Evolution of Elemental Abundances during B-Class Solar Flares: Soft X-Ray Spectral Measurements with Chandrayaan-2 XSM

Biswajit Mondal, Aveek Sarkar, Santosh V. Vadawale, N. P. S. Mithun, P. Janardhan, Giulio Del Zanna, Helen E. Mason, Urmila Mitra-Kraev, and S. Narendranath

1 Physical Research Laboratory, Navrangpura, Ahmedabad, Gujarat-380 009, India; biswaajitm@prl.res.in, biswaajitm7mondal94@gmail.com
2 Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar, Gujarat-382 355, India
3 DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK
4 Space Astronomy Group, U R Rao Satellite Centre, ISRO, Bengaluru-560 017, India

Received 2021 May 19; revised 2021 July 8; accepted 2021 July 9; published 2021 October 6

Abstract

The Solar X-ray Monitor (XSM) payload on board Chandrayaan-2 provides disk-integrated solar spectra in the 1–15 keV energy range with an energy resolution of 180 eV (at 5.9 keV) and a cadence of 1 s. During the period from 2019 September to 2020 May, covering the minimum of Solar Cycle 24, it observed nine B-class flares ranging from B1.3 to B4.5. Using time-resolved spectroscopic analysis during these flares, we examined the evolution of temperature, emission measure, and absolute elemental abundances of four elements—Mg, Al, Si, and S. These are the first measurements of absolute abundances during such small flares and this study offers a unique insight into the evolution of absolute abundances as the flares evolve. Our results demonstrate that the abundances of these four elements decrease toward their photospheric values during the peak phase of the flares. During the decay phase, the abundances are observed to quickly return to their preflare coronal values. The depletion of elemental abundances during the flares is consistent with the standard flare model, suggesting the injection of fresh material into coronal loops as a result of chromospheric evaporation. To explain the quick recovery of the so-called coronal “First Ionization Potential bias” we propose two scenarios based on the Ponderomotive force model.

Unified Astronomy Thesaurus concepts: Solar x-ray flares (1816); Solar abundances (1474)

1. Introduction

The study of elemental abundances in different layers of the solar atmosphere is of great interest in solar physics. It can provide information about the mass and energy transfer between these layers. It has been observed that elements with a First Ionization Potential (FIP) less than 10 eV are 3–4 times more abundant, relative to those with a high FIP, in the quiescent cores of active regions (ARs), while their values in the quiet Sun are closer to their photospheric values. This phenomenon is known as coronal FIP bias. See, for example, Feldman (1992), Feldman & Laming (2000), Feldman & Widing (2003), Saba (1995), Del Zanna (2013), Del Zanna & Mason (2014), and especially the recent review by Del Zanna & Mason (2018). Most previous observations were, however, unable to establish the absolute values of the abundances, as line-to-continuum measurements have been lacking. Del Zanna (2013) used instead an emission measure argument to show that low-FIP elements have abundances 3.2 times higher than their photospheric values in the 3 MK plasma of quiescent AR cores. Lower values, around 2, are found for the 2 MK plasma in the cores, while large abundance variations are found in other structures such as the 1 MK cooler loops or in brightenings.

Other stars also show chemical abundance variations, although generally active stars show an inverse FIP bias, i.e. the opposite of what is observed in quiescent ARs (Drake et al. 1994, 1997; Laming & Drake 1999). Recently, the inverse FIP bias has also been observed close to large sunspots producing large flares (see, e.g., Doschek et al. 2015). Several theories have attempted (e.g., Hénoux 1998) to explain the FIP bias, the most recent one being based on the Ponderomotive force model (Laming 2004, 2009, 2012, 2015, 2017, 2021), which is able to reproduce the overall features of both the FIP and inverse FIP bias. Studies of chemical abundance variations are therefore important in general for astrophysics, as the observed variations are likely related to the (still unknown) physical processes that heat the plasma to coronal temperatures.

By analyzing extreme ultraviolet (EUV) low-temperature (less than 1 MK) spectral lines of flares and surges observed by Skylab, Feldman & Widing (1990) and Feldman (1992) noted that the relative abundances of several elements (e.g., O and Mg) were close to their photospheric values. These were interpreted to be consequences of chromospheric evaporation during the events, injecting photospheric plasma into the corona.

Later, with the improved spectroscopic capability in the X-rays and EUV, nearly photospheric abundances have been found for several large flares (Del Zanna & Woods 2013; Sylwester et al. 2014, 2015; Warren 2014; Dennis et al. 2015; Katsuda et al. 2020). In these cases, the observations were of hot (about 10 MK) flare plasma, and line-to-continuum measurements indicated that indeed the absolute values were close to photospheric. We note, however, that a large scatter of values has been reported, partly due to the uncertainty in the continuum evaluation, and partly due to the use of different analysis techniques. One interesting aspect of such studies is that none reported variations during the events, which are generally long-lasting over several hours.

Detailed studies of larger flares were possible because of their strong signal-to-noise ratio. However, it is also important to investigate their smaller counterparts. Observations show that smaller flares occur much more frequently than the bigger ones (Hudson 1991), so understanding their physics will be of great interest. As detailed observations have been lacking, it is not clear if the evolution of these smaller events follows the standard flare model. It is only recently, with the advent of...
better instrumentation, that in-depth studies of smaller flares are becoming feasible (Kuhar et al. 2018; Mitra-Kraev & Del Zanna 2019; Athiray et al. 2020; Cooper et al. 2020; Glesener et al. 2020; To et al. 2020; Duncan et al. 2021; Vadawale et al. 2021a). Lately, using X-ray time-resolved spectroscopy, Narendranath et al. (2020) have carried out abundance studies of flares as small as GOES B9 class. Like the larger ones, these small flares have also shown a depletion of low-FIP elements relative to H during their evolution.

