Coronal Abundances in an Active Region: Evolution and Underlying Chromospheric and Transition Region Properties

Paola Testa1, Juan Martínez-Sykora2,3,4,5, and Bart De Pontieu2,4,5

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, MA 02138, USA; pesta@cfa.harvard.edu
2 Lockheed Martin Solar & Astrophysics Laboratory, 3251 Hanover St, Palo Alto, CA 94304, USA
3 Bay Area Environmental Research Institute, NASA Research Park, Moffett Field, CA 94035, USA
4 Rosseland Centre for Solar Physics, University of Oslo, P.O. Box 1029 Blindern, NO-0315 Oslo, Norway
5 Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, NO-0315 Oslo, Norway

Received 2022 November 14; revised 2023 January 12; accepted 2023 January 13; published 2023 February 16

Abstract

The element abundances in the solar corona and solar wind are often different from those of the solar photosphere, typically with a relative enrichment of elements with low first ionization potential (FIP effect). Here, we study the spatial distribution and temporal evolution of the coronal chemical composition in an active region (AR) over about 10 days, using Hinode/EIS spectra, and we also analyze coordinated IRIS observations of the chromospheric and transition region emission to investigate any evidence of the footprints of the FIP effect in the lower atmosphere. To derive the coronal abundances, we use a spectral inversion method recently developed for the MUSE investigation. We find that, in the studied active region (AR 12738), the coronal FIP bias, as diagnosed by the Si/S abundance ratio, presents significant spatial variations, with its highest values (∼2.5–3.5) in the outflow regions at the boundary of the AR, but typically modest temporal variability. Some moss regions and some regions around the AR sunspot show enhanced FIP bias (∼2–2.5) with respect to the AR core, which has only a small FIP bias of ∼1.5. The FIP bias appears most variable in these moss regions. The IRIS observations reveal that the chromospheric turbulence, as derived from IRIS inversions of the Mg II spectra, is enhanced in the outflow regions characterized by the high FIP bias, providing significant new constraints to both models aimed at explaining the formation of AR outflows and models of chemical fractionation.

Unified Astronomy Thesaurus concepts: Active solar corona (1988); Solar coronal heating (1989); Solar corona (1483); Solar chromosphere (1479); Solar transition region (1532); Solar extreme-ultraviolet emission (1493); Solar ultraviolet emission (1533); Solar physics (1476); Solar abundances (1474)

1. Introduction

The chemical composition of solar plasmas is observed to vary substantially in different regions of the Sun. Early spectroscopic studies of the solar corona revealed departures from the underlying photospheric composition (e.g., Meyer 1985; Feldman 1992). In particular, in the solar corona, elements with low First Ionization Potential (FIP) such as, e.g., Mg, Fe, Si are typically found to be more abundant (by a factor 2–4) compared with high-FIP elements such as, e.g., C, N, O; this phenomenon is therefore called the FIP effect, and the extent of the enhancement of element abundances is called the FIP bias. The apparent dependence of chemical fractionation on the first ionization potential of the elements indicates that this process is likely occurring in the chromosphere, where neutral with low FIP are ionized. This also suggests a link to the processes responsible for coronal heating (see, e.g., Testa 2010; Laming 2012, 2015; Testa et al. 2015, and references therein), which are still poorly understood (e.g., Klimchuk 2006; Testa et al. 2015; Testa & Reale 2022). Further studies showed that chemical fractionation varies substantially in different regions of the Sun with varying magnetic topologies (see examples in Brooks et al. 2015; Mihailescu et al. 2022). In particular, a strong FIP effect is often observed in high-temperature (≥2 MK) active region (AR) core loops, post-flare loops, ∼1 MK AR fan loops, AR outflows, and coronal mass ejections (e.g., Feldman 1992; Warren et al. 2011a; Brooks et al. 2011; Zurbuchen et al. 2016). However, in the transition region, newly emerging ARs, coronal holes, and transient heating events such as microflares and flares, typically the chemical composition appears closer to photospheric (e.g., McKenzie & Feldman 1992; Widing 1997; Warren et al. 2016; Young 2018). Some locations in ARs and flares sometimes even show an inverse FIP effect (e.g., Doschek et al. 2015; Doschek & Warren 2016, 2017; Brooks 2018; Baker et al. 2019, 2020), i.e., with high-FIP elements enhanced relatively to low-FIP elements, which is also typically observed in more active stars (e.g., Testa 2010; Testa et al. 2015). Furthermore, the chemical composition of the solar wind is an indicator of the source region on the Sun (e.g., Brooks et al. 2011, 2015), and is critical to establishing the magnetic connectivity from the wind to the surface.

In ARs, the coronal chemical composition has also been observed to change as the AR evolves, with varied results. Early Skylab observations of newly emerged ARs point to a significant increase of FIP bias with the aging of the AR, by up to an order of magnitude, continuing to increase in the later phases past the initial emergence phase, although the later decay and dispersal phases were not observed (Widing & Feldman 2001). A couple of more recent studies based on observations with the Hinode (Kosugi et al. 2007) Extreme-
ultraviolet Imaging Spectrograph (EIS; Culhane et al. 2007) have found examples of evolution of the chemical composition in ARs in the decay phase. In particular, Hinode/EIS observations of AR 11389, a mature AR in its decay phase, sampling its coronal composition over a couple of days, point to a decrease of FIP bias with time (Baker et al. 2015). Another EIS spectral study of an unc numbering AR show some similarities, with large fluctuations and an overall decrease of FIP bias over about 4 days of the advanced decay phase (Ko et al. 2016). These very few studies of FIP bias evolution in ARs indicate that compositional changes in coronal plasma in AR are not as simple as suggested by early Skylab studies, and that the more complex relationship between abundance anomalies and AR properties and evolution needs to be determined through more extended studies.

