect by enhancing low-FIP elements in the corona. Waves with a subphotospheric origin, that might be prevalent around sunspots, cause the inverse FIP effect by depleting low-FIP elements in the corona. In both cases, there is a clear prediction that the ponderomotive forces are acting on low-FIP elements. Furthermore, recently a solar cyclic variation in coronal elemental abundances has been found for the Sun when it is observed as a star (Brooks et al. 2017). This has important implications for comparisons of coronal abundances with fixed stellar properties, but the magnitude of the effect is not fully understood in stars.

For the Sun, there is some evidence that the cyclic variation results from changes in the low-FIP elements, since a similar cyclic variation is not seen directly in the high-FIP element Ne (Schmelz et al. 2005; Del Zanna & Andretta 2011). On the contrary, the Ne/O abundance ratio appears to vary with the solar cycle in the solar corona and solar wind (Shearer et al. 2014; Landi & Testa 2015; Brooks et al. 2018), which could in principle be due to changes in the Ne abundance. Solar-like stars of a similar spectral type to the Sun may show cyclic variations, but it may be more difficult to detect on later spectral-type stars—where the inverse FIP effect is seen. These stars are fully convective and may be less likely to show cyclic variations anyway, but confirmation of the nature of the effect may further implicate subphotospheric drivers as the cause of the inverse FIP effect.

Doschek et al. (2015) tried to determine which elements were being affected in their observations by looking at the spatial homogeneity of the Ar XIV and Ca XIV emission, but did not draw a firm conclusion. Doschek & Warren (2016) followed a method originally proposed by Del Zanna (2013b) to address the same question. In this method, the path length is calculated and compared directly to the loop spatial dimensions (length and width). If the path length is larger/smaller than expected from the observational measurements then it implies that something is over/under-estimated in the calculation. Since the intensity, electron density, and line contribution function are all measured or assumed known, the remaining factor in the calculation is the elemental abundance. Doschek & Warren (2016) concluded that the low-FIP elements were depleted in the case they analyzed because their calculated path length for the low-FIP elements Ca was too small, suggesting that its abundance was depleted. The conclusion relies on the Del Zanna (2013b) method, which assumes a filling factor of one. This may (or may not) apply to particular post-flare loops; see for example Teriaca et al. (2006).

The first event found by Doschek et al. (2015) is interesting (flare of 2014 December 20), because it appears to result from the simultaneous release of magnetic energy across a post-flare loop arcade, with many of the loops exhibiting similar properties in terms of width, length, temperature, density, and evolution. The cooling time for loops with similar properties is broadly the same, and Winebarger et al. (2003) showed that the expected lifetime of loops at each temperature is also related to the observed delay between the peak emission at different wavelengths. Under the assumption that the loop cooling time is dominated by radiative cooling, Aschwanden et al. (2003) also pointed out that the time delay between the peak emission at different temperatures can be related to the radiative loss function and the low-FIP element abundance enhancement factor. In the case where low-FIP elements are depleted, the cooling delay is longer. Motivated to search for a clear diagnostic of HFE or LFD we explore the impact on the radiative cooling of similar loops with different radiative power-loss functions since the most significant difference between the post-flare loops and the inverse FIP region, in this flare, would appear to be the coronal elemental composition itself. As a result, we develop a new diagnostic that can distinguish between the two scenarios. We then apply the diagnostic in a preliminary analysis of the 2014 December 20 inverse FIP event.