The Solar X-ray Monitor (XSM; Vadawale et al. 2014; Shanmugam et al. 2020) on board the Chandrayaan-2 provides soft X-ray disk-integrated solar spectra, with a good energy resolution (180 eV at 5.9 keV) and a high cadence (1 s). Its high sensitivity and capability of measuring elemental abundances on an absolute scale (i.e., with respect to H) enable us to perform a comprehensive study of smaller flares. The instrument has captured several sub-A class flares during the minimum of solar cycle 24 (Vadawale et al. 2021a). The statistical analysis of these tiny flares demonstrates the possible role of nanoflares in heating the quietest solar corona during this period. The instrument has also been used to study elemental abundances of the 2 MK quiescent solar corona during the aforementioned solar minimum (Vadawale et al. 2021b). During this time, the coronal FIP bias was found to be about 2, less than the FIP bias of an AR (around 3–4). The overall emission of the global corona during this quiet phase of the Sun was found to be dominated by X-ray bright points.

In this work, we present the evolution of temperature, emission measure, and absolute abundances of Mg, Al, Si, and S during a set of nine GOES B1.3–B4.5 class flares. These flares were observed during the minimum of solar cycle 24. At the time of these observations the Sun was extremely quiet, less dynamic and had single isolated ARs on the disk. For the first time, we show a clear and consistent variation of elemental abundances over the entire duration of these flares.

The rest of the paper is organized as follows. In Section 2 we present the observation, XSM data analysis, and identification of events. In Section 3 we describe the details of the spectroscopic analysis. After discussing the overall results in Section 4, we summarize the article in Section 5.

2. Observations and Data Analysis

XSM observes the Sun as a star from a lunar orbit. It measures the soft X-ray spectrum in the 1–15 keV energy range with an energy resolution better than 180 eV at 5.9 keV. The unique design of XSM makes it possible to measure the X-ray spectrum with a stable energy resolution over a broad range of solar X-ray intensities, from lower than A class up to X class. For this purpose, it uses a Silicon Drift Detector as the sensing device and a filter wheel mechanism along with the onboard logic for autodetection of large flares to extend its dynamic range. In the present work, we focus on the largest observed flares, all of which are B class. These flares were observed during the first two prime observing seasons of the XSM from 2019 September 12 to November 20 (DD1) and 2020 February 14 to May 19 (DD2)–see Mithun et al. (2020) and Vanitha et al. (2020) for details on XSM observing seasons, referred to as “dawn-dusk” (DD) and “noon-midnight” seasons.

XSM acquires spectra every second, which are stored as raw, day-wise (level-1) data files. Due to the varying visibility of the Sun within the XSM field of view (FOV), there are periods when the Sun moves out of the FOV or is occulted by the Moon, and these periods provide the background observations. The raw data include both solar and background observations. The XSM Data Analysis Software (XSMDAS; Mithun et al. 2021) generates level-2 science data for durations for which the Sun was within the FOV, by selecting appropriate Good Time Intervals (GTI) based on the observing geometry and a few other instrumental parameters. The default level-2 data contain the effective area corrected light curve of 1 s and spectra of 60 s cadence. XSMDAS also supports a user-defined GTI and time cadence to generate customized data products, which we utilize for the present analysis as discussed below.

Figure 1 (panels a and b) shows the solar X-ray light curve observed by the XSM in the energy range of 1–15 keV during DD seasons DD1 and DD2. Shaded regions of the light curve show enhanced X-ray emission due to the presence of ARs. The different colors represent different NOAA ARs, with each of them showing a number of flaring episodes. Since the objective of the present analysis is to investigate the temporal evolution of the flares, we select all of the large flares for which the XSM count rate increases by more than 200 counts per second from the preflare baseline. We find a total of ten events satisfying this criterion, and these events have been marked by vertical red lines in the figure. However, the flare of 2019 November 5, peaking at 06:11 UT, was only partially observed by the XSM. We therefore exclude this event from further analysis.

Figure 2 shows an enlarged view of the X-ray light curves observed by the XSM (blue) for these nine flares, which have been designated with appropriate identifiers corresponding to the flare peak time, following the standard convention (Leibacher et al. 2010). The figure also includes 1–8 Å GOES-16 X-Ray Sensors (XRS) light curves in gray for comparison, showing that the nine selected flares are all small B-class events with the peak flux ranging from $1.34 \times 10^{-7}$ W m$^{-2}$ to $4.50 \times 10^{-7}$ W m$^{-2}$. It should be noted that some of the earlier studies (e.g., Christe et al. 2008; Hannah et al. 2008) have referred to such events as microflares; however, since the XSM has observed many weaker sub-A class events that have been referred to as microflares in an earlier paper (Vadawale et al. 2021a), we continue to refer to the selected events as B-class flares.

Since the XSM observes disk-integrated X-ray emission from the Sun, we use Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA; Lemen et al. 2012) images in the 94 Å channel to examine the spatial distribution of the enhanced activity on the solar disk. AIA images at the time of the flares (examples in Figure 1(c)) show that only isolated ARs are present on the solar disk. For each flare we derive the AIA 94 Å light curve integrated over the regions around the respective AR (marked by small yellow boxes on the corresponding full-disk AIA images in Figure 1(c)); they are shown with brown dashed curves in Figure 2. Their similarity with the XSM light curves confirm that the entire enhancement of X-ray intensity observed by the XSM during these flares originated within the respective AR. This confirms that the disk-integrated XSM observations can be used to study the temporal evolution and properties of the flaring plasma.

