Title: THE Fe-LINE FEATURE IN THE X-RAY SPECTRUM OF SOLAR FLARES: FIRST RESULTS FROM SOXS MISSION

Abstract: We present the first results from the "Low Energy Detector" payload of "Solar X-ray Spectrometer (SOXS)" mission, which was launched onboard GSAT-2 Indian spacecraft on 08 May 2003 by GSLV-D2 rocket to study the solar flares. The SOXS Low Energy Detector (SLD) payload was designed, developed and fabricated by Physical Research Laboratory (PRL) in collaboration with Space Application Centre (SAC), Ahmedabad and ISRO Satellite Centre (ISAC), Bangalore of Indian Space Research Organization (ISRO). The SLD payload employs the state-of-the-art solid-state detectors viz. Si PIN and Cadmium-Zinc-Telluride (CZT) devices that operate at near room temperature (-20 °C). The dynamic energy range of Si PIN and CZT detectors are 4-25 keV and 4-56 keV respectively. The Si PIN provides sub-keV energy resolution while CZT reveals ~1.7 keV energy resolution throughout the dynamic range. The high sensitivity and sub-keV energy resolution of Si PIN detector allows measuring the intensity, peak energy and equivalent width of the Fe-line complex at approximately 6.7 keV as a function of time in all 10 M-class flares studied in this
investigation. The peak energy (Ep) of Fe-line feature varies between 6.4 and 6.7 keV with increase in temperature from 9 to 58 MK. We found that the equivalent width (w) of Fe-line feature increases exponentially with temperature up to 30 MK but later it increases very slowly up to 40 Mk. It remains between 3.5 and 4 keV in the temperature range of 30-45 MK. We compare our measurements of w with calculations made earlier by various investigators and propose that these measurements may improve theoretical models. We interpret the variation of both Ep and w with temperature as the changes in the ionization and recombination conditions in the plasma during the flare interval and as a consequence the contribution from different ionic emission lines also varies.
14 June 2006

Dear Editor,

Please refer our paper SOLA66 entitled “THE Fe-LINE FEATURE IN THE X-RAY SPECTRUM OF SOLAR FLARES: FIRST RESULTS FROM SOXS MISSION” sent with referee’s comments for revision. Firstly we are extremely grateful to referee for his valuable suggestions. Please find attached herewith replies to referee’s comments and the revised manuscript of our paper for kind consideration for publication. I am sorry for delay in submitting revised version. In fact delay caused because of death of my mother and also due to undertaking further detailed analysis of the events in the light of referee’s comments. We express our sincere thanks to referee for his comments that improved our paper. Kindly do needful for its publication.

Regards.
Rajmal Jain

Response to Reviewer’s Comments

There are several points that should be addressed before this paper could be considered for publication in Solar Physics.

- We are grateful to referee for his comments, which helped us in improving the paper.

As a general comment, there is significant repetition of information about the instrumentation that has already been presented in the paper by Jain et al., 2005 and published in Solar Physics (227, 89 - 122, 2005). In particular, sections 1 and 2.1 of the present paper should be reduced in length.

- Repetitions are removed. We have reduced the instrumentation part in section 1 as well as in section 2.1

In addition, the information contained in Figure 3 is covered in detail in the earlier paper.

- Figure 3 is dropped.
However several important points regarding instrument performance and spectral data analysis are not presented very clearly. For example: How have instrument energy scale and linearity been established both pre-launch and in flight; and with what uncertainty? Statements of instrument energy channel width are useful but do not tell the whole story.

- This question is now addressed in brief detail in section 2.1

In particular, how does the 1 sigma error in E(p) shown in Figure 9 relate to uncertainty in energy scale calibration?

- This is answered in section 2.1 as well as in section 3.1 and 3.1.2.

The data presented in Figure 9 show no surprises but it is not clear what information can realistically be deduced from them. It is suggested in this connection that the 0.082 keV channel width could allow temperature measurement "with better precision". This statement should be justified

- We humbly appreciate this question and it has improved our paper. We modified our manuscript in the light of this question in section 3.1.2 and in section 4 - discussion.

It is stated in section 3.1.3 that line and continuum observations offer a means of determining the Iron abundance but no estimates are provided. To measure element abundance in this way requires a demonstration that a real continuum signal, not contaminated by background, has been measured - this issue should be addressed and a result presented if feasible.

- We have modified the manuscript in the light of this comment and Figures 3 and 5 in this revised manuscript gives demonstration/ justification of signal, which is not contaminated by background. Also abundance is relative and it has been now described in the revised version. We also propose a method of deriving relative abundance of Fe by measuring in future the equivalent width of Fe/Ni line feature.
Some mathematical clarification - rather than the block diagram in Figure 5, is needed to explain the use of the detector response matrix to generate photon spectra and the fitting of these spectra with Chianti calculations.

- Mathematical formulation is presented as suggested and Figure 5 is dropped.

Plots of line equivalent width and Fe complex peak energy against temperature are no doubt interesting but it is difficult to find significant new results that have been deduced from them in this paper. If these indeed exist, they should be clearly identified.

The discussion section is focused mainly on the data presented in Figure 13. This is of some interest and so should be described and assessed in e.g. section 3.1.3. Section 4 should then be used to provide a short summary of ALL of the new results in the paper and of their significance.

- These questions are addressed in section 3.1.2 and 3.1.3 and section 4. In fact to address these questions we undertook further detailed analysis of spectra of 10 flares instead of 8 flares taken in earlier version. This exercise plus modified software revealed major breakthrough in results of measurement of equivalent width as shown in section 3.1.3 and discussed section 4. Again we express our sincere thanks to referee.

Finally, plots of E(p) and T against time for the more intense flares could be of some value. These should be compared with the instrument's own light-curve and or with GOES plots.

- We considered a few intense flares as suggested by referee in this investigation before revision and the results are presented in section 3.1.1 and 3.2.