Recent promising models have been developed in which chemical fractionation is driven by the ponderomotive force of Alfvén waves due to the propagation and/or reflection of MHD waves in the chromosphere (Laming 2004, 2009, 2012, 2015). In these models, there is an intimate connection between the processes leading to chemical fractionation and those responsible for coronal heating, therefore suggesting the abundance anomalies can also yield important insights into the long-standing issue of the heating of stellar coronae. Although these models are able to generally reproduce scenarios in which FIP effect and inverse FIP effect can occur (e.g., Laming 2015), not all observational aspects are predicted (e.g., the extent of variability of FIP effect in ARs; Doschek & Warren 2019), and further observational constraints on these models are needed in order to make significant progress (Laming 2015).

Robust measurements of the dependence of chemical fractionation on active region properties and evolution (magnetic field complexity and evolution, as well as coronal activity evolution), and of correlations between coronal composition and chromospheric/transition region (TR) properties, have the potential to put very tight constraints on models—and thus to shed light on the physical processes leading to fractionation. However, the paucity of existing studies of variability of the coronal composition during a significant portion of the AR evolution has not provided a clear picture of its properties and evolution. Also, there is a lack of studies exploring the connection with the lower atmospheric layers, which are where the fractionation is expected to happen.

In this paper, we provide new constraints to the models by analyzing coordinated observations of an AR observed for over 10 days by Hinode/EIS and by the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014). Hinode/EIS spectra are used to derive the spatial and temporal properties of coronal abundances, while IRIS spectral observations provide insights into the underlying chromospheric and transition region properties, allowing us to explore the correlations between coronal composition and lower atmospheric conditions.

### 2. Observations and Data Analysis

We searched the Hinode/EIS and IRIS databases for data sets suitable for our investigation, in particular those covering several days of an AR evolution, with ~daily cadence for both spectrographs, and for which the EIS observations have sufficient spectral coverage to determine the coronal abundances. We selected EIS spectra with a large set of Fe lines (Fe VIII–Fe XVI) able to constrain the temperature distribution and density of the coronal plasma, and also including Si X and S X, which are typically used to derive the FIP bias from EIS spectra (e.g., Brooks et al. 2011; Baker et al. 2015).

Here, we present analysis of a time series of EIS and IRIS spectra of AR 12738, observed from 2019 April 10 to 2019 April 19 (listed in Table 1) In Figure 1 we show Hinode and SDO observations of the target AR, at three different times during its disk passage, to illustrate the morphology and evolution of the photospheric magnetic field and of the coronal emission in this active region. The Hinode/EIS rasters we analyze (study acronym HPW021VEL260x512v2) use the 2” slit, 40 s exposure time at each of the 87 slit positions, and raster steps of 3”, thereby covering a field of view of about 260” × 512” (in about 1 hr); this study includes a large number of lines suitable for determining temperature, density, and abundances of active region plasma. The Hinode/EIS data sets were reduced (to correct the raw data for dark current, cosmic rays, and hot, warm, and dusty pixels, as well as to remove instrumental effects of orbital variation, CCD detector offset, and slit tilt) using standard routines available in the Hinode/EIS branch of Solar Software (Freeland & Handy 1998). The IRIS observations we analyze

---

**Table 1**

| Startime (UT) | Study Name | x, y | OBSID | texp (s) | n. Rasters | x, y |
|---------------|------------|-----|-------|---------|------------|-----|
| 2019-04-10 05:47 | HPW021VEL260x512v2 | −75°, 158° | 3620259477 | 8 | 1 | −75°, 139° |
| 2019-04-10 12:15 | HPW021VEL260x512v2 | −60°, 210° | 3620108077 | 8 | 5 | −60°, 169° |
| 2019-04-11 15:02 | HPW021VEL260x512v2 | −314°, 146° | 3620108077 | 8 | 1 | −253°, 186° |
| 2019-04-13 13:34 | HPW021VEL260x512v2 | −225°, 147° | 3620108077 | 8 | 2 | −183°, 227° |
| 2019-04-15 12:43 | HPW021VEL260x512v2 | −154°, 124° | 3620108077 | 8 | 2 | −62°, 199° |
| 2019-04-15 21:53 | HPW021VEL260x512v2 | 351°, 149° | 3620108077 | 8 | 2 | 443°, 201° |
| 2019-04-15 21:53 | HPW021VEL260x512v2 | 361°, 108° | 3620108077 | 8 | 2 | 443°, 201° |
| 2019-04-16 01:03 | HPW021VEL260x512v2 | 392°, 96° | 3620108077 | 8 | 3 | 443°, 201° |
| 2019-04-16 02:01 | HPW021VEL260x512v2 | 391°, 114° | 3620108077 | 8 | 3 | 476°, 199° |
| 2019-04-17 01:16 | HPW021VEL260x512v2 | 699°, 65° | 3630108077 | 8 | 3 | 677°, 173° |
| 2019-04-17 15:42 | HPW021VEL260x512v2 | 782°, 68° | 3610108077 | 8 | 7 | 790°, 158° |
| 2019-04-18 12:08 | HPW021VEL260x512v2 | 829°, 65° | 3620108077 | 8 | 4 | 886°, 133° |
| 2019-04-19 04:48 | HPW021VEL260x512v2 | 872°, 85° | 3620108077 | 8 | 3 | 924°, 123° |
| 2019-04-19 12:20 | HPW021VEL260x512v2 | 919°, 21° | 3620108077 | 8 | 6 | 934°, 117° |
are very large, dense, 320-step rasters, rebinned 2 × 2, with exposure time of 8 s (except for only one observation on 2019 April 10 at 15:02 UT that has 4 s exposures) and raster steps of 0.35″, thus covering a field of view of about 112″ × 174″ (in about 50 minutes for the 8 s exposure, and ∼27 minutes for the 4 s exposure). We use IRIS calibrated level 2 data, which have been processed for dark current, flat field, and geometrical corrections (De Pontieu et al. 2014).