2. Modeling

The total radiated power emitted from an optically thin plasma can be expressed (in units of erg cm$^{-2}$ s$^{-1}$) as

$$E_R = N_eN_H\Omega(T_e, N_e),$$

(1)

where $N_e$ is the electron density, $N_H$ is the hydrogen density, $T_e$ is the electron temperature, and $\Omega$ ($T_e, N_e$) is the radiative power-loss function. To assess the impact of the inverse FIP effect on the radiative cooling of loops we computed $\Omega$ ($T_e, N_e$) for three cases. Recent studies of elemental abundances in solar flares using the most up-to-date atomic data, and comprehensive observations from Solar Dynamics Observatory (SDO)/EVE, show that flares predominantly evaporate photospheric plasma (Warren 2014). So we adopted the photospheric abundances of Grevesse et al. (2007) as a baseline for “normal” radiative cooling in post-flare loops. The calculation was made using the CHIANTI v8 atomic database (Dere et al. 1997; Del Zanna et al. 2015) adopting the ionization fractions from Dere et al. (2009). The curve is shown in Figure 1.

For the inverse FIP effect, we made two further calculations. To model the effect of low-FIP element depletion (LFD model), we adopted a set of abundances computed as follows. We first calculated the ratio of the photospheric abundances of Grevesse et al. (2007) to the coronal abundances of Feldman et al. (1992). The original photospheric abundances of Grevesse et al. (2007) were then multiplied by this ratio, or depletion factor. The method ensures that all elements that are not enhanced in the corona (high FIP) maintain abundances close to their photospheric values in the inverse model. In contrast, low-FIP elements are depleted in the inverse model by a factor comparable to the usual degree of coronal enhancement. To model the effect of high-FIP element enhancement (HFE model), we took the average enhancement factor ($\sim$4) for the low-FIP elements in the coronal abundances of Feldman et al. (1992), and applied it to the high-FIP element abundances only. In the HFE model, the low-FIP elements retain their photospheric abundances. Note that for elements with FIP lower than 10 eV, the enhancement factors in Feldman et al. (1992) fall in the range 3.9–5.7, so taking the average is close to the lower end of this scale. A
Figure 1. Radiated power loss as a function of electron temperature calculated at an electron density of $10^{10}$ cm$^{-3}$ for three cases: photospheric abundances (red), a depletion of low-FIP elements (blue), and an enhancement of high-FIP elements (magenta). The functions calculated with low-FIP element depletion and high-FIP element enhancement show opposite behavior with respect to the photospheric radiated power loss. The high continuum emission above 10 MK in the HFE model is due to the enhancement of He. The data used to create this figure are available.

higher value would lead to greater radiative losses and therefore faster cooling. Conversely, we could have made a different choice of abundances for both the LFD and HFE models. Values in the literature show a range of average enhancement factors and adopting lower values would clearly push the LFD and HFE radiative loss curves back toward the photospheric case. Comparing, for example, the photospheric abundances of Caffau et al. (2011) with the coronal abundances of Schmelz et al. (2012), we find only a factor of 2 enhancement. All of the other atomic data used in the LFD and HFE models are the same as in the photospheric abundances case. The LFD and HFE model radiative power-loss functions are also shown in Figure 1. Machine readable text files containing these functions are available.

Figure 1 shows very significant differences between the three models. The peak of the radiative power loss in the LFD model is about 60% of the peak in the case of photospheric abundances. In contrast, the peak of the radiative power loss in the HFE model is about a factor of 4 higher than that in the photospheric abundances case. What is most interesting is that the LFD and HFE models show opposite behavior with respect to the photospheric radiative loss function.

To explore the impact of these calculations on post-flare loop cooling in detail, we have performed a flare simulation, incorporating all three $\Omega(T_e, N_e)$ functions, using the enthalpy-based thermal evolution of loops (EBTEL) hydrodynamic model (Klimchuk et al. 2008; Cargill et al. 2012). EBTEL solves simplified versions of the hydrodynamic equations that treat field-aligned average values of temperature, pressure, and density. The plasma response to an impulsive energy release calculated by EBTEL has been compared to results from more sophisticated 1D hydrodynamic simulations including the Palermo-Harvard code (Peres et al. 1982), the Naval Research Laboratory solar flux-tube model (Mariska et al. 1982), and the adaptively refined Godunov solver (Antiochos et al. 1999). Good agreement was found (Klimchuk et al. 2008). For details of the assumptions and methods used in designing EBTEL see the papers referenced above.