English usage and style in the paper could be significantly improved.

- We have put full efforts to improve English of the paper.
THE Fe-LINE FEATURE IN THE X-RAY SPECTRUM OF
SOLAR FLARES: FIRST RESULTS FROM SOXS MISSION

Rajmal Jain, Anil K. Pradhan*, P. Sreekumar*, Vishal Joshi, K. J. Shah, Jayshree J.
Trivedi, S. L. Kayasth, Vishal M. Shah and M. R. Deshpande

Physical Research Laboratory
(Dept. of Space, Govt. of India)
Navrangpura, Ahmedabad – 380 009, India

+ Dept. of Astronomy,
The Ohio State University, USA

*- Space Astronomy and Instrumentation Division,
ISRO Satellite Centre, Bangalore – 560 037, India

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Contact person:
Dr. Rajmal Jain
Email ID: rajmal@prl.res.in
Abstract: We present the first results from the “Low Energy Detector” payload of “Solar X-ray Spectrometer (SOXS)” mission, which was launched onboard GSAT-2 Indian spacecraft on 08 May 2003 by GSLV-D2 rocket to study the solar flares. The SOXS Low Energy Detector (SLD) payload was designed, developed and fabricated by Physical Research Laboratory (PRL) in collaboration with Space Application Centre (SAC), Ahmedabad and ISRO Satellite Centre (ISAC), Bangalore of Indian Space Research Organization (ISRO). The SLD payload employs the state-of-the-art solid-state detectors viz. Si PIN and Cadmium-Zinc-Telluride (CZT) devices that operate at near room temperature (-20 °C). The dynamic energy range of Si PIN and CZT detectors are 4-25 keV and 4-56 keV respectively. The Si PIN provides sub-keV energy resolution while CZT reveals ~1.7 keV energy resolution throughout the dynamic range. The high sensitivity and sub-keV energy resolution of Si PIN detector allows measuring the intensity, peak energy and equivalent width of the Fe-line complex at approximately 6.7 keV as a function of time in all 10 M-class flares studied in this investigation. The peak energy ($E_p$) of Fe-line feature varies between 6.4 and 6.7 keV with increase in temperature from 9 to 58 MK. We found that the equivalent width ($w$) of Fe-line feature increases exponentially with temperature up to 30 MK but later it increases very slowly up to 40 Mk. It remains between 3.5 and 4 keV in the temperature range of 30-45 MK. We compare our measurements of $w$ with calculations made earlier by various investigators and propose that these measurements may improve theoretical models. We interpret the variation of both $E_p$ and $w$ with temperature as the changes in the ionization and recombination conditions in the plasma during the flare interval and as a consequence the contribution from different ionic emission lines also varies.

Key words: Solar Flares; X-ray emission; Fe-line Feature; Equivalent width
1. Introduction

The “Solar X-ray Spectrometer (SOXS)” mission (Jain et. al, 2000a, b, 2005) was launched onboard an Indian geostationary satellite namely GSAT-2 on 08 May 2003 by GSLV-D2 rocket. The SOXS Low Energy Detector (SLD) mission (Jain et. al, 2000a, b, 2005) aims to study the high energy and temporal resolution X-ray spectra from solar flares employing solid state detectors viz. Silicon PIN detector for 4 - 25 keV (area 11.56 sq. mm); and Cadmium Zinc Telluride (CZT) detector for 4 - 56 keV energy range (area 25 sq. mm). Details related to the SLD instrumentation, the operation of the detectors, temporal and spectral resolution and the data format were presented earlier by Jain et al., (2005). The SLD payload is designed and developed at the Physical Research Laboratory (PRL) in collaboration with ISRO Satellite Centre (ISAC), Bangalore, and Space Application Centre (SAC), Ahmedabad.

The solar corona exhibits many X-ray lines below 10 keV and in order to improve our current understanding on the X-ray line emission characteristics the synoptic observations at energies below 10 keV are of utmost importance, which may reveal the temperature enhancement during flares of different magnitude. On the other hand, it has been shown by Jain et al (2000a, b, 2005) that iron complex lines (Fe XXV, XXVI) at 6.7 keV and Fe/Ni complex lines at 8 keV appear only during solar flare activity, however, understanding of their emission characteristics require extremely high spectral and temporal resolution observations. The high sensitivity and sub-keV energy resolution of Si PIN detector allows the intensity and mean energy of the Fe-line complex at approximately 6.7 keV to be measured as a function of time in all classes of flares.

This line complex is due mostly to the 1s-2p transitions in Li-like, He-like and H-like iron, Fexxiv, Fexxv and Fexxvi respectively, with associated satellite lines. Another weaker line complex at ~ 8 keV made up of emission from He-like nickel and more highly excited
Fexxv ions is also evident in the more intense flares (Phillips, 2004, Phillips et. al., 2004). Detailed calculations of emission line intensities as a function of temperature, with provision for different element abundance sets (e.g., photospheric or coronal), are given by the MEKAL/SPEX atomic codes (Mewe et al., 1985a, b, Phillips et. al., 2004) and the CHIANTI code (Dere et al., 1997). These codes also include thermal continuum intensities. These codes are used to interpret the SLD spectral observations in terms of the plasma temperature and emission measure. The centroid energy and width of the iron-line complex at \( \sim 6.7 \) keV, the intensity of the Fe/Ni line complex at \( \sim 8 \) keV, and the line-to-continuum ratio are the functions of the plasma temperature and can be used to limit the range of possible plasma parameters. However detailed study of such features of the Fe and Fe/Ni line complexes has not been carried out earlier mainly due to non-availability of spectral observations in the energy range 3 - 10 keV and in particular with high spectral and temporal resolution, which are critically required to measure precisely the line features and plasma parameters. The high spectral and temporal resolution spectra may reveal many unidentified lines as shown by RESIK Bragg crystal spectrometer aboard CORONAS-F (Sylwester et al., 2004). Phillips et al., (2004) carried out study of solar flare thermal spectrum using RHESSI, RESIK and GOES mission data and determined absolute elemental abundances, which however may have subjected to uncertainties due to measurements from three different instruments that were not calibrated by a single common technique. However, the SOXS mission is providing the X-ray spectra in the desired 4 - 10 keV energy band with improved spectral and temporal resolution. Therefore the purpose of this paper is to study the X-ray emission characteristics of Fe-line feature in solar flares using the high sensitivity and sub-keV energy resolution capabilities of Si PIN detector of SOXS mission. We present the current study of the Fe-line emission as the first results from the observations made by the SLD/ SOXS mission. In section 2 we present the observations
made by the SLD payload. Section 3 describes analysis techniques and the results obtained. We discuss our findings in section 4 and conclude in section 5.