We also use coordinated imaging observations, taken with the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), which are characterized by 0.6 pixels and 12 s cadence and sample the transition region and corona across a broad temperature range (Boerner et al. 2012, 2014). In particular, we used the AIA data cubes coordinated with and co-aligned to the IRIS data sets, which are distributed from the IRIS search data page. The AIA data are used for co-alignment between the instruments; particularly useful are the extreme-ultraviolet 193 Å narrowband images, for co-alignment with the EIS coronal data, and the UV 1700 Å channel, for co-alignment with the IRIS data. The AIA coronal data are also used to investigate the coronal activity level of the AR and its variability. Furthermore, we also use X-ray images taken with the Hinode X-ray Telescope (XRT; Golub et al. 2007). We analyze calibrated level 1 XRT data (also normalized by the exposure time) for all the short-exposure (0.5–2.9 s) synoptic images in the Be-thin passband from 2019 April 10 to 2019 April 19; we focus on the short-exposure data because we are focusing on the only AR on disk, which was therefore the brightest region in the images.

The EIS and IRIS spectral data were analyzed using a variety of methods, as we briefly describe in the following. Most previous EIS studies aimed at determining coronal abundances (e.g., Brooks et al. 2011; Baker et al. 2013, 2015; Ko et al. 2016; Baker et al. 2018) use an FIP bias diagnostic based on single-line fits with the following analysis steps: (a) the plasma temperature distribution (also called differential emission measure, DEM) is derived using a set of Fe lines formed at different temperature (Fe VIII–Fe XVI) and taking into account the sensitivity of the line emissivities by using densities

---

The Astrophysical Journal, 944:117 (12pp), 2023 February 20 Testa, Martínez-Sykora, & De Pontieu

---

Footnote 7: https://iris.lmsal.com/search/

Footnote 8: XRT typically takes for each passband synoptic images with two or three different exposure times, which later are combined into a composite image with dark and bright regions all well-exposed (level 2 XRT data; available at http://solar.physics.montana.edu/HINODE/XRT/SCIA/latest_month.html).
The analysis of IRIS spectra includes the analysis of the TR and chromospheric emission. We fit the Si IV 1402 Å line using a single Gaussian function to derive line intensity, Doppler shift, and nonthermal broadening. We also apply IRIS inversions to the optically thick Mg II h & k chromospheric line ratio. A paper in preparation (Kashyap & Drake 1998) has the advantage of providing estimates of uncertainties for the derived DEMs, but has the disadvantage of being markedly slow (this likely being one of the main reasons for the paucity of extensive abundance studies analyzing the temporal variation in large fields of view).

Analogously to the above cited EIS studies, we used single Gaussian functions to fit the unblended calibrated spectra for Fe VIII (185.21 Å), Fe IX (188.50 Å), Fe X (184.54 Å), Fe XIV (264.79 Å), Fe XV (284.16 Å), Fe XVI (262.98 Å), S X (264.23 Å), and Si X (258.38 Å), while multiple components were used to fit the blended regions including Fe XI (188.22 Å), Fe XII (195.12 Å), and Fe XIII (203.83 Å). Here, however, we apply a new inversion method, which is much faster (by more than an order of magnitude), while retaining significant accuracy, as we will show in the following. This method is based on a compressed sensing method (Cheung et al. 2019) we developed for the future NASA MIDEX mission MUSE (Multi-slit Solar Explorer; De Pontieu et al. 2020; Cheung et al. 2022; De Pontieu et al. 2022) to robustly retrieve plasma properties (such as DEM, plasma velocity, and density) from a variety of possible spectrometer configurations. In Cheung et al. (2019), one of the several tests of the method showed its application to EIS data (their Figure 3). This technique has recently also been applied to derive the magnetic field from magnetic-field-induced transitions (MIT) using 3D radiative MHD numerical models (Martinez-Sykora et al. 2022). Here, we modified the method to derive DEM, density, and abundances from the set of EIS lines. In particular, for the results presented here, we derive, for each spatial pixel, $\text{DEM}(n, T)$ by inverting the Fe lines of different ionization stages listed above, and then we derive the FIP bias from the ratio of the observed to predicted Si X/S X line ratio. A paper in preparation (J. Martinez-Sykora & P. Testa 2023, in preparation) will present a detailed description of the method and the tests we performed also using 3D MHD numerical simulations (similar to what was presented in Martinez-Sykora et al. 2022). As a demonstration of the performance of this new method, we have applied it to EIS spectral observations of AR 11389 on 2012 January 4 at 09:40 UT previously analyzed by Baker et al. (2015), to compare our results with theirs. The FIP bias map we obtained is shown in Figure 2, and is in excellent agreement with the map Baker et al. (2015) presented in their Figure 2.