The use of EBTEL restricts our analysis to a very simplified model. Several of the assumptions place limitations on our results and it is appropriate to comment on some of them here. First, there is no provision for specifying the location of the flare energy release or the geometrical structure of the loop. These can affect the response to the heating. In this work, however, our principle goal is to investigate the diagnostic potential of the method by examining how the loop evolution changes when we use different $\Omega(T_e, N_e)$ functions, so restricting other parameters in the model is not an initial concern. Second, because the EBTEL simulation treats field-aligned average values we have to use a spatially invariant radiative power-loss function. This is also an approximation since actual observations seem to hint that abundances, and therefore radiative losses, can be different between the loop footpoints and the apex (Baker et al. 2013). In fact, in the event we analyze here, the inverse FIP effect appears confined to the footpoint regions of the post-flare loop arcade. These observations suggest that the loop cooling could be different between footpoint and apex, but our results assume that the loop is cooling as a whole. It would be interesting to compare our results and these observations with more sophisticated hydrodynamic simulations incorporating spatially and temporally dependent radiative cooling in the future.

Note that EBTEL uses parameterized versions of the radiative loss function for computational speed. Since we are not concerned with speed for our single specialized simulation, we modified the EBTEL procedures to input our calculated radiative power-loss functions at the full temperature resolution. For the interested reader, we found that using the full temperature resolution results in a factor of 3.4 slow down in calculation speed. This is not important for our study, but may be significant for simulations involving large numbers of field lines.

We simulated the flare as a single impulsive heating event on a single thread. Properties of the loop in the model of course affect the simulation. For example, the loop length affects the loop lifetime. We chose the loop properties to broadly agree with those of the post-flare loop arcade in the inverse FIP flare (see Section 3). The loop half-length, $L$, is 36 Mm, and the loop radius, $\sigma$, is 775 km. The heating is in the form a background static rate of $5 \times 10^{-7}$ erg cm$^{-3}$ s$^{-1}$ and then the imposition of an impulsive heating rate 4000 times stronger than the background, i.e., $2 \times 10^{-2}$ erg cm$^{-3}$ s$^{-1}$. The heating event is a step function that is switched on for 300 s and was chosen to raise the loop temperature to 19.5–21.5 MK. The density exceeds $\log N_e = 9.5$ in all three cases. The loop then drains and cools.

We simulated the spectral emission for three lines covering a broad range of temperatures using the flare simulations based on each abundance model for $\Omega(T_e, N_e)$. We used Si VII 275.368 Å, Fe XII 195.119 Å, and Fe XVI 262.984 Å. These lines are formed at 0.63 MK, 1.58 MK, and 2.75 MK, respectively. We calculate the spectral line intensities using
the formula

\[ I_j = A(Z)G(T, N)N^2 \, ds, \]

where \( I_j \) is the intensity arising from a transition from atomic level \( i \) to \( j \), \( A(Z) \) is the adopted elemental abundance, \( G(T, N) \) is the contribution function (containing all of the—assumed known—atomic physics of the line formation, including in this definition the hydrogen to electron density ratio), and \( ds \) is the column depth. \( N \) and \( T \) are the field-aligned average values of \( N_e \) and \( T_e \) output from the EBTEL simulation, and \( G(T, N) \) is interpolated to these values. It therefore represents the emission averaged over the whole loop.

There is a complex relationship between the measured loop width and actual loop radius (López Fuentes et al. 2006; Brooks et al. 2012). Here we assume that the measured width is representative of the loop radius, and define \( ds \) as \( 2\sigma \). For computing the emission measure, \( N_e^2 ds \), the electron density is by far the dominant term, so this assumption does not greatly affect the computed intensities.