In order to investigate the temporal evolution during the selected flares, we divide each flare duration into multiple smaller time intervals corresponding to various phases of each flare. The intervals for each flare, shown as alternate background shades in Figure 2, are selected based on visual inspection of the XSM light curve in the energy range of
1–15 keV, such that all intervals have a sufficient number of counts to perform spectral analysis. These time intervals are then used as user GTI in XSMDAS to generate a series of spectra for all nine flares. The modeling of these spectra is then carried out using two different approaches, as discussed in detail in the next section. The first approach assumes that the emission arises from plasma having two distinct components corresponding to the flaring plasma and the rest of the coronal plasma, respectively. The second approach assumes that the emission arises from a single component isothermal plasma. The first approach requires a spectrum corresponding to a nonflaring plasma, which is generated for the nonflaring time intervals as shown in Figure 3(a) for two representative flares, SOL2020-04-06T05:48 and SOL2020-04-06T08:32. The blue line shows the full day light curve, while the green shaded regions show periods for which the nonflaring emission spectrum is generated. Such nonflaring time intervals are visually selected from the corresponding daily light curves for all flares, with the exception of the two flares SOL2019-09-30T23:00 and SOL2019-10-01T01:44. For these two flares, it is difficult to select a reliable nonflaring duration because of the multiple small flaring episodes occurring within the same AR as shown in Figure 3(b). Moreover, the AR starts appearing from the eastern limb of the Sun during these two events. Hence, the spectral analysis of these flares is restricted to the isothermal plasma assumption (second approach).

3. Time-resolved Spectral Analysis

Soft X-ray spectra of the solar corona provides information on the physical conditions and radiative processes in the emitting plasma. It typically consists of a continuum arising from free–free, free–bound, and two-photon radiative processes superimposed by emission lines corresponding to different ionization states of various elements. The expected spectrum for a given set of physical parameters such as temperature \( T \) and density (usually represented as emission measure, EM), as well as the abundances of various elements, can be analytically calculated (Del Zanna & Mason 2018). This analytical or synthetic spectrum, when fitted to the observed spectrum, can constrain the physical parameters of the observed plasma. We use the CHIANTI database version 10 (Del Zanna et al. 2021) to generate the synthetic spectra and XSPEC (an X-ray spectral fitting package; Arnaud et al. 1999) to fit the spectrum. Since the synthetic spectrum calculated by CHIANTI cannot be directly used in XSPEC for spectral fitting, we have developed a local XSPEC model, chisoft, from a wide range of precalculated spectra, as described in Appendix (the same model was used for the spectral analysis of the quiet Sun and microflare spectra presented by Vadawale et al. 2021a, 2021b).

The main objective of our analysis is to study the evolution of plasma properties during the course of the nine selected B-class flares. Since these are relatively small flares, it is likely that during different flare phases there are considerable contributions from nonflaring plasma. Usually, such contributions are subtracted from
Figure 2. The 1–15 keV XSM X-ray light curves (blue) for the selected flares. The observed GOES-16 XRS fluxes of these flares are shown by gray lines, while the brown dashed lines show the normalized (with XSM count rates) AIA 94 Å fluxes, spatially integrated over the associated ARs as marked by the yellow boxes in Figure 1(c). Background green and orange shaded regions represent durations for which the integrated XSM spectra have been generated for time-resolved spectroscopy as described in Section 2. The vertical red dotted lines represent the flare peak time. Black horizontal dotted lines in panels (c–i) are the average count rates for the nonflaring plasma as discussed in Section 3. The black scale bars at the top left of each panel represent a 20 minute time interval on the x-axis. A flare ID for each flare corresponding to the flare peak time in the format SOLyyyy-mm-ddThh:mm is given on the top of every panel.

Figure 3. Full day XSM 1–15 keV solar X-ray light curve on 2020 April 06 (a) and 2019 September 30 (b). Selected flare peak times for the same day are shown by the red vertical lines. In panel a the green shaded regions demarcate the time durations used to generate the nonflaring emission spectrum required for the two temperature spectral fitting for the flares SOL2020-04-06T05:48 and SOL2020-04-06T08:32. The brown, violet, and blue shaded regions show the time interval of the spectra shown in Figure 4. Panel b shows multiple small flaring episodes before and after the flare SOL2019-09-30T23:00. All of these flares occur within the same AR, which appeared at the eastern limb of the Sun. Because of this, a reliable nonflaring emission could not be established for this flare.
| Flare ID<sup>a</sup> | NOAA<sup>b</sup> AR | Model<sup>c</sup> | max. <sup>d</sup>T<sup>e</sup> × 10<sup>6</sup>K (Time bin) | max. <sup>f</sup>EM × 10<sup>46</sup> cm<sup>-3</sup> (Time bin) | Mg<sup>f</sup> | Al<sup>f</sup> | Si<sup>f</sup> | S<sup>f</sup> |
|-----------------|------------------|----------------|---------------------|---------------------|-------------|-------------|-------------|-------------|
| SOL2019-09-30T23:00 | 1T | (22: 54–23: 03) | 6.78±0.10<sup>1</sup> -0.12 | 19.4±1.56<sup>1</sup> 1.22 | 7.42±0.04<sup>1</sup> 0.05 | 6.49±0.09<sup>1</sup> -0.12 | 7.55±0.02<sup>1</sup> -0.02 | 6.93±0.03<sup>1</sup> |
| SOL2019-10-01T01:44 | 1T | (01: 42–01: 46) | 7.38±0.13<sup>1</sup> -0.17 | 16.2±2.04<sup>1</sup> 1.32 | 7.42±0.05<sup>1</sup> -0.07 | 6.49±0.10<sup>1</sup> -0.17 | 7.62±0.02<sup>1</sup> -0.03 | 7.02±0.03<sup>1</sup> |
| SOL2020-03-11T05:56 | 1T | (00: 50–00: 53) | 6.54±0.07<sup>1</sup> -0.10 | 36.8±2.46<sup>1</sup> 1.97 | 7.49±0.04<sup>1</sup> -0.11 | 6.50±0.08<sup>1</sup> 0.01 | 7.72±0.02<sup>1</sup> -0.02 | 7.09±0.02<sup>1</sup> |
| SOL2020-04-04T00:52 | 1T | (00: 50–00: 53) | 9.06±0.08<sup>1</sup> -0.14 | 42.3±2.20<sup>1</sup> 2.54 | 7.31±0.04<sup>1</sup> 0.05 | 6.41±0.10<sup>1</sup> -0.14 | 7.55±0.02<sup>1</sup> -0.02 | 7.02±0.02<sup>1</sup> |
| SOL2020-04-06T05:48 | 1T | (05: 45–05: 50) | 7.02±0.09<sup>1</sup> -0.10 | 32.5±2.13<sup>1</sup> 1.99 | 7.48±0.03<sup>1</sup> 0.04 | 6.50±0.09<sup>1</sup> -0.11 | 7.73±0.02<sup>1</sup> -0.02 | 7.13±0.02<sup>1</sup> |
| SOL2020-04-06T08:32 | 1T | (08: 30–08: 34) | 7.40±0.10<sup>1</sup> -0.15 | 23.0±2.88<sup>1</sup> 1.80 | 7.51±0.04<sup>1</sup> 0.06 | 6.37±0.13<sup>1</sup> -0.24 | 7.76±0.02<sup>1</sup> -0.02 | 7.08±0.03<sup>1</sup> |
| SOL2020-04-07T01:58 | 1T | (01: 56–02: 01) | 8.08±0.05<sup>1</sup> -0.11 | 47.6±3.38<sup>1</sup> 2.57 | 7.51±0.04<sup>1</sup> 0.06 | 6.48±0.09<sup>1</sup> -0.12 | 7.71±0.02<sup>1</sup> -0.02 | 7.08±0.02<sup>1</sup> |
| SOL2020-04-09T09:32 | 1T | (09: 08–09: 13) | 6.44±0.09<sup>1</sup> -0.16 | 28.8±1.84<sup>1</sup> 1.78 | 7.46±0.03<sup>1</sup> 0.05 | 6.50±0.09<sup>1</sup> -0.10 | 7.71±0.02<sup>1</sup> -0.02 | 7.12±0.02<sup>1</sup> |
| SOL2020-03-30T12:16 | 1T | (12: 15–12: 18) | 7.39±0.14<sup>1</sup> -0.18 | 15.5±2.14<sup>1</sup> 1.88 | 7.46±0.06<sup>1</sup> 0.06 | 6.44±0.15<sup>1</sup> -0.22 | 7.68±0.03<sup>1</sup> -0.03 | 7.13±0.05<sup>1</sup> |