The analysis of IRIS spectra includes the analysis of the TR and chromospheric emission. We fit the Si IV 1402 Å line using a single Gaussian function to derive line intensity, Doppler shift, and nonthermal broadening. We also apply IRIS inversions to the optically thick Mg II h & k chromospheric lines: this inversion method is based on machine and deep learning techniques that allow the inference of the thermodynamic conditions of the lower atmosphere from IRIS spectra by taking into account non-LTE conditions in the chromosphere (Sainz Dalda et al. 2019).

The objectives of our study are (a) to analyze the spatial distribution and temporal evolution of the coronal abundance anomalies in an active region observed for a significant portion of its limb-to-limb passage, and (b) to investigate whether a footprint of the chemical fractionation can be discerned in the lower atmosphere (chromosphere and transition region). We first describe our findings related to the former objective, and then we discuss our exploration relevant to the latter objective.

3. Results

The objectives of our study are (a) to analyze the spatial distribution and temporal evolution of the coronal abundance anomalies in an active region observed for a significant portion of its limb-to-limb passage, and (b) to investigate whether a footprint of the chemical fractionation can be discerned in the lower atmosphere (chromosphere and transition region). We first describe our findings related to the former objective, and then we discuss our exploration relevant to the latter objective.

3.1. FIP Bias Spatial and Temporal Distribution

As described in the previous section, we use a dozen lines, including Fe lines of different ionization stages, providing temperature and density diagnostics, and SX and Si X lines that constrain the FIP bias. The analysis provides for each observation a map of several quantities: line intensity, Doppler shift, and nonthermal broadening can be derived from the line fitting, and the inversion method additionally provides FIP bias and emission measure as a function of density and temperature ($\text{DEM}(n, T)$). For the DEM inversion, we assumed a density grid with 0.3 bin size in Log($n$), between 8 and 11, while for the temperature, we assume Log($T$) binning of 0.05, between 5.5 and 6.75. It should also be noted that the SX is a weak line,
Figure 3. Example of maps of coronal plasma properties derived from the Hinode/EIS observations, for one of the 15 EIS data sets analyzed (see also Figure 4), when AR 12738 was close to disk center. From left: nonthermal velocity and Doppler shift from the FeXIII 202 Å line, intensity in the Fe XII 195 Å line, and FIP bias, derived as described in Section 2.

and it has relatively low signal-to-noise in several areas of the active region. Therefore, we have rebinned the Si X (and Si X) spectra by a factor 4 in the y-direction, so the FIP bias maps have effective pixels of $2" \times 4"$.

In Figure 3, we show an example of the maps of the line properties (intensity, Doppler shift, and nonthermal broadening), as well as of the FIP bias, obtained from an observation on 2019 April 15, when the AR 12738 was not far from disk center. The Doppler shift and nonthermal broadening (from Fe XIII) spatial distribution is in agreement with what is typically found from Hinode/EIS observations in active regions, with large blueshifts and broadening (for $\log(T[K]) \gtrsim 6.15$) at the weakly emitting edges of AR, where the so-called “AR outflows” are (e.g., Warren et al. 2011b). The velocities and broadening are otherwise typically small in the AR (see also, e.g., Brooks et al. 2011; Brooks & Warren 2016). The FIP bias is also increased in the outflow regions, in agreement with previous studies (e.g., Brooks et al. 2011, 2015), which pointed out this property as a potential way to trace sources of parts of the slow solar wind to the solar surface. Most of the AR plasma shows a modest FIP bias of $\sim 1.5 - 2$.

Figure 4 presents the maps of FIP bias, as well as coronal morphology (Si X intensity), for the full time series of EIS observations analyzed here, from close to the eastern limb (on 2019 April 10) to the western limb (on 2019 April 19; see Table 1). These data indicate that a large FIP bias is typically found in the outflow regions (see eastern edge of AR, which is in EIS f.o.v. for the observations on 04–10 to 04–16), in some large and cool (fan) loops (at the northern side of the EIS f.o.v., especially on 04/10–12), in some moss regions (the moss being the high-density TR of hot loops; e.g., Fletcher & De Pontieu 1999; Brooks et al. 2009; Tripathi et al. 2010; Testa et al. 2013; see bright Si X structures in the AR core), and at times, close to the sunspot (on the western side of AR, in EIS f.o.v. for the observations on 04–15 to 04–17).

Very limited evolution is observed in the FIP bias of outflow regions, where it is consistently high (3), and in the AR core, where it is $\lesssim 2$. Some moss regions are where the FIP bias appears to be most variable (over timescales of hours, to which the cadence of these EIS observations is sensitive), with some of these regions intermittently showing enhanced FIP bias with respect to the rest of the AR core. To illustrate these results, in Figure 5 we show the variability of FIP bias values for a few different locations sampling outflow regions, moss, and the AR core. We average the FIP bias values for each location over an area of about $14" \times 14"$ (and double that for the AR core). We note that not all locations are in the Hinode/EIS f.o.v. at all times, because of the variation in pointings, which focus on different parts of the AR at different times (see also Figure 4).