2. Observations

2.1 INSTRUMENTATION:

The instrumentation of the SLD payload, its in-flight calibration and operation has been described by Jain et al. (2005). However, a brief description of the experiment is as following. The SOXS consists of two independent payloads viz. SOXS Low Energy Detector (SLD) and SOXS High Energy Detector (SHD) payloads. The SLD payload is functioning satisfactorily onboard the GSAT-2 spacecraft and so far more than 300 flares of importance greater than GOES C1.0 have been observed. The spectral resolution revealed by Si detector is 0.7 keV @ 6 keV and 0.8 keV @ 22.2 keV, which is better over the earlier detectors used for solar flare research in this energy range. However, spectral resolution achieved from CZT detector is poor i.e., almost 1.7 keV but it remains stable throughout its dynamic energy range of 4 – 56 keV. Further their temporal resolution capabilities are also superb however we designed for 100 ms during flare mode in order to achieve feasible energy spectrum.

We used 8-bit ADC as a pulse-height analyzer for Si and CZT detectors to form the spectra in the dynamic energy range 4-25 and 4-56 keV respectively, which revealing 0.082 keV and 0.218 keV as channel width for Si and CZT detectors respectively. Pre-launch Si and CZT detectors were characterized and calibrated (Jain et al., 2003) using radioactive sources viz. Fe$^{55}$ emitting line at energy 5.9 keV; Cd$^{109}$ – 22.2 and 25.0 keV, and Am$^{241}$ – lines at 13.9, 17.8, 20.8, 26.3, 33.0 and 59.5 keV. The energy scale was established by setting the gain of the amplifier to match the observed peak energy of the Fe$^{55}$ standard radioactive source to theoretically known its peak energy. In order to cross check the full energy scale (0-255 channels) we carried out the above experiment with Cd$^{109}$ and Am$^{241}$ radioactive sources. Once
the energy scale was established the gain was fixed with that particular fixed value resistor. Next, the peak detector and shaping amplifier were biased in such a way that they operate in highly linear region. The linearity between energy (pulse height) scale and peak energy was observed with an uncertainty of ±1 channel. The linearity was tested using above radioactive sources during vibration, thermo-vac and at launch-pad and no variation was observed. In-flight calibration is carried out by onboard Cd\textsuperscript{109} weak radioactive source, which is mounted inside the collimator (Jain et al., 2005), which emit lines at 22.2 and 25 keV. Integrating over long period we have calibrated many times and found peak of 22.2 keV line for Si and both lines for CZT detectors fall at the same channel where pre-launch was peaking, however within uncertainty of ±1 channel.

The critical operating temperature of both the detectors in the range -5 to -30 °C is achieved using thermoelectric cooler that coupled with the detector. The detector package is mounted on a Sun Aspect System which keeps the Sun in the center of the detector for an interval between 03:40 – 06:40 UT everyday. However after 06:40 UT the temperature on the detectors exceeds the limit to cool down by thermoelectric cooler. The SLD data is of two types - temporal mode (light curves) and spectral mode.

2.2 DATA SET:
The first light from the Sun was fed into the detectors on 08 June 2003. The flare trigger threshold was intentionally kept higher so as to observe the signal in contrast to background. The temporal data i.e., intensity (counts/s) as a function of time is revealed in four energy band viz. 6-7 keV (L1), 7-10 keV (L2), 10-20 keV (L3) and 4-25 keV (T) by Si detector, while in five energy bands by CZT detector viz. 6-7 keV, 7-10 keV, 10-20 keV, 20-30 keV and 30-56 keV. In Table I we show the flare events analyzed by us to study the X-ray spectral evolution of Fe-line feature in the flare plasma. We selected a total ten flares of \textit{GOES} importance class
M for the current study as first results. However in preview to goal of studying Fe-line feature the data from Si detector is used.

2.2.1 Temporal Mode:

In Figure 1 we show the temporal mode observations i.e. light curves of 31 October 2004 flare in four energy windows of Si detector. The time resolution for temporal and spectral mode observations during quiet period is 1 s and 3 s respectively but during flare it is 100 ms for both temporal and spectral modes. The intensity (counts/s) of the light curve shown in Figure 1 is 20 s moving average of the 100 ms observed data. It may be noted that the flare is composed of slow rising thermal phase followed by superhot phase. The flare was also observed by GOES mission as shown in Table I.
<table>
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<th>S. No.</th>
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<th>Active Region</th>
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<td>0409</td>
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<td>0526</td>
<td>0531</td>
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<tr>
<td>10</td>
<td>25 Aug 2005</td>
<td>0436</td>
<td>0439</td>
<td>0452</td>
</tr>
</tbody>
</table>
Figure 1: Light curves of 31 October 2004 solar flare as recorded in L1, L2, L3 and T energy bands (see text) of Si detector of SLD/ SOXS mission
2.2.1 *Spectral Mode:*

The energy region 4 - 15 keV in solar flare X-ray spectrum is of great importance in inferring the properties of the hottest parts of the thermal plasma created during a solar flare. It contains emission lines of highly ionized Ca, Fe, and Ni atoms and a continuum that falls off steeply with increasing energy. In this context, SLD is the first payload, which has dedicatedly dynamic energy range 4 - 25 keV to study the line emission and continuum with sub-keV spectral resolution. This is achieved by employing Si PIN detector as described in the preceding section.