Notes.

<sup>a</sup> Flare ID corresponds to the time at the peak of the flare in the format SOLyyyy-mm-ddThh:mm.

<sup>b</sup> Active region number defined by NOAA for the associated flares.

<sup>c</sup> Model used for the spectral fitting. 1T indicates the single component isothermal model. 2T indicates the two component model, where one component represent the flaring plasma emission and other component represent the nonflaring (NF) plasma emission, whose fitted parameters are given in the third row of each flare group.

<sup>d</sup> Maximum temperature for the flares and the associated time bin in UT.

<sup>e</sup> Maximum emission measure and the associated time bin in UT.

<sup>f</sup> Elemental abundances when the emission measure is peaking. Errors represent the 1σ limits associated with the parameters.

the flare spectrum by considering a preflare spectrum as background. However, this is not preferable in the case of XSM because the Sun angle, and thus the effective area of the instrument, changes continuously. Hence, we model the spectrum of the nonflaring plasma independently and include it as a fixed component while fitting the flare spectrum. An additional advantage of this approach is that in most cases it is possible to co-add several epochs having the same intensity and spectra, as shown in Figure 3(a), to increase the statistical significance of the nonflaring spectrum. We then fit this nonflaring X-ray spectrum with our isothermal model. Though the model allows one to vary the abundances of all elements in the range of Z = 2 to 30, we
retain the abundances of only Mg, Al, and Si, for which the line features are observable in the spectra, as free parameters. Abundances of the remaining elements are fixed to their respective coronal values taken from the combined dataset “sun_coronal_1999_fludra_ext_abund” (hereafter A_F99) available within the CHIANTI package. These are so-called “hybrid” abundances, where the abundances of low (high) FIP elements were increased (decreased) compared to their photospheric values, by about a factor of two. The other two free parameters of the model are temperature (T) and emission measure (EM). We carry out the spectral analysis to determine the T, EM, and abundances of Mg, Al, and Si of nonflaring plasma for all the flares except SOL2019-09-30T23:00 and SOL2019-10-01T01:44, as discussed in Section 2. Table 1 shows the best-fitted parameters for all of the nonflaring spectra.

Next, we focus on the spectra generated for the different phases of the selected nine flares as shown in Figure 2. We fit each spectrum with a model consisting of two isothermal components. All parameters of the first component are fixed to their respective values obtained from nonflaring intervals, whereas for the second component, T, EM, Mg, Al, and Si are kept as free parameters and fitted for each spectrum. We also keep the S abundance as a free parameter whenever fitting for S is statistically feasible. During the flare peak, occasionally Ar and Ca line complexes are also visible; however, because of their poor statistics, including them in the spectral fits and deriving their abundances leads to large error bars. Hence, we fix their abundances as a constant parameter during spectral fitting. We have verified that keeping abundances of these two elements either as free or fixed do not affect any other fit parameters. The one sigma uncertainties on all free parameters are obtained using the standard procedure in XSPEC. The representative spectral fits for the flare SOL2020-04-06T05:48, for the three time durations (marked by brown, violet, and blue shaded regions in Figure 3(a)), are shown in Figure 4(a). The fit results for all phases of the same flare are shown in Figure 5.

For the two flares SOL2019-09-30T23:00 and SOL2019-10-01T01:44, it was not possible to carry out the spectral analysis with the two component model due to the lack of reliable nonflaring spectra. Hence, for these two flares, we resorted to using only a model with a single temperature. However, in order to investigate any differences between the results obtained by the two spectral fitting approaches, we also carried out a time-resolved spectral analysis, for all nine flares, under the isothermal assumption with a single component model.