The simulation assumes that ionization equilibrium has had time to be established. This is not an unreasonable assumption for this event. Doschek et al. (2015) measured densities in the range of \( \log N_e = 10.5–11.5 \) for the inverse FIP region. At the lower density, the ionization relaxation timescales for \( \text{Si} \) and \( \text{Fe} \) at the formation temperatures of \( \text{Si} \text{VII} 275.368 \text{Å}, \text{Fe XII} 195.119 \text{Å}, \) and \( \text{Fe} \text{XVI} 262.984 \text{Å} \) are less than \( 30 \text{s} \) in a constant density model (Lanzafame et al. 2002), whereas emission in the highest temperature \( \text{Fe XVI} 262.984 \text{Å} \) line does not form in our simulation until after \( 11 \text{~min} \). We define the line formation time as the time at which the emission reaches 25% of the peak.

We computed the contribution functions at each timestep using the simulation densities and temperatures and the photospheric abundances of Grevesse et al. (2007) adjusted by the same factors used to construct the radiative loss functions in the HFE and LFD models. We considered photospheric abundances for comparison with the majority of the normal post-flare loops in the inverse FIP flare. The method we develop, however, is not sensitive to the abundances used for the contribution functions. The magnitude of the intensities will increase or decrease, but the lifetime of the cooling loop is unchanged, and this is the key diagnostic.

We show the results in Figure 2. As we already hinted, the calculations based on the LFD and HFE models show opposite behavior with respect to the computations based on photospheric abundances. Defining the lifetime as being the time period when the intensity is above 25% of the maximum, the higher temperature (\( \text{Fe XVI} \)) emission lasts longer in the LFD model (2280 s) than in the photospheric case (1920 s), but the emission from the HFE model is shorter (1680 s), though not very different. This difference is accentuated at lower temperatures. At the formation temperature of \( \text{Fe XII} 1.58 \text{MK} \), the emission from the HFE model again has a lifetime slightly shorter, but close to, that of the photospheric abundance case; 1020 s and 1280 s, respectively. Conversely, the lifetime for the LFD case is much longer (almost double), 2400 s. The differences are even more dramatic at the formation temperature of \( \text{Si VII} 0.63 \text{MK} \). While the lifetime of the loop in the HFE model is 1140 s compared to 1880 s for the photospheric abundance case, the loop persists five times longer (5560 s) in the LFD model.

In the Introduction we mentioned that the time delay between the peak emission at different temperatures is affected by the radiative loss function. The cooling delay is longer when low-FIP elements are depleted. We can also see this in Figure 2. The time delay between the peak emission in \( \text{Fe XVI} \) and \( \text{Fe XII} \) is 1400 s when photospheric abundances are assumed, but is shorter (1120 s) and longer (2120 s) in the HFE and LFD models, respectively. Again, the difference is larger at lower temperatures. The time delay between the peak emission in \( \text{Fe XII} \) and \( \text{Si VII} \) is 1500 s using photospheric abundances, 1220 s in the HFE model, and 3020 s in the LFD model.

To summarize, for loops with similar properties, the radiative cooling due to a depletion of low-FIP elements results in a significantly extended emission lifetime compared to that of normal post-flare loops. The time delays between emission at different temperatures are also longer. An enhancement of high-FIP elements produces the opposite effect. These differences are potentially detectable in inverse FIP observations.

### 3. Observations

As a demonstration of the practical usage of our new diagnostic, we examine the flare of 2014 December 20, where the first evidence of the inverse FIP effect on the Sun was discovered by Doschek et al. (2015). The flare under discussion was an X1.8 event. It began around 00:10UT and the GOES X-ray flux peaked at 00:28UT. An extensive post-flare loop arcade was formed, with loops persisting well into the long-duration decay phase of the event. The X-ray flux did not fall below the M-class until after 03:00UT.