The energy spectrum, intensity (counts/s) as a function of energy at a given time, in the energy range 4 – 25 keV distributed over 256 channels with channel width of 0.082 keV, obtained from the instrument is in the form of count spectra, The detected count spectrum is in fact given by the convolution of the actual photon spectrum by the response matrix as shown in relation (1). The response matrix of an X-ray detector allows reconstructing source photon spectra from the observed counts (counts per channel in PHA).

$$C_i = \int_0^{255} \frac{dN}{dE} R(i, E) dE = \sum_j \frac{dN}{dE} (E_j) R_{ij} \Delta E_j \quad \text{(1)}$$

where $C_i$ are the detected counts in the i-th PHA channel, $dN/dE$ is the photon input spectrum, $R$ is the overall response matrix and $j$ runs on a discrete binning of the photon input energy $E$, each j-th bin with $\Delta E_j$ width. In formula (1) the matrix $R_{ij}$ is an overall response matrix, having dimension of [cm$^2$ keV$^{-1}$], indicating probability or efficiency of the detector folded over effective area and FWHM.

The Si detector’s count spectra at the peak time of 31 October 2004 flare is shown in Figure 2. The low intensity below 6 keV is due to aluminum plus kapton filter mounted on the detector head to cut the X-ray photons up to 4 keV and electrons up to 300 keV falling in the line-of-
sight of the detector (Jain et al., 2005). It may be noted that in Si count spectra the Fe and Fe/Ni lines are unambiguously visible at ~6.7 and ~8 keV respectively.

Figure 2: Count Spectra from Si PIN detector for 31 October 2004 flare at 05:30:59 UT. Note Fe and Fe/Ni line features.
3. Analysis and Results

The raw data for temporal and spectral mode observations is first corrected for any spurious or false flare as well as for pre-flare background (Jain et al., 2005). The spectrum at a given time is made by integrating the high cadence (100 ms) spectra over an interval of 30 to 100 s period. The photon spectrum is produced by de-convolution of the count spectrum over the instrumental response as follows.

Let \( N_{ij} \) are the corrected PHA spectral data where \( i \) is spectral record from 0 to \( n \) and \( j \) is channel number ranging from 0 to 255 for that particular spectral record. Firstly, in order to calculate the background spectra we select range of \( N_{ij} \) where the Sun is quiet for a significant period (>20 min) between \( i_b \) and \( i_e \) on the observational interval. Here \( i_b \) and \( i_e \) are the beginning and end spectral record for the quiet interval. Integrated background counts spectra (\( IB_j \)) may be written as follows.

\[
IB_j = \sum_{b}^{i_e} N_{ij} \frac{T_{i_e} - T_{i_b}}{T_{i_e} - T_{i_b}} \quad \text{----------------- (2)}
\]

Now, for generating a photon spectrum of the flare for a given interval viz. \( k_b \) to \( k_e \), during the flare duration, we first generate count spectra for this time interval as shown in relation (3). .

\[
IF_j = \sum_{k_b}^{k_e} N_{ij} \frac{T_{k_e} - T_{k_b}}{T_{k_e} - T_{k_b}} \quad \text{----------------- (3)}
\]

However, to obtain pure flare count spectra (\( CF_j \)) we have to subtract the background count spectra (\( IB_j \)) from \( IF_j \), so we obtain,

\[
CF_j = (IF_j - IB_j) \quad \text{----------------- (4)}
\]
and finally the count spectra ($C_i$) are de-convoluted over the instrumental response ($R_j$) to obtain the flare photon spectra ($PF_j$) as shown in the relation (5).

\[ PF_j = \frac{CF_j}{R_j} \quad \text{(5)} \]

These photon spectra are indeed useful to study the X-ray line and continuum emission. We demonstrate in Figure 3 that the flare signal is not contaminated with background by showing the photon spectra of the background and the flare observed on 31 October 2004. The various steps from data acquisition to data analysis were presented in detail by Jain et al., (2005). The photon spectra are used to study the evolution of Fe and Fe/Ni lines in a given flare as a function of time formed by integrating the several spectra observed at the cadence of 100ms or 3s interval.

Figure 3: Photon spectra of background (left) and the flare (right) intervals on 31 October 2004. Note that photon flux in the flare is 2-3 orders higher than the background below 9 keV and 1-2 order higher in the continuum.
3.1 X-RAY EMISSION FROM Fe-LINE:

In order to study the Fe and Fe/Ni line emission it is rather more important to study their evolution with the flare development i.e., as a function of temperature because the line emission and its intensity vary with temperature and emission measure (Phillips, 2004). Shown in Figure 4 is a sequence of photon spectra of 31 October 2004 flare in the energy range 5 to 12 keV. The sequence shows evolution of the Fe and Fe/Ni lines as a function of time. It may be noted from this figure that the peak intensity, peak energy and area under the curve of the lines vary over time. In fact the plasma temperature and hence emission measure vary over time and these factors mainly controls the shape of the line. However, non-thermal contribution also plays role but in this paper we consider only temperature and emission measure as important parameters.