The spectral fits with the single component model for the same spectra of the flare SOL2020-04-06T05:48 are shown in Figure 4(b) and the fit results for all phases of the flare are overplotted in Figure 5. We find that, for all flares where both the two component and single component analysis is possible, the results obtained with both approaches are similar within error bars. Table 1 shows the values for the time intervals containing the temperature and emission measure peaks. This suggests that even for these small B-class flares, the emission from the flaring plasma dominates over the emission from the nonflaring plasma and, hence for the flares SOL2019-09-30T23:00 and SOL2019-10-01T01:44, the results of the single component analysis also represent variations associated to the flare loops.

4. Results and Discussion

In this study, we have performed a spectroscopic analysis of nine B-class flares. Using time-resolved spectroscopy of these flares, we have shown the evolution of elemental abundances, temperature, and emission measure over their lifetime. Results from a representative flare (SOL2020-04-06T05:48) are demonstrated in Figure 5. The different panels demonstrate the time evolution of temperature (a), emission measure (b), and abundances of four elements (c–f), namely, Mg, Al, Si, and S. Temperature (Figure 6), emission measure (Figure 7), and abundance (Figures 8–10) evolution of all other flares are shown separately. In the background of each plot, the light curve of the respective flare is shown with a solid gray line.

Temperatures (Figure 5(a), Figure 6) and emission measures (Figure 5(b), Figure 7) of these flares rise with their soft X-ray activity, showing maxima near the time of the flare peaks.
most of the flares, the temperature peaks lie ahead of the emission measure peaks. These can be identified by comparing Figure 6 with Figure 7 (or Table 1). However, two flares, namely, SOL2019-09-30T23:00 and SOL2020-03-11T05:56 (panels a and c), do not follow the trend, possibly due to larger time bins at the flare peak compared to the small flare duration. During the impulsive phases, elemental abundances (Figures 5(c)–(f), Figures 8–10) are seen to reduce quickly from the coronal value to near photospheric values, while the minima occur almost simultaneously with the emission measure peaks. However, the abundances swiftly return to the coronal values during the decay phases of the flares.

Considering our “Sun as a star” observation, one may think the quick recovery of the coronal abundances may not be physical but merely an effect of emission swapping from the flaring loop to the rest of the corona. However, results derived using our two temperature models, where emission from flaring and nonflaring plasmas are treated separately, show a similar abundance recovery (red points in Figures 5(c)–(f), Figures 8–10). This confirms that this abundance recovery is not due to emission swapping.

Following the standard flare model (CSHKP: Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976), the evolution of temperature and emission measure can be explained by invoking chromospheric evaporation. After the flare onset, both temperature and emission measure start rising. When the coronal temperature achieves its peak, the heat energy from the reconnection site travels down to the chromosphere and starts evaporating chromospheric plasma into the loop with high velocity (Antonucci et al. 1985). The peak of the emission measure is recorded once the loop gets filled with the high-density heated evaporated material (Ryan et al. 2012; Klimchuk 2017). As the evaporative upflow can bring in fresh unfractiated chromospheric material into the corona, it can also explain the quick abundance depletion. However, an explanation of the fast recovery (in a timescale of order minutes) of the coronal FIP bias during the decay phases of the flares is supported by additional mechanisms.

One of the most widely accepted theories to explain the FIP bias in the closed loop coronal plasma is based on the Ponderomotive force model. The said force originates at the chromospheric layers of the magnetic flux tubes due to multiple reflections of the coronal Alfvén waves (Laming 2004).
According to this theory, the FIP-dependent elemental fractionation arises because the upwards Ponderomotive forces act only on the ions. Since the density and temperature of the chromospheric layer favor the ionization of low-FIP elements, only these elements get fractionated there. Low-FIP ions then experience the Ponderomotive force and drift upwards, enhancing their concentration in closed coronal loops. Observations suggest it takes several days for the FIP bias to get established in non-flaring ARs (Widing & Feldman 2001), although we note that the Skylab measurements discussed by Widing & Feldman (2001) refer to cool transition region lines and the results are not directly related to the abundances of the hot core loops. In this context, two possibilities can be thought to be responsible for the quick transitions (of order minutes) of the coronal FIP bias during the impulsive and decay phases of all observed flares in this study. The schematic representations of these two possibilities are presented in Figure 11.

The first possibility envisages that the newly evaporated chromospheric material comes from a region beneath the fractionation layer, having almost nonfractionated photospheric plasma. It has been observed earlier that the injection of fresh material continues throughout the duration of the flare (Zarro & Lemen 1988; Czaykowska et al. 1999). The injection velocity is highest during the impulsive phase of the flare and gradually reduces toward the decay phase (Fletcher et al. 2011). At the time of the initial phase, when the upflow velocity is high, plasma does not get enough time to spend in the fractionation layer to get fractionated and thus unfractonated photospheric plasma is injected into the coronal loop—exhibiting a depletion of the coronal FIP bias. Once the upflow speed reduces below $\sim 1 \text{ km s}^{-1}$ (Laming 2004, 2017) at the top of the chromosphere, it is plausible to assume that the evaporated material takes longer to cross the thin fractionation layer and gets fractionated while traveling through it. In this scenario, the quick enhancement of the FIP bias is not only due to the slow drift of the ions but also due to the bulk velocity of the already (partly) fractionated material filling the loop. As the velocity of the evaporated material decreases, the plasma gets fractionated to a higher degree, and thus the FIP bias is restored to the pre-flare level by the time the flare emission decays completely.

The second possibility relies on the flare-driven high amplitude Alfvén waves. Immediately after the flare, heat energy carried by the suprathermal electrons (Benz 2017) may travel faster toward the loop footpoints than the Alfvén waves.

Figure 6. Temperature evolution, similar to Figure 5(a), but for different flares.
to evaporate plasma from the chromosphere. The evaporated chromospheric nonfractionated plasma is responsible for the initial depletion of the FIP bias. However, once the newly generated Alfvén waves reach the fractionation layer, they start fractionating plasma through the generation of the Ponderomotive force. The high amplitude nature of these waves helps to fractionate plasma in a faster timescale (Dahlburg et al. 2016). These Alfvén waves may also carry a significant fraction of the released magnetic energy from the flaring site to the chromosphere, which may also assist the evaporation (Fletcher & Hudson 2008). The fractionated plasma then gets transported to the coronal loop, assisted by the evaporative upflow, which helps to recover the coronal FIP bias in a faster timescale.