The inverse FIP effect was seen due to enhanced \( \text{Ar XIV} 194.396 \text{Å} \) emission, relative to \( \text{Ca XIV} 193.874 \text{Å} \), from around 00:15UT and was strongest around 01:00UT. Figure 3 shows raster scan data in the two spectral lines from the Extreme-ultraviolet Imaging Spectrometer (EIS; Culhane et al. 2007) on \textit{Hinode} (Kosugi et al. 2007). The data were obtained in the flare observation mode by responding to the trigger from the X-ray Telescope (XRT; Golub et al. 2007). Once triggered, the 2″ slit was deployed to scan a field of view (FOV) of 240″ by 304″ in coarse 3″ steps. The exposure time was 5 s so that the FOV was covered in just under 9 minutes. An extensive line list was telemetred to the ground. The flare response stopped running around 01:10UT.

We show a measure of the FIP bias (ratio of coronal to photospheric abundance) in the right-hand panel of Figure 3, which is constructed from the \( \text{Ar XIV} 194.396 \text{Å} \) to \( \text{Ca XIV} 193.874 \text{Å} \) line intensity ratio. The image was filtered at 2.5% of the peak intensity in both lines to reduce noise, and only signals above the calibration uncertainty in the intensity ratio were retained. The ratio was also normalized to the photospheric abundance ratio. The figure clearly shows the location of the strongest inverse FIP signal.

The EIS data were processed using standard procedures available in \textit{SolarSoft}, i.e., \textit{EIS, PREP}. We applied the ground radiometric calibration (Lang et al. 2006) since the two lines are very close in wavelength and the degradation ratio between them shows a difference of less than 3% according to both Del Zanna (2013a) and Warren et al. (2014). In any case, we only use the FIP bias to locate the inverse FIP region and do not make use of any quantitative data. We collected data from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on
the Solar Dynamics Observatory (SDO; Boerner et al. 2012) covering 2 hr before and after the strongest inverse FIP signal is seen. These data are level-1 and have been flat-fielded and normalized to the 2.9 s exposure time.

To locate the inverse FIP region on the AIA images we coaligned a 335 Å filter image taken at 01:05UT with the EIS Ar XIV 194.396 Å raster scan taken at 00:59UT. The 335 Å filter has a strong peak at 2.5 MK resulting from Fe XVI emission, so it is closest in formation temperature to the ArXIV line (3.4 MK). The AIA image was rescaled to the EIS pixel grid size and the two images were coaligned through multiple cross-correlation steps.

We show examples of the behavior of the post-flare loop system in the AIA 335 Å and 193 Å filters in Figure 4. We picked out a few (10) loops in the arcade for spot checks and measured their lengths, widths, and lifetimes. To do this, we followed the procedure of Aschwanden et al. (2008; as modified and implemented by Warren et al. 2008), and identified relatively isolated loops, selected a clean segment, straightened them, and averaged the cross-loop intensity profiles along the segments. We then selected two positions at the edges of the loops to identify the background emission, and fit a Gaussian function to the averaged background subtracted cross-loop intensity profile to obtain the loop width (Gaussian width, $\sigma$) and the total intensity. This procedure was then repeated throughout the time series of the observations to obtain the light curves. Furthermore, we measured the loop half-lengths, using the same procedure, by selecting and straightening loop segments extending from the (visually identified) footpoints to the loops’ apex. The widths fall in the range of 635–1280 km (FWHM) and the half-lengths fall in the range of 17.9–35.8 Mm. These measurements motivated the model parameters for our simulation in Section 2.

The colored boxes in Figure 4 indicate the segments we chose for the light curve (and loop width) measurements, and are different than the larger segments we used for the half-length measurements. Here we discuss the cleanest light curves for only four of the loops. The light curves were somewhat messy due to the fact that the loops are rapidly varying and moving in the FOV, and because the flare saturates some frames of the 193 Å images, as we can see in Figure 4, hence the reason for focusing on a restricted sample. In fact, as we can see in the Figure, several light curves appear to exhibit multiple brightenings, either due to rebrightening of the same loop (see, e.g., the blue curve in the top panel of Figure 4), or due to the appearance of different loops (e.g., the red curve in the bottom panel).