The Fe line feature is here defined as the excess above the continuum, as observed by Si spectrometer with spectral resolution (FWHM) ≤ 0.7 keV, in the energy range 5.8 - 7.5 keV (Phillips, 2004). It may be noted from the temporal evolution of this line shown in Figure 4 that Fe-line features including the peak energy, equivalent width (w) and intensity vary over the flare evolution, which suggests that the abundance and peak energy of the emission line vary as a function of temperature. In this paper we intend to investigate the variation in peak energy of the Fe-line feature derived by Gaussian fit, which lead us to measure the central peak energy for a given spectra, and equivalent width (w) over the temperature. We analyzed 10 to 27 spectra, for each flares under study, depending on the duration of the flare. SOXSoft package (Patel and Jain, 2005) is the software package used for data analysis. SOXSoft is specially developed for SOXS mission for data processing and spectra formation.

Once the photon spectra formed we undertake their analysis for deriving plasma parameters such as temperature, emission measure and spectral index using SOXSoft spectra fit program. This program takes main routine from Solarsoft where Mewe and Chianti codes can
be used to derive the plasma parameters. In order to fit the spectra in the energy range between 5 and 15 keV and particularly the Fe-line feature by isothermal plasma we use Chianti code because thermal continuum from it is within 1% of the detailed calculations of Culhane ((1969) and the approximation of Mewe et al., (1985a). We use the best-fit to the line feature based on the minimum reduced $\chi^2$ (difference counts). In order to derive the line parameters such as the peak energy ($E_p$), net area and gross area under the curve and equivalent width we subtracted the continuum contribution to the spectrum.
Figure 4: Sequence of X-ray photon spectrum in the energy range 5 – 12 keV of 31 October 2004 flare showing evolution of Fe and Fe/Ni line features. X-axis error bar is channel width of 0.082 keV, while Y-axis error bar is ± 1σ of the photon flux in the given channel.
3.1.1 *Evolution of Temperature and Emission Measure:*

Temperatures are derived from the continuum part in the photon spectrum by a best-fit of photon flux from Chianti code of isothermal plasma temperature and emission measure for the energy range generally between 9.5 and 20 keV. In Figure 5, for example, we show such best fit of photon flux for a single spectrum of 14 August 2004 and 31 October 2004 flare events. The temperature and emission measure derived for these spectra are 57.4 MK and 1.5e49 cm$^{-3}$, and 29.3 MK and 1.3e49 cm$^{-3}$ respectively. The isothermal fit by Chianti code using Solarsoft is accepted if reduced $\chi^2 < 5$. For example the residual counts for the continuum fit for a $\chi^2$ of 0.59 and 1.55 (cf. Figure 5) are shown in Figure 6. In this way, we obtain temperature and emission measure values for each photon spectra of a given time of the flare. We studied almost 10 to 27 integrated photon spectra for each flare depending upon its duration. In Figure 7, as an example, we show the temperature and emission measure evolution for two flares viz. 14 August and 31 October 2004 flares. We compare the temperature evolution with the light curve of each individual flare event observed by Si detector in 4-25 keV. We found that the evolution of the temperature is almost similar to the light curve of the flare, and peaking around flare maximum. This indicates that flare X-ray photon emission is rather strongly governed by temperature of the plasma. On the other hand, emission measure (cf. Figure 7) was between 1 and 2X10$^{49}$ cm$^{-3}$ in 14 August 2004 flare and between 1 and 3X10$^{49}$ cm$^{-3}$ throughout the flare of 31 October 2004 except in one spectrum it was seen higher than 4X10$^{49}$ cm$^{-3}$. 
Figure 5: The X-ray photon spectra of 14 August 2004 and 31 October 2004 at 05:43:49 UT and 05:28:59 UT respectively. Note the 9.5 – 16 keV continuum fit by isothermal plasma temperature (superhot) and emission measure. Contribution from the continuum emission down to 4 keV is shown by the extrapolated dash-dot straight line from the continuum fit. X-axis error bar is channel width of 0.082 keV, while Y-axis error bar is ± 1σ of the photon flux in the given channel.
Figure 6: The residual (difference) counts of isothermal plasma continuum fit (cf. Figure 6) for 14 August 2004 and 31 October 2004 spectra.

Figure 7: Evolution of temperature and emission measure derived from the continuum of the X-ray photon spectra of 14 August 2004 (left) and 31 October 2004 (right) flares.
3.1.2 Peak Energy of Fe-Line Features:

The thermal component in Si PIN spectra is observed to have a prominent broadened emission line features at 6.7 keV and a less intense line feature at 8 keV indicating high plasma temperatures. The 6.7 keV features corresponds to a group of emission lines due to Fe xxv, associated dielectronic satellites of ions from Fe xix to Fe xxiv, and fluorescence-formed lines of Fe ii, and a second group due to Fe xxvi (Lyα) lines and associated satellites. The Fe xxv lines are excited at electron temperatures $T_e \geq 12$ MK, while the Fe xxvi lines are excited at $T_e \geq 30$ MK (Phillips, 2004). This line complex is referred in this paper as the Fe line feature. Thus we may conclude that the Fe-line feature is made up of many individual lines each having its own temperature dependence. Their contribution to the total emission of Fe line feature will therefore change as the temperature of a solar flare plasma changes in both space and time. This results in changes to the energies of the Fe-line feature, as defined by the energy of the peak intensity ($E_p$). The variation in central peak energy of Fe line feature may be between 6.3 and 7.0 depending on the temperature of the flare plasma that ranging range from 10 to >100 MK. Changes in $E_p$, if large enough, therefore provide a possible useful temperature diagnostic. However, measurement of $E_p$ requires high spectral resolution, which Si detector provides. In our case $E_p$ of the Fe line feature can be measured with an uncertainty of ± 1 channel i.e. ± 0.082 keV. Assuming that large sample of spectra analyzed for ten flares may give first order estimate of variation of $E_p$ of Fe line feature as a function of temperature we attempted to derive peak energy firstly fitting the line by Chianti codes and then by Gaussian-fit. The peak energy variation may, at a first glance, reveal the process of ionization at a given temperature-taking place to emit the appropriate Fe line emission.