Although all of the observed flares show a similar variation of the abundance evolution, the abundance recovery timescale during the decay phase varies from flare to flare. In general, it ranges between ~10 to ~90 minutes. The second scenario, which explains the faster fractionation as well as transport, appears to be a more plausible mechanism to explain the faster recovery of the FIP bias. Whereas, if the recovery happens over a longer timescale (~several hours) it can be explained through the former. Reconnection driven Alfvén waves are yet to be observed in flaring loops. However, the observations presented in this article imply their role in altering the coronal FIP bias.

XSM observes the Sun as a star and therefore misses any spatial information. However, it is to be noted from SDO observations that the flaring reconnection and the postflare loops have fairly complicated geometric structures. Though the schematics of Figure 11 consider a single magnetic structure, in reality it can be more complicated.

We also note a couple of other interesting points—Figure 5 shows that, unlike the other three elements, the abundance of Si does not quite reach the photospheric value during the episodic event. The same is true for other flares as well. The abundance values of Si near the flare peak (Table 1, except the flares SOL2019-09-30T23:00, SOL2019-10-01T01:44, and SOL2020-04-04T00:52) are in good agreement with earlier large flare observation (Veck & Parkinson 1981). It may be possible that at the chromospheric height where the evaporating plasma originates, the abundance of Si is already greater than that of the photosphere, indicating the fractionation of Si at a lower chromospheric height. As a result, the evaporated plasma in the flaring loop exhibits an Si abundance between photospheric and photospheric values.
the coronal values, whereas the other elements exhibit a photospheric abundance.

It has been seen that the abundance of Mg during flare peaks depletes down to subphotospheric values (Figure 5(c), 8) on many occasions. Such an abundance depletion may be mistaken as evidence of the inverse FIP effect. However, we find that this could be due to the effect of input abundances of unresolved lines in the continuum spectra. When we change the input abundances from A_F99 (CHIANTI abundance dataset: “sun_coronal_fludra_1999_ext.abund”) to A_F92 (CHIANTI abundance dataset: “sun_coronal_feldman_1992_ext.abund”), the abundance of Mg remains within the photospheric range. For a similar reason, the measured abundances of flares SOL2019-09-30T23:00 (Panel a of Figures 8, 10), SOL2019-10-01T01:44 (Panel b of Figures 8, 10), and SOL2020-04-04T00:52 (Panel d of Figures 8, 10), record lower values than do the other flares. To check further how input abundances affect our derived parameters, we compare our single component fit results (Figure 12) of a typical B-class flare SOL2020-04-06T05:48 for two sets of input abundances, namely, A_F92 and A_F99. The temperature values (Figure 12(a)) for both of the input abundances remain almost unaltered. However, the rest of the parameters maintain a nearly constant offset. This is due to elements having a higher presence in the solar atmosphere, such as O, C, etc., in addition to H and He. They play a crucial role in determining the soft X-ray continuum. When changing the abundances, the overall continuum gets changed. Figure 12(b) shows the soft X-ray continuum at different temperatures. It also shows how the continuum shifts when the abundance list is changed from A_F92 and A_F99. Since the continuum gets changed, the derived parameters resulting from the continuum are also affected. Though the exact values of the absolute abundances depend on the chosen input abundance list, the abundance evolutionary trend during flares and the coronal abundance recovery timescale remain independent of the abundance list.

Having analyzed several B-class flares and identified their spectroscopic behavior over time, we can conclude that these flares also follow the standard flare model. In a manner similar to their larger, more energetic counterparts, they also show near photospheric abundances during their evolution. During the postflare phases, the quick recovery of the coronal abundances on a timescale of minutes can be successfully explained through the Ponderomotive force model. To study this issue further, a careful analysis of multiwavelength imaging and spectroscopic observations is necessary. We have carried out a
campaign of multiwavelength observations (with Hinode/EIS and XRT), and the results will be discussed in follow-up papers.

5. Summary

In this article, we presented the temporal evolution of elemental abundances during solar flares of GOES B1–B4 class, the weakest events for which such studies have been possible so far, using observations with XSM on board Chandrayaan-2. This study was possible due to the extremely quiet solar conditions currently prevailing along with the availability of appropriate instrumentation. By modeling the soft X-ray spectra obtained with the XSM during different phases of these flares, measurements of temperature, emission measure, and abundances of Mg, Al, Si, and S were obtained. We have shown that the abundances of these elements are nearly photospheric during the peak phase, compared to their 3–4 times higher preflare values. Beyond the flare peak, the abundances are seen to get enriched again and they recover back to the coronal values at the end of the flare. This suggests that during the flares, the coronal loops are quickly filled with plasma originating from the lower parts of the solar atmosphere without having sufficient time for the usually observed fractionation in nonflaring loops to take place. Our observation of the quick recovery to the coronal values shows that any process giving rise to such fraction must be occurring on a timescale of a few tens of minutes.
Figure 10. Evolution of the absolute Si abundance, similar to Figure 5(e), but for different flares.
We are thankful to an anonymous referee for providing us with very useful feedback. XSM was designed and developed by the Physical Research Laboratory (PRL), Ahmedabad, with support from the Space Application Centre (SAC), Ahmedabad, the U. R. Rao Satellite Centre (URSC), Bengaluru, and the Laboratory for Electro-Optics Systems (LEOS), Bengaluru. We thank various facilities and the technical teams of all of the above centers and the Chandrayaan-2 project, mission operations, and ground segment.