We also derived the average FIP bias for the brightest regions in the Si X emission (yellow–orange squares in Figure 5). The FIP bias in these bright regions shows some variability, in particular with an increase from initial values of $\sim 1.8$ to $\sim 2.3$ in the first $\sim 6$ days of the time series, and then a decrease to $\sim 1.7$. These brightest regions are interesting also for comparison with previous works of Baker et al. (2015) and Ko et al. (2016), which mostly focused on the bright AR core, although we note that part of the variation we observe might be due to the changing EIS f.o.v., which covers different portions of the AR at different times (see Figure 4).

In Figure 5, we also show lightcurves in several coronal passbands observed with Hinode/XRT and SDO/AIA. For XRT, we selected all the short-exposure synoptic images in the Be-thin passband, in which the AR core is bright (but not saturated), and we average the intensity in the f.o.v. shown in Figure 1 (left panel). For the AIA coronal narrowbands, we use the AIA data cubes coaligned to the IRIS data (see middle panels in Figure 1), and average the emission in the whole f.o.v. and for the entire time series ($\sim 1$ hr). The comparison of these lightcurves with the plots of the FIP bias variability in various locations does not show a clear correlation between the FIP bias and the coronal properties, except possibly for the average in Si X bright regions (yellow–orange squares in Figure 5), which is lower in the last 4 days when the coronal
activity has decreased (although the peak is around day 5.5, when the decrease in coronal activity had already happened).

The analysis of EIS spectra also provides information on the plasma density and thermal distribution in the active region, as well as their evolution. Although they are not a primary focus of this work, we summarize the results in Figure 6. We show, for four data sets sampling the EIS time series every ~3 days, the maps of emission measure integrated in three different
temperature ranges (and over all density values), as well as the maps of the density obtained as a weighted average, using $\text{DEM}(n,T)$ as weights. Specifically, we define the weighted average density in the spatial pixel of coordinate $(x,y)$ as

$$\langle n_{x,y} \rangle = \frac{\sum_n n \times (\sum_T \text{DEM}(x,y,n,T))}{\sum_n \sum_T \text{DEM}(x,y,n,T)},$$

where $\text{DEM}(x,y,n,T)$ is the DEM, as a function of density and temperature, in that spatial pixel. This figure shows that the active region is not very active, and it is characterized by a small decrease in density and emission measure after the first few days. Indeed, AR 12738 was the only AR on disk for most of the time series analyzed here, and we can use the GOES X-ray curve as a proxy of its activity: the observed GOES X-ray level is always at or below B level during the $\sim$10 days interval of our observations, with a few mid-B-class events observed in the first few days (until 2019 April 14) and no events from 04–15 to 04–19. Similarly, the Hinode/XRT and AIA lightcurves we showed in Figure 5 indicate an overall decrease of activity after the first three days.

### 3.2. IRIS Chromospheric and Transition Region Properties, and Relations with Coronal FIP Bias

We then analyzed the coordinated IRIS observations, derived for each data set maps of SiIV line properties (intensity, velocity, and nonthermal broadening), and applied
Figure 6. Evolution of DEM in three temperature bands (for Log(T[K]) below 6, between 6 and 6.5, and 6.5 and above (in the first first three columns, from left to right, respectively), of plasma density (fourth column) derived as the average of density weighted by the DEM(n,T), and of FIP bias (rightmost column), for four data sets sampling (every ~3 days) the entire interval of the AR observations analyzed in this paper.
IRIS\(^2\) inversions to the Mg II spectra to derive a model atmosphere (chromospheric temperature, electron density, line-of-sight velocity, \(v_{\text{los}}\), and turbulent velocity, \(v_{\text{turb}}\), also known as microturbulence, as a function of the optical depth \(\tau\) at 500 nm). In Figure 7, we show an example of these maps from the start of the observing sequences on 2019 April 10, where for the IRIS\(^2\) results we show the map of \(v_{\text{turb}}\) at \(\tau = -4.2\) (typically the inversions are better constrained in the \(\tau\) range \(\sim -3.8\) to \(\sim -5\)). The choice of showing the \(v_{\text{turb}}\) is motivated by both theoretical and observational results: the fractionation model of Laming (e.g., Laming 2015 and references therein) predicts a dependence of FIP bias on the magnetic waves propagating and/or reflecting in the chromosphere, and recent observations of a sunspot found Alfvénic waves associated with FIP bias enhancements (Baker et al. 2021; Murabito et al. 2021; Stangalini et al. 2021). Assuming all the microturbulence comes from temporal unresolved Alfvén waves, the time integration provides an upper limit of the frequencies, and the values of the microturbulence will be associated with the amplitude. However, other physical processes may contribute to microturbulence, e.g., other unresolved flows, jets, turbulence, heating, or opacities. Furthermore, a visual inspection of the IRIS\(^2\)-derived quantities indicates a potential correlation of \(v_{\text{turb}}\) around \(\tau = -4.2\) with the FIP bias, as visible in Figure 7. For the observation shown in Figure 7, the Pearson cross-correlation coefficient between FIP bias and \(v_{\text{turb}}\) at \(\tau = -4.2\) is 0.35, indicating a moderate correlation between the two variables. We find that the correspondence between FIP bias and \(v_{\text{turb}}\) is mostly evident in the areas in the eastern side at the boundary of the AR, in particular in the outflow regions. The presence of correlation is interesting and not necessarily expected, given the connectivity between the high-FIP-bias coronal regions and the footpoints, which might not overlap, and therefore the observed correlation might be underestimated. We note that calculations of the cross-correlation just in these high-FIP-bias areas do not show significant correlation, and that this is not unexpected, because at any given location the IRIS and EIS data are typically obtained at quite different times (from minutes to hours, even for EIS and IRIS scans taken roughly simultaneously, because of the different scanning direction for the two instruments, i.e., W–E for EIS and E–W for IRIS; see Figure 9 and text of Testa et al. (2016) for an example). In Figure 8, we show two more examples of the FIP bias–\(v_{\text{turb}}\) correlation for two observations at different times.
(2019 April 11 at 15UT and 2019 April 17 at 15UT). The f.o.v. of the EIS and IRIS observations on 2019 April 11 covers the high-FIP-bias area at the AR boundary and shows a cross-correlation coefficient (0.31) similar to that of the first observation, whereas the latter observation has a different f.o.v. excluding most of those areas and no significant correlation between chromospheric $v_{\text{turb}}$ and FIP bias is observed.