In Figure 8 we show the variation of peak energy ($E_p$) as a function of temperature of Fe-line feature. We measured $E_p$ for each photon spectra at a given time of a flare for which
temperature was derived from continuum. A total 135 spectra from all 10 flares were analyzed to measure \( E_p \). Later, in order to get better statistical confidence, we distributed the 135 \( E_p \) measured values in the interval of 1 MK according to their respective spectra temperature. For example, all \( E_p \) measurements from the spectra falling in the temperature range between 9 and 11 MK were averaged to mean \( E_p \) value at 10 MK and also a standard deviation (\( \sigma \)) of the \( E_p \) values was obtained. This mean \( E_p \) value is shown with \( \pm 1 \sigma \) at mean temperature 10 MK. The \( E_p \) for each photon spectra of each individual flare was derived by line parameter software analysis of Soxsoft that employs Chianti code to derive plasma parameters as mentioned earlier. The X-axis error bar is channel width i.e. 0.082 keV corresponding to \( \sim 1 \) MK temperature and it is same throughout all the spectra analyzed by us, and therefore not represented in the plot. Figure 8 shows that \( E_p \) increases with temperature in agreement to Phillips (2004), and Oelgoetz and Pradhan (2004) but after 25 MK it reduces. Our results indicate that in the temperature range of 10-58 MK measured by us the Fe line feature is mostly dominated by Fe xxv emission. However, our current results are first order estimates in view of measurements of \( E_p \) that limited to \( \pm 1 \) channel.
3.1.3 Equivalent Width of Fe-line features in Flare Plasma:

The observations of the Fe line and Fe/Ni line features and neighboring continuum offer a means of determining the iron abundance $A_{\text{flare}}(\text{Fe})$ and similarly the nickel abundance $A_{\text{flare}}(\text{Fe}/\text{Ni})$ during flares by measuring their relative intensities as a function of temperature. The thermal plasma during flares is located in the coronal loop structures typically $10^4$ km above the photosphere. On a chromospheric evaporation picture, this plasma is formed from the chromosphere and therefore should reflect the chromospheric composition. Fludra and Schmelz (1999) and Phillips et al., (2003) showed that elements with a variety of first ionization potential (FIP) are in ratios that are characteristics of the corona i.e., with low-FIP ($\text{FIP} \leq 10$ eV) elements enhanced by a factor of 3 or 4 but with high-FIP elements approximately the same or depleted by a factor up to 2 compared with photospheric abundance. However, elements enhancement might depend upon flare intensity and duration. Thus study of large
number of variety of flares is important. Further Fe and Ni both are low-FIP elements and therefore SLD/SOXS observations of Fe and Fe/Ni line features in contrast to neighborhood continuum may allow to determine relative abundance of Fe and Fe/Ni in flare plasma.

A measure of the Fe-line feature’s intensity with respect to the continuum is provided by the equivalent width ($w$), measured in keV, defined as following and which can be determined from Si/SLD spectra.

$$w = \int_{\text{Line}} \frac{[I(E_f) - I(E_c)]}{I(E_c)} \, dE \quad \text{-------- (5)}$$

Here $I(E_f)$ and $I(E_c)$ are the intensity of the Fe-line feature and continuum in a given channel, and $dE$ is feature width in keV.

Figure 9 shows equivalent width ($w$) of Fe-line features as a function of temperature in six flares viz. 19 November 2003, 31 October 2004, 07 January 2004, 14 July 2004, 25 August 2005 and 14 August 2004 arranged in the increasing order of intensity (cf. Table I). It may be noted from Figure 9 that the temperature in the flares of GOES intensity $<$ M5.0 (top panel) does not exceed 32 MK, while in higher intense flares (bottom panel) temperature ranges between 15 and 58 MK. Further, $w$ increases exponentially with temperature up to 30 MK and then moves slowly up to 40 MK. In intense flares (bottom panel) a downfall in $w$ was observed after 40 MK with increase in temperature. Our investigation suggests that the equivalent width ($w$) is irrespective to flare location on the Sun rather it depends upon the temperature of the flare at a given time. Thus in order to get better statistical confidence we measured the
equivalent width \((w)\) in 135 spectra of 10 M-class flares under current investigation.

Figure 9: Variation of equivalent width \((w)\) of Fe-line feature as a function of temperature in six flares arranged in ascending order of intensity. Note that plasma temperature in flares of intensity below M5 (top panel) does not exceed 35 MK.
Shown in Figure 10 is variation of the $w$ with temperature, which, nevertheless like Figure 9, also shows an exponential rise of $w$ until 30 MK and later slowly. However it may be noted from this figure that $w$ remains almost between 3.5 and 4.0 keV in the temperature range 30 – 45 MK and then begins to reduce rapidly above 45 MK. Temperatures more than 58 MK were not found in any flare under study so variation of $w$ beyond 58 MK currently could not be measured.
Figure 10: Variation of equivalent width ($w$) as a function of temperature when combined for all ten flares under study.
3.2 IONIZATION STATE IN FLARES:

Phillips (2004) showed that assumption of steady-state equilibrium in the flare plasma may not be valid due to rapid change of temperature in the rise phase of the flare. Therefore if non-equilibrium conditions exist in the flares, the plasma would be expected to be in an ionizing state during the rise phase. However, the ionization equilibrium is a good approximation unless the temperature gradient \( \frac{dT_e}{dt} \geq 0.5 \text{ MK/s} \) (Phillips et al., 1974 and Mewe et al., 1985) or \( N_e \geq 10^{10} \text{ cm}^{-3} \). Thus it is very important to derive the quantity \( \frac{dT_e}{dt}/T_e \) and to observe its variation over the flare duration in order to compare with ionization and recombination time scales. We undertook this study for four flares viz. 07 January 2004, 14 August 2004, 31 October 2004 and 25 August 2005 out of 10 flares as we have long duration data for these flares. We do not find \( \frac{dT_e}{dt} \) in excess to 0.1 MK/s, a factor 5 less than required for non-equilibrium conditions except in the flare of 14 August 2004 where \( \frac{dT_e}{dt} \) is \( \sim 0.3 \text{ MK/s} \) close to non-equilibrium condition. However, in fact, \( N_e \) is found \( \geq 10^{10} \text{ cm}^{-3} \) throughout the flare duration and the temperature gradient \( \frac{dT_e}{dt} \) varies between -0.05 and 0.1 and therefore the flare cannot be regarded in equilibrium steady state during rise or decay phase. Figure 11 (a, b) shows three curves viz. light curve (top panel) from Si detector in 10 – 20 keV energy band, \( T_e \) (middle panel), and \( \frac{dT_e}{dt}/T_e \) (bottom panel) as a function of time. It may be noted from this figure that intensity and temperature variation of the flare as a function of time in general are almost similar. However, in two cases viz. 31 October 2004 and 25 August 2005, during rise phase the intensity rises continuously but temperature begins to rise after \( \sim 100 \text{ s} \). In consistent to intensity and temperature variation the \( \frac{dT_e}{dt}/T_e \) also fluctuates during rise phase as well as decay phase. We found that in the beginning of the flare \( \frac{dT_e}{dt}/T_e \) rises to a positive value for a 20-30 s and later it drops down to negative value for a long period, mostly decay phase. Based on the measurements of temperature gradient i.e., \( \frac{dT_e}{dt} > 0 \) from our observations
during rise phase of the flare the inverse of \((dT_e/dt)/T_e\) may be considered as ionization time, and similarly when \(dT_e/dt < 0\) the inverse of \((dT_e/dt)/T_e\) may be considered as recombination time (Phillips, 2004). We get ionization time of about 300 s and the whole decay phase as recombination time but in general more than 900 s except in 14 August 2004 flare where ionization and recombination times are found \(\sim 90\) and \(> 1800\) s respectively. The ionization time scale is also representative of ionization of \(\text{Fe}^{+23}\) to \(\text{Fe}^{+24}\) ions, which enabling us to estimate the ionization rate coefficient \((Q_i)\) of the order of \(\sim 10^{-12} \text{ cm}^3 \text{ s}^{-1}\) and similarly recombination time scales representing recombination of of \(\text{Fe}^{+25}\) to \(\text{Fe}^{+24}\) ions gives estimate of recombination rate coefficient \((\alpha_i)\) of the order of \(\sim 10^{-13} \text{ cm}^3 \text{ s}^{-1}\), assuming \(N_e\) of the order of \(10^{10} \text{ cm}^{-3}\).

Figure 11a: Top panels: light curve of 31 October 2004 (left) and 07 January 2004 (right) flares in 10 – 20 keV energy band as observed by Si detector of SLD/SOXS mission. Middle panels: variation of temperature \((T_e)\), and, Bottom panels: variation of \((dT_e/dt)/T_e\) as a function of time in both flares.
Figure 11b: Top panel: light curve of 25 August 2005 (left) and 14 August 2004 (right) flares in 10 – 20 keV energy band as observed by Si detector of SLD/SOXS mission. Middle panels: variation of temperature ($T_e$), and, Bottom panels: variation of ($dT_e/dt$)/$T_e$ as a function of time in both flares.

4. Discussion

It is well established that during the flare interval the plasma is not at one temperature rather it varies as a function of time (Feldman et al., 1995). However, in addition to this fact, our study shows temperature does not vary smoothly rather fluctuates in general during the whole flare interval and rapidly in particular during rise phase (cf. Figure 7 and 11). This fluctuation in flare plasma temperature ($T_e$) affects the ionization state and thereby as a consequence of it we observe variation in peak energy ($E_p$) and equivalent width ($w$) of the Fe-line emission. Our photon spectral observations from the 10 flares under study show minimum critical temperature
required for Fe-line feature to be visible is 9 MK, which may also be seen from Figure 8 and 9. With increase in temperature viz. $9 < T_e < 30$ MK He-like Ca-line (3.86 – 3.90 keV), and He-like Fe-lines and satellite (6.4 – 6.7 keV) are most intense. Our Si detector begins spectral observations from 4 keV and therefore question to observing Ca-line feature around 3.8 keV does not exist. However the observed increase in $T_e$ unambiguously represents change in peak energy because of excitation of different principal lines of He-like Fe xxv, satellites and resonance lines in agreement to earlier calculations (Gabriel, 1972, Boiko et al., 1978, Doschek et al., 1981, Feldman et al., 1995, Kato et al., 1997, Phillips, 2004).

The strength of Fe-line feature above the continuum i.e. equivalent width ($w$) also found varying over the $T_e$ of the flare plasma. With increase in temperature we observed an exponential rise in $w$ up to 30 MK and then it moves up slowly up to 40 MK from where a downfall in $w$ was seen. It was found that $w$ remains between 3.5 and 4.0 keV in the temperature range of 30 and 45 MK. The equivalent width ($w$) measured by us in general appears in agreement with those calculated by Phillips (2004) from the Chianti code considering the coronal abundances of Feldman and Laming (2000). However, while comparing in detail our measurements with those calculated by Phillips (2004) we find two important differences viz. the $w$ is significantly larger than 3 keV that predicted as maximum by Phillips at 25 MK plasma temperatures, and the turn over temperature is 40 MK in contrast to 25 MK that calculated by him. This motivated us to compare our measurements with that calculated earlier by Raymond and Smith (1977), Sarazin and Bahcall (1977), Rothenflug and Arnaud (1985) and Phillips (2004) as shown in Figure 12. It may be immediately noted from this figure that our measured values of $w$ are significantly higher than earlier calculations by Raymond and Smith (1977), referred as RS77, Sarazin and Bahcall (1977), referred as SB77 and Rothenflug and Arnaud (1985), referred as RA85 in the temperature range 18 to 58 MK. However, below 18 MK our measurements are close to SB77 and RA85. On the other hand
while comparing our \( w \) measurements with those of Philips (2004), referred as P04, we find them significantly smaller and higher at temperature below and above 25 MK respectively.