Figure 11. Schematic representation of flaring loop dynamics with lighter colors representing low-FIP bias, and darker colors indicating high-FIP bias. Scenario 1: (1a) Impulsive phase—After the flare onset (at time $t_0$), heat energy travels down to the chromosphere and evaporates the plasma there. The temperature peak is identified at the start (time $t_1$) of the chromospheric evaporation. During the initial phase, plasma evaporates with high velocity and quickly passes through the fractionation layer without getting fractionated, resulting in depletion of the coronal FIP bias. The EM peak is achieved (time $t_2$) once the loop gets filled with the chromospheric plasma. At around the same time, the abundances of the FIP elements also attain their minima. (1b) Decay phase—The speed of the evaporative upflow slows down significantly, allowing plasma enough time in the fractionation layer to get fractionated. The fractionated plasma eventually fills the coronal part of the loop, thereby demonstrating the recovery of the coronal FIP bias. (1c) Representative curves of temperature, EM, and elemental abundance evolution. Time $t_4$ marks the time of complete recovery of the coronal FIP bias. Scenario 2: (2a) At the time of the flare onset (time $t_0$), high amplitude Alfvén waves are initiated. The released heat energy gets transported to the chromosphere by suprathermal electrons, at speeds faster than those of the Alfvén waves. Evaporation starts at time $t_1$, and reduces the coronal FIP bias. The temperature peak is observed around this time. (2b) The EM peak and abundance minima are achieved when the loop is filled with the evaporated plasma ($t_2$). Once the flare-driven Alfvén waves arrive at the chromosphere (time $t_3$), they rapidly fractionate the plasma. These Alfvén waves also carry significant heat from the flaring site to assist the evaporation. The fractionated plasma is then transported to the coronal part of the loop through evaporative upflows, which help in rapidly recovering the coronal FIP bias. (2c) Representative curves of temperature, EM, and elemental abundances for the second scenario.

Figure 12. The six panels on the left show the results of the time-resolved X-ray spectral fitting using a single component model for the flare SOL2020-04-06T05:48. The blue points with error bars show the fitted parameters by taking a fixed abundance parameter from A_F92 and the magenta points with error bars show the same by using abundances values from A_F99. The panel on the right represents the continuum spectrum at different temperature with a fixed emission measure of $2.0 \times 10^{47} \text{cm}^{-3}$ by using the elemental abundances from A_F92 (solid lines) and A_F99 (dashed lines).

We thank an anonymous referee for providing us with very useful feedback. XSM was designed and developed by the Physical Research Laboratory (PRL), Ahmedabad, with support from the Space Application Centre (SAC), Ahmedabad, the U. R.

Rao Satellite Centre (URSC), Bengaluru, and the Laboratory for Electro-Optics Systems (LEOS), Bengaluru. We thank various facilities and the technical teams of all of the above centers and the Chandrayaan-2 project, mission operations, and ground segment.
An XSPEC Model for Ionized Plasma Emission Using CHIANTI

In this work, we model the observed soft X-ray spectrum of solar flares with the line and continuum emission from an isothermal plasma characterized by a temperature, emission measure, and abundances of various elements, computed using the CHIANTI atomic database (Del Zanna et al. 2021). As such a model is not readily available in the X-ray spectral fitting package XSPEC (Arnaud et al. 1999) used for the analysis, we have incorporated it as a local model named chisoth.

While it is possible to include this as a model in PyXspec, the Python version of XSPEC, by using the functions available in CHIANTIPy, the execution time for each model calculation is prohibitively large. Another possibility is to use the option of table model in XSPEC, where the model spectra over a multidimensional grid of parameters are stored in a file and a spectrum for any required set of parameters is obtained by interpolation. However, this is also not a viable option due to the requirement of abundances of elements being independent parameters, resulting in very large file sizes. Thus, we adopt a different approach and store a library of spectra only over a grid of temperatures, but for each individual element. Then, the total model spectrum for a required temperature and abundances is obtained by the weighted addition of interpolated spectra of each element, as detailed below. The precomputed element-wise spectra are recorded in a FITS file and the model is implemented in C++, which can be compiled and loaded into XSPEC following the standard procedure.5

In order to generate the spectral library, line and continuum spectra for each element (Z = 1 to 30) at unity abundance were computed over a logarithmic grid (\( \delta \log(T) = 0.004 \)) K of temperatures from 0.3 to 50 MK using CHIANTI routines. Line spectra were obtained by using ch_synthetic.pro, while the continuum spectra were obtained using individual routines for different emission processes, and all were added together to obtain the total spectra for each element at different temperatures, which are recorded in a FITS file.

Within the XSPEC model, the spectrum for each element at any temperature \( T \) within the range is obtained by linear interpolation between the spectra at the nearest two grid points available in the spectral library. Then the total spectrum \( I(T, E) \) is obtained by the weighted addition of spectra of individual elements as:

\[
I(T, E) = EM \ast [I_H(T, E) + I_{He}(T, E) \ast N_{He} + \cdots + I_{Fe}(T, E) \ast N_{Fe} + \cdots + I_{Zn}(T, E) \ast N_{Zn}]
\]

(A1)

where \( EM \) is the volume emission measure, \( I_X(T, E) \) is the spectrum for element \( X \) at unity abundance and emission measure and \( N_X \) is the abundance of element \( X \) relative to that of H, which is related to the usually used logarithmic value \( A_X \) as:

\[
A_X = 12 + \log_{10}(N_X)
\]

(A2)

The model takes logarithm of temperature (\( \log T \)), abundances (\( A_X \)) of the elements with \( Z = 2 \) to \( Z = 30 \), and volume emission measure as input parameters. It may be noted that the volume emission measure is implemented as an overall normalization factor, which is in units of \( 10^{46} \text{ cm}^{-3} \). Using the features in XSPEC, it is possible to freeze specific parameters such as abundances of certain elements to fixed values while keeping others free during spectral fitting. It is also possible to fit the spectrum with a sum of multiple isothermal emission models, as used in this work.