As in Section 2, we define the loop lifetime as the time period when the intensity is above 25% of the maximum. Thus defined, the 335 Å loop lifetimes fall in the range of 6–17 minutes (360–1020 s). In the 193 Å filter the post-flare loop lifetimes fall in the range of 1.5–10 minutes (90–600 s). We also checked that the lifetime of these loops that appeared around the time of the inverse FIP signal are representative of most of the loops in the post-flare arcade by examining a sample of 20 loops that occurred 15 and 5 minutes before, and

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Computed intensities of the Si IV 275.368 Å, Fe XII 195.119 Å, and Fe XVI 262.984 Å spectral lines based on an EBTEL simulation of a single impulsive heating event in a single strand. The simulation was performed for three different radiated power-loss functions, representing photospheric abundances (red) and two inverse FIP models: low-FIP element depletion (LFD, blue) and high-FIP element enhancement (HFE, magenta). There are increasing differences in the strand lifetime going from the higher temperature line (Fe XVI 262.984 Å) to the lower temperature line (Si IV 275.368 Å).
5 and 15 minutes after, the appearance of the inverse FIP region. Half of these loops had lifetimes that fall within the same range, and all but one had a lifetime less than 17 minutes (similar to the 335 Å loops). We conclude then that the post-flare loops in the arcade evolve on fairly similar time scales at each temperature, which is consistent with their broadly similar properties. We discuss the one exceptional 193 Å loop further below.

The observed loops are somewhat more transient than those found in our simulations, which probably reflects differences in the modeled and observed properties. As noted, Doschek et al. (2015) measured densities in the range of log $N_e = 10.5–11.5$ for the inverse FIP region, whereas log $N_e > 10.0$ is difficult to achieve in our simulations. Higher densities would lead to stronger radiative cooling and therefore shorter lifetimes.

Figure 5 shows the behavior of the 193 Å light curve for the inverse FIP region. The 211 Å image in the left panel shows the location of the inverse FIP region. It is close to the footpoint of one of the post-flare loops that is rooted in the strong magnetic field of the sunspot. The light curve is dramatically different from any of those found for the (small) sample of loops we checked. The duration is about 42 minutes (>2520 s). This is more than a factor of four longer than the lifetimes of the other loop segments we measured in the 193 Å filter, and immediately suggests that low-FIP elements are depleted. Furthermore, the lifetimes of all the post-flare loop segments in 335 Å (and most of the segments in 193 Å) are shorter than in our simulations for any of the radiative loss functions. Only two of the 193 Å loop segments have lifetimes that come close to the simulated durations from the HFE model. In contrast, the lifetime of the inverse FIP region in the 193 Å filter is quite close to the lifetime simulated for the LFD inverse model (2380 s). Although this result provides only weak support (since the simulation clearly does not capture the evolution of all the loops correctly), it also agrees with the conclusion that the low-FIP elements are depleted.

Note that we assume that the inverse FIP region persists as long as the intensity enhancement seen in the images. The EIS data do not cover the full duration of the extracted light curve in Figure 5 so strictly speaking we cannot confirm this. They are, however, consistent with the long duration since the inverse FIP region was detected by EIS at 00:47UT and is still visible at 01:05UT just before the EIS observations stopped. So even in the EIS data the anomaly exists for at least 18–27 minutes and there are no more data during the remaining ~30 minutes of the intensity enhancement.

As discussed above, there was one exceptional 193 Å loop we measured with a long duration. This loop had a lifetime of about 42 minutes, which is the same as that of the inverse FIP region. As with that region, it was measured close to the loop footpoint, and this suggests that it could be a candidate to show the same abundance anomaly effect. Unfortunately, the EIS slit does not appear to cross this footpoint region when the loop forms, so we could not verify this conjecture.