Our findings suggest different ionic participations of Fe-line feature as a function of plasma temperature that governs ionization and recombination at a given time. For example the \( w \) of \( \text{Fe}^{xxv} \) line is higher than \( \text{Fe}^{xxiii} \), \( \text{Fe}^{xxiv} \) and \( \text{Fe}^{xxvi} \) up to 100 MK. Above 100 MK emissions from \( \text{Fe}^{xxvi} \) becomes stronger and the total \( w \) is dominated by this emission. However, contribution to \( w \) from \( \text{Fe}^{xxii} \), \( \text{Fe}^{xxiii} \) and \( \text{Fe}^{xxiv} \) almost stops around 21, 35 and 115 MK respectively. Therefore, in the temperature range of 9 – 58 MK for the flares studied in this investigation major contribution for \( w \) may be considered from these ionic emissions and \( \text{Fe}^{xxv} \). However, a little contribution from \( \text{Fe}^{xxvi} \) may be considered when temperature exceeds 30 MK. Thus variation in our measured \( w \) as well as Ep values as a function of temperature may be interpreted as varying participation of different ionic emissions of Fe with temperature. Thus we may conclude that the difference in calculations of \( w \) by earlier investigators may be due to selection of ionic codes and also coronal abundance of Fe line feature. Our experimental measurements of equivalent width and its variation over temperature may help in general to improve theoretical calculations as well as to revise the coronal abundance of Fe line feature that predicted earlier by Feldman and Laming (2000). However, in order to estimate the coronal abundance of Fe we have to measure it relative to intensity of other element. The theoretical relative abundance of Fe in the corona (Fe/H = 1.26 \( X \) 10\(^{-4}\)) is estimated to be 4 times to photospheric abundance. However, we propose to derive relative abundance of Fe in the corona by measuring the ratio of equivalent width (\( w \)) of Fe line feature to Fe/Ni line feature as these two features are distinctly visible in our spectra. We plan to undertake this work as future investigation.
Figure 12: Comparison of our measured values of equivalent width ($w$) with previous results from RS77 (Raymond and Smith, 1977), SB77 (Sarazin and Bahcall, 1977), RA95 (Rothenflug and Arnaud, 1985) and P04 (Phillips, 2004).
5. Conclusion

The Si PIN detector of the SOXS Low Energy Detector (SLD) payload provides a unique opportunity to study the Fe-line and Fe/Ni line features in great details. In this paper we carried out study of Fe-line feature in order to investigate the variation of peak energy ($E_p$) and equivalent width ($w$) as a function of temperature of the flare plasma. We found that peak energy of Fe-line feature varies from 6.4 at 9 MK temperatures to 6.7 at 25 MK. More interestingly, equivalent width ($w$) rises exponentially up to 30 MK and then moves up slowly and remains between 3.5 and 4 keV in the temperature range 30-40 MK, which later comes down with temperature. We interpret the variation of both $E_p$ and $w$ with temperature as the changes in the ionization and recombination conditions in the flare plasma during the flare duration and as a consequence the contribution from different ionic emission lines also varies. Our measurements of $w$ are compared with previous calculations and found that they are close to the results of Phillips (2004). It is proposed that our measurements of $w$ may help in improving theoretical calculations of equivalent width as well as coronal abundance of Fe line feature if compared with the intensity of Fe/Ni line feature.

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Figure Legends (captions)

Figure 1: Light curves of 31 October 2004 solar flare as recorded in L1, L2, L3 and T energy bands (see text) of Si detector of SLD/ SOXS mission

Figure 2: Count Spectra from Si PIN detector for 31 October 2004 flare at 05:30:59 UT. Note Fe and Fe/Ni line features.

Figure 3: Photon spectra of background (left) and the flare (right) intervals on 31 October 2004. Note that photon flux in the flare is 2-3 orders higher than the background below 9 keV and 1-2 order higher in the continuum.

Figure 4: Sequence of X-ray photon spectrum in the energy range 5 – 12 keV of 31 October 2004 flare showing evolution of Fe and Fe/Ni line features. X-axis error bar is channel width of 0.082 keV, while Y-axis error bar is ± 1σ of the photon flux in the given channel.

Figure 5: The X-ray photon spectra of 14 August 2004 and 31 October 2004 at 05:43:49 UT and 05:28:59 UT respectively. Note the 9.5 – 16 keV continuum fit by isothermal plasma temperature (superhot) and emission measure. Contribution from the continuum emission down to 4 keV is shown by the extrapolated dash-dot straight line from the continuum fit. X-axis error bar is channel width of 0.082 keV, while Y-axis error bar is ± 1σ of the photon flux in the given channel.

Figure 6: The residual (difference) counts of isothermal plasma continuum fit (cf. Figure 6) for 14 August 2004 and 31 October 2004 spectra.

Figure 7: Evolution of temperature and emission measure derived from the continuum of the X-ray photon spectra of 14 August 2004 (left) and 31 October 2004 (right) flares.

Figure 8: Variation of peak energy (E_p) of Fe-line feature as a function of temperature. In y-axis error of ±1σ in E_p is shown.

Figure 9: Variation of equivalent width (w) of Fe-line feature as a function of temperature in six flares arranged in ascending order of intensity. Note that plasma temperature in flares of intensity below M5 (top panel) does not exceed 35 MK.
Figure 10: Variation of equivalent width ($w$) as a function of temperature when combined for all ten flares under study.

Figure 11a: Top panels: light curve of 31 October 2004 (left) and 07 January 2004 (right) flares in 10 – 20 keV energy band as observed by Si detector