The high-FIP-bias areas in the AR outflow regions also appear to have less redshifted Si IV with respect to the AR core, which generally shows significant redshift in its Si IV emission; these results are in agreement with our recent investigation of the TR and chromospheric counterparts of outflow regions (Polito et al. 2020). We do not see significantly different Si IV nonthermal broadening in the high-FIP-bias areas. This is analogous to the findings of Barczynski et al. (2021) that the measured transition region (IRIS Si IV) nonthermal velocities are similar in upflow regions and active region cores. This is, of course, a very intriguing result, as other TR and chromospheric line properties, such as, e.g., Si IV and C II Doppler shifts and Mg II line asymmetries (Polito et al. 2020; Barczynski et al. 2021), instead have different values in outflows regions with respect to AR cores. We will speculate more on these findings in the discussion section below.

4. Discussion and Conclusions

The composition of the solar corona and the solar wind often differs from that of the solar photosphere, typically with a relative enrichment of elements with low first ionization potential (FIP effect). This chemical fractionation is poorly understood, but it can provide crucial clues about the physical processes at work in the solar atmosphere. In fact, the fractionation is surely originating in the chromosphere where the first ionization occurs, and it must be linked to the coronal heating mechanism. However, it also carries its signature throughout the many layers and magnetic structuring of the corona and into the solar wind. The variation of the chemical fractionation, both in space and in time, can therefore be used as a tracer of the mass and energy flow throughout the solar atmosphere—and thus provide insights on the drivers of the observed outflows.

In this paper, we have analyzed spectroscopic observations of an active region, over several days, with IRIS and Hinode/EIS. The IRIS and Hinode observations allowed us to study the solar atmosphere from the chromosphere to the transition region (TR) and the corona, and to measure the FIP effect and its evolution over several days, with about daily cadence. By combining observations of different atmospheric layers, we
have also investigated possible correlations between the chemical fractionation observed in the corona with plasma properties in the lower atmosphere.

In order to derive the coronal abundance from the Hinode/EIS spectra, we apply a modified version of a recent compressed sensing method for the spectral inversions (Cheung et al. 2019; J. Martinez-Sykora & P. Testa 2023, in preparation), similar to the version used by Martinez-Sykora et al. (2022) to derive DEM(n,T,B) using magnetic-field-induced transitions. This inversion method allows the plasma temperature distribution, density, and abundances to be derived in a robust fashion, and it is significantly faster than the typically used MCMC method (Kashyap & Drake 1998), facilitating the analysis of long time series. Here, we showed (Figure 2) the satisfactory results of a test of this new method against literature results (Baker et al. 2015) obtained with the MCMC DEM inversion method, although a thorough presentation of the method and its testing is deferred to an upcoming paper (J. Martinez-Sykora & P. Testa 2023, in preparation).