4. Summary and Discussion

We have developed a new diagnostic that can determine whether high-FIP elements are enhanced or low-FIP elements are depleted in inverse FIP effect regions on the Sun. The method relies on the markedly different radiated power-loss functions, which result from modeling the degree of enhancement or depletion of the high- or low-FIP elements. In numerical hydrodynamic simulations of impulsively heated loops, these radiated power-loss functions lead to significantly different loop cooling times depending on the specific abundance pattern. In particular, loops forming around 1–2 MK last significantly longer than loops filled with photospheric plasma if the low-FIP elements are depleted. They persist even longer at cooler (0.6 MK) temperatures. In contrast, when high-FIP elements are enhanced, loops forming around 1–2 MK cool more rapidly than loops filled with photospheric plasma.

We applied the new method to the analysis of the X1.8 flare that occurred on 2014 December 20. The post-flare loops in the arcade produced by the energy release show broadly similar properties such as width, length, temperature, and density, so
would be expected to evolve on similar timescales if they are filled with plasma evaporated from the photosphere as in many flares (Warren 2014). In the inverse FIP region the composition is different, however, and according to our diagnostic, may show a different evolution. We found that the small sample of loops we analyzed lasted for <10 minutes in the AIA 193 Å filter. Conversely, the inverse FIP region persisted for about 40 minutes. This suggests that low-FIP elements are depleted in the inverse FIP region.

Our analysis is really a demonstration that the method can work. Many loops appeared during the evolution of the post-flare arcade and we only sampled a few that existed at the time of the inverse FIP event. We do not claim that our measurements are representative of all the loops in the arcade throughout the full duration of the flare. Our objective here is to introduce our new diagnostic method, and show that it can be applied to real inverse FIP observations. Further detailed analysis will be needed to fully understand the 2014 December
20 event. For example, one important point to mention is that as the flare ribbons sweep across the sunspot in the active region they appear to be partly stopped in the inverse FIP region by the strong magnetic field of a light bridge. This could lead to a pile-up of energy input there, that may extend the loop footpoint lifetime, and could also be involved in the generation of the inverse FIP effect itself.

Furthermore, our modeling scenario is fairly simplistic. We simulated a single impulsive event in a single strand, but the loop lifetime could be related to the number of strands rather than the cooling time. Most of the loops in the post-flare loop arcade could be composed of a few strands, whereas the loop rooted in the inverse FIP region could contain relatively more strands. The behavior of different strands in the region of the flare ribbons over the sunspot could also be important. We have implicitly assumed that the inverse FIP region is within the post-flare loops and that a loop model is applicable to it. It could be the case, however, that the inverse FIP emission is a result of interactions between the post-flare loops and the sunspot magnetic field.

Nevertheless, the results presented here are in agreement with the model of the FIP and inverse FIP effects proposed by Laming (2004). In that model, the ponderomotive forces acting on Alfvén waves result in changes in the behavior of the low-FIP elements only. In the inverse FIP effect, the low-FIP elements are depleted, resulting in longer loop cooling times, as we find here.

It is also interesting that the inverse FIP region is confined close to the loop footpoint and does not fill the whole loop. This behavior is reminiscent of observations of the normal FIP effect in active region loops. Baker et al. (2013) show examples of loops with coronal composition near the footpoint, and traces of enhanced composition along parts of the loops. Their argument is that these signatures are the first signs of fractionated plasma mixing in the loops. If the FIP effect is caused by the ponderomotive force as in the Laming (2004) model, and the inverse effect is caused by the same mechanism only acting on oppositely directed Alfvén waves, then we might expect similar signatures of the process. Unfortunately there are no EIS observations taken later in the flare to examine whether the post-flare loops become completely filled.

Our results may be of interest to stellar astronomers who observe both the FIP effect and inverse FIP effect in solar-like stars but have no comparable way to determine which elements are enhanced or depleted. The radiative power-loss functions we provide could be used in hydrodynamic modeling of the emission from these objects. They could also be used for simulations of abundance anomalies in flaring loops on active stars such as those that have been observed on the M dwarf CN Leonis or the eclipsing binary Algol: an evolution from subphotospheric to photospheric abundance was detected during giant flares on both (Favata & Schmitt 1999; Liefke et al. 2010).

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