In order to verify the adequacy of the grid of temperatures used in the model, we carried out a comparison of the spectra obtained from the XSPEC model at nongrid temperature values with those obtained directly from CHIANTI. Figure A1 shows such a comparison at four representative temperatures. The upper panel shows the spectra obtained from XSPEC model and CHIANTI, convolved with the XSM response, and the lower panel shows the ratio between the two. It can be seen from the figure that the differences are less than 0.1%, demonstrating the adequacy of the XSPEC model for analysis of broadband soft X-ray spectra of the Sun.

**ORCID iDs**

Biswajit Mondal © https://orcid.org/0000-0002-7020-2826

Aveek Sarkar © https://orcid.org/0000-0002-4781-5798

---

5 https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSappendixLocal.html
References

Antonucci, E., Dennis, B. R., Gabriel, A. H., & Simnett, G. M. 1985, SoPh, 96, 129
Arnaud, K., Dorman, B., & Gordon, C. 1999, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Athiray, P. S., Vievering, J., Glesener, L., et al. 2020, ApJ, 891, 78
Benz, A. O. 2017, LRSP, 14, 2
Carmichael, H. 1964, in The Physics of Solar Flares, Proc. of the AAS-NASA Symp. (Washington, DC: NASA), 451
Christe, S., Hannah, I. G., Krucker, S., McTiernan, J., & Lin, R. P. 2008, ApJ, 677, 1385
Cooper, K., Hannah, I. G., Grefenstette, B. W., et al. 2020, ApJL, 893, L40
Czaykowska, A., Pontieu, B. D., Alexander, D., & Rank, G. 1999, ApJ, 521, L75
Dahlburg, R. B., Laming, J. M., Taylor, B. D., & Obenshain, K. 2016, ApJ, 831, 160
Del Zanna, G., Dere, K. P., Young, P. R., & Landi, E. 2021, ApJ, 909, 38
Del Zanna, G., & Mason, H. E. 2012, A&A, 545, A59
Dennis, B. R., Phillips, K. J. H., Schwartz, R. A., et al. 2015, ApJ, 803, 67
Doschek, G. A., Warren, H. P., & Feldman, U. 2015, ApJL, 808, L7
Drake, J. J., Laming, J. M., & Widing, K. G. 1997, ApJ, 478, 403
Drake, S. A., Singh, K. P., White, N. E., & Simon, T. 1994, ApJL, 436, L87
Duncan, I., Glesener, L., Grefenstette, B. W., et al. 2021, ApJ, 908, 29
Feldman, U. 1992, Phys, 46, 202
Feldman, U., & Widing, K. G. 2000, ApJ, 542, 61
Feldman, U., & Widing, K. G. 1990, ApJ, 363, 292
Feldman, U., & Widing, K. G. 2003, SSRv, 107, 665
Fletcher, L., Dennis, B. R., Hudson, H. S., et al. 2011, SSRv, 159, 19
Fletcher, L., & Hudson, H. S. 2008, ApJ, 675, 1645
Glesener, L., Krucker, S., Duncan, I., et al. 2020, ApJL, 891, L34
Hannah, I. G., Christe, S., Krucker, S., et al. 2008, ApJ, 677, 704
Hénoux, J.-C. 1998, SSRv, 85, 215
Hisayama, T. 1974, SoPh, 34, 323
Hudson, H. S. 1991, SoPh, 133, 357
Katsuda, S., Ohno, M., Mori, K., et al. 2020, ApJ, 891, 126
Klimchuk, J. A. 2017, arXiv:1709.07320
Kopp, R. A., & Pneuman, G. W. 1976, SoPh, 50, 85
Kuhar, M., Krucker, S., Glesener, L., et al. 2018, ApJL, 856, L32
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, LRSP, 12, 1
Laming, J. M. 2017, ApJ, 844, 153
Laming, J. M. 2021, ApJ, 909, 17
Laming, J. M., & Drake, J. J. 1999, ApJ, 516, 324
Leibacher, J., Sakurai, T., Schrijver, C. J., & van Driel-Gesztelyi, L. 2010, SoPh, 263, 1
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 73
Mithun, N., Vadawale, S., Patel, A., et al. 2021, A&A, 628, A134
Mithun, N. P. S., Vadawale, S. V., Sarkar, A., et al. 2020, SoPh, 295, 139
Mitra-Kraev, U., & Del Zanna, G. 2019, A&A, 628, A134
Mondal et al.
Narendranath, S., Sreekumar, P., Pillai, N. S., et al. 2020, SoPh, 295, 175
Ryan, D. F., Milligan, R. O., Gallagher, P. T., et al. 2012, ApJS, 202, 11
Saba, J. R. 1995, AdSpR, 15, 13
Shanmugam, M., Vadawale, S. V., Patel, A. R., et al. 2020, CSci, 118, 45
Sturrock, P. A. 1966, Natur, 211, 695
Sylwester, B., Phillips, K. J. H., Sylwester, J., & Kepa, A. 2015, ApJ, 805, 49
Sylwester, B., Sylwester, J., Phillips, K. J. H., Kepa, A., & Mrozek, T. 2014, ApJ, 787, 122
To, A. S. H., Long, D. M., Baker, D., et al. 2021, ApJ, 911, 86
Vadawale, S., Shanmugam, M., Acharya, Y., et al. 2014, AdSpR, 54, 2021
Vadawale, S. V., Mithun, N. P. S., Mondal, B., et al. 2021a,ApJL, 912, L13
Vadawale, S. V., Mondal, B., Mithun, N. P. S., et al. 2021b, ApJL, 912, L12
Vanitha, M., Veeramuthuvel, P., Kalpana, K., & Nagesh, G. 2020, LPSC, 2326, 1994
Veck, N. J., & Parkinson, J. H. 1981, MNRAS, 197, 41
Warren, H. P. 2014, ApJL, 786, L2
Widing, K. G., & Feldman, U. 2001, ApJ, 555, 426
Zarro, D. M., & Lemen, J. R. 1988, ApJ, 329, 456