We then presented the results of the application of the method to a time series of 15 Hinode/EIS observations of AR 12378 covering about 10 days. The FIP bias maps show that: (a) most of the AR plasma shows a modest, and fairly constant, FIP bias of ~1.5–2; (b) high-intensity (in SiX emission) regions show slightly larger FIP bias of ~1.7–2.2, with smaller values later in the time series, as discussed in more detail below; (c) outflow regions at the AR boundary consistently show high FIP bias; (d) high FIP bias is also found in some large and cool (fan) loops, in some moss regions, and at times, in some areas close to the sunspot; (e) the FIP bias in some moss regions changes quite rapidly (over timescales of hours), and it is intermittently found at enhanced values of >2 or at lower values similar to the rest of the AR core. The time series of maps of FIP bias obtained for these observations do not show overall very marked temporal variability in the FIP bias level of different solar features. Previous studies of the evolution of FIP bias in AR indicated an increase in FIP bias during the initial flux emergence phase (Sheeley 1995; Widing 1997; Widing & Feldman 2001; Baker et al. 2018). For decaying ARs, recent EIS studies suggest a small decrease of FIP bias (Baker et al. 2015; Ko et al. 2016). Analyses of Skylab data seem to indicate a continued increase, for several days (~7), of FIP bias in ARs to very large (~7) values (Widing & Feldman 2001). We note, however, that the Skylab results were based on Mg/Ne abundance ratios, possibly explaining some of the discrepancies with the recent more recent EIS results mostly based on Si/S, where S is at the boundary between high- and low-FIP elements and might behave differently. Our observations of AR 12378 show a rather quiet AR that is slowly decaying (see Figures 5 and 6). Baker et al. (2015) measured variations in FIP bias from observations 2 days apart, while Ko et al. (2016) used time series covering about 4 days of the AR evolution, and in both cases they observe a small FIP bias decrease of the order of 10%–15%. Furthermore, in Ko et al. (2016), where the high-cadence observations sample small timescales, they find FIP bias variability (both increases and decreases of up to ~15%) on timescales of hours (see their Figure 10). We note that both Baker et al. (2015) and Ko et al. (2016) mostly focused on the bright AR core, so, for a more meaningful comparison here, we also derived the FIP bias for the brightest regions (see yellow–orange squares in Figure 4) and possibly see a small decay in FIP bias value over the 10 day period (<10%). The lower values are found in the later part of the time series when the AR is less active.

A novel aspect of our study, compared to previous FIP bias studies, is that we accompanied the Hinode/EIS chemical fractionation measurement with coordinated IRIS spectral observations of the underlying chromosphere and transition region. The aim of this combined approach is to try to connect coronal abundance anomalies to conditions in the lower atmosphere, and especially the chromosphere, where the FIP effect is thought to originate. Overall, we did not find significant correlations between FIP bias and transition region properties, as observed by IRIS in SiIV, besides the fact that outflow regions are characterized by relatively smaller redshifts than the typical AR core SiIV Doppler shifts, in agreement with previous findings by Polito et al. (2020) and Barczynski et al. (2021). The IRIS chromospheric inversions suggest a correspondence between chromospheric turbulence $v_{\text{turb}}$ and FIP bias; at least for the high-FIP-bias areas corresponding to outflow regions. This result supports recent findings of a correlation between coronal outflows and flows in the TR and chromosphere (Polito et al. 2020). However, no increase in $v_{\text{turb}}$ is evident for the high-FIP-bias areas observed close to a sunspot. The difference in underlying chromospheric turbulence between the high-FIP-bias areas in outflow regions and close to the sunspot might be explained by different scenarios: it might suggest differences in the mechanisms leading to the fractionation in the two types of regions, or the $v_{\text{turb}}$ in outflows might possibly be related to the formation of the flows and not be causally connected to the chemical fractionation, or it might be due to differences in viewing angle between the line of sight and magnetic field between the two regions.

Another puzzling finding is the lack of correlation between FIP bias and the SiIV nonthermal broadening. If the chromospheric turbulence is indeed at least partly connected to Alfvén waves, which are in some models central to the fractionation process (e.g., Laming 2015), one would expect to see a trace in the transition region plasmas, specifically in the line broadening. The lack of correlation between FIP bias and nonthermal broadening might constrain the properties of the waves and where and how they might get dissipated. These findings therefore provide new challenging observational constraints on modeling and theory of chemical fractionation.

In future work, we will apply our new inversion method to other time series of Hinode/EIS and IRIS coordinated AR observations, for ARs at different activity levels and evolutionary stages, to test whether the correlations between $v_{\text{turb}}$ and FIP bias are present in all ARs and with similar properties, and we will also investigate whether any other correlation with TR and/or chromospheric variables might be present in other ARs.

We would like to thank the referee for useful comments that helped improve the paper. P.T. and J.M.S. were funded for this work by the NASA Heliophysics Guest Investigator grant 80NSSC21K0737, and by the NASA Heliophysics Supporting Research grant 80NSSC21K1684. P.T. was also supported by contract 810002705 (IRIS) and NASA contract NNM07AB07C (Hinode/XRT) to the Smithsonian Astrophysical Observatory. B.D.P. and J.M.S. were supported by NASA contract NNG09FA40C (IRIS). We are very grateful to Lucas Guliano for helping with the processing of the Hinode/XRT data. This research has made use of NASA’s Astrophysics Data
System and of the SolarSoft package for IDL. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as a domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in cooperation with the ESA and NSC (Norway). SDO data were obtained courtesy of NASA/SDO and the AIA and HMI science teams. IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations executed at NASA Ames Research Center and major contributions to downlink communications funded by ESA and the Norwegian Space Centre.

**ORCID iDs**

Paola Testa [https://orcid.org/0000-0002-0405-0668](https://orcid.org/0000-0002-0405-0668)
Juan Martínez-Sykora [https://orcid.org/0000-0002-0333-5717](https://orcid.org/0000-0002-0333-5717)
Bart De Pontieu [https://orcid.org/0000-0002-8370-952X](https://orcid.org/0000-0002-8370-952X)

**References**

Baker, D., Brooks, D. H., Démoûlin, P., et al. 2013, ApJ, 778, 69
Baker, D., Brooks, D. H., Démoûlin, P., et al. 2015, ApJ, 802, 104
Baker, D., Brooks, D. H., van Driel-Gesztelyi, L., et al. 2018, ApJ, 856, 71
Baker, D., Stangalini, M., Valori, G., et al. 2021, ApJ, 907, 16
Baker, D., van Driel-Gesztelyi, L., Brooks, D. H., et al. 2019, ApJ, 875, 35
Baker, D., van Driel-Gesztelyi, L., Brooks, D. H., et al. 2020, ApJ, 894, 35
Barczynski, K., Harra, L., Kleint, L., Panos, B., & Brooks, D. H. 2021, A&A, 651, A112
Boerner, P., Edwards, C., Lemen, J., et al. 2012, SoPh, 275, 41
Boerner, P. F., Testa, P., Warren, H., Weber, M. A., & Schrijver, C. J. 2014, SoPh, 289, 2377
Brooks, D. H. 2018, ApJ, 863, 140
Brooks, D. H., Ugarte-Urra, I., & Warren, H. P. 2015, NatCo, 6, 5947
Brooks, D. H., & Warren, H. P. 2016, ApJ, 820, 63
Brooks, D. H., Warren, H. P., Williams, D. R., & Watanabe, T. 2009, ApJ, 705, 1522
Brooks, D. H., Warren, H. P., & Young, P. R. 2011, ApJ, 730, 85
Cheung, M. C. M., De Pontieu, B., Martínez-Sykora, J., et al. 2019, ApJ, 882, 13
Cheung, M. C. M., Martínez-Sykora, J., Testa, P., et al. 2022, ApJ, 926, 53
Culhane, J. L., Harra, L. K., James, A. M., et al. 2007, SoPh, 243, 19
De Pontieu, B., Martínez-Sykora, J., Testa, P., et al. 2020, ApJ, 888, 3
De Pontieu, B., Testa, P., Martínez-Sykora, J., et al. 2022, ApJ, 926, 52
De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, SoPh, 289, 2733
Doschek, G. A., & Warren, H. P. 2016, ApJ, 825, 36
Doschek, G. A., & Warren, H. P. 2017, ApJ, 844, 52
Doschek, G. A., & Warren, H. P. 2019, ApJ, 884, 158
Doschek, G. A., Warren, H. P., & Feldman, U. 2015, ApJL, 808, L7
Feldman, U. 1992, PhyS, 46, 202
Fletcher, L., & De Pontieu, B. 1999, ApJL, 520, L135
Freeland, S. L., & Handy, B. N. 1998, SoPh, 182, 497
Golub, L., Deluca, E., Austin, G., et al. 2007, SoPh, 243, 63
Kashyap, V., & Drake, J. J. 1998, ApJ, 503, 450
Klimchuk, J. A. 2006, SoPh, 234, 41
Ko, Y.-K., Young, P. R., Muglach, K., Warren, H. P., & Ugarte-Urra, I. 2016, ApJ, 826, 126
Kosugi, T., Matsuzaki, K., Sakao, T., et al. 2007, SoPh, 243, 3
Laming, J. M. 2004, ApJ, 614, 1063
Laming, J. M. 2009, ApJ, 695, 954
Laming, J. M. 2012, ApJ, 744, 115
Laming, J. M. 2015, SoPh, 12, 2
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Martínez-Sykora, J., Hansteen, V. H., De Pontieu, B., & Landi, E. 2022, ApJ, 938, 60
McKenzie, D. L., & Feldman, U. 1992, ApJ, 389, 764
Meyer, J.-P. 1985, ApJS, 57, 151
Mihaléscu, T., Baker, D., Green, L. M., et al. 2022, ApJ, 933, 245
Murabito, M., Stangalini, M., Baker, D., et al. 2021, A&A, 656, A87
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, SoPh, 275, 3
Polito, V., De Pontieu, B., Testa, P., Brooks, D. H., & Hansteen, V. 2020, ApJ, 903, 68
Sanz Daldà, A., de la Cruz Rodríguez, J., De Pontieu, B., & Gošić, M. 2019, ApJL, 875, L18
Sheeley, N. R. J. 1995, ApJ, 440, 884
Stangalini, M., Baker, D., Valori, G., et al. 2021, RSPTA, 379, 20200216
Testa, P. 2010, PNAS, 107, 7158
Testa, P., De Pontieu, B., & Hansteen, V. 2016, ApJL, 827, 99
Testa, P., De Pontieu, B., Martínez-Sykora, J., et al. 2013, ApJL, 770, L1
Testa, P., & Reale, F. 2022, arXiv:2206.03530
Testa, P., Saar, S. H., & Drake, J. J. 2015, RSPTA, 373, 20140259
Tripathi, D., Mason, H. E., Del Zanna, G., & Young, P. R. 2010, A&A, 518, A42
Warren, H. P., Brooks, D. H., Doschek, G. A., & Feldman, U. 2016, ApJ, 824, 56
Warren, H. P., Brooks, D. H., & Winebarger, A. R. 2011a, ApJ, 734, 90
Warren, H. P., Ugarte-Urra, I., Young, P. R., & Stenborg, G. 2011b, ApJ, 727, 58
Widing, K. G. 1997, ApJ, 480, 400
Widing, K. G., & Feldman, U. 2001, ApJ, 555, 426
Young, P. R. 2018, ApJL, 855, 15
Zurbuchen, T. H., Weberg, M., von Steiger, R., et al. 2016, ApJ, 826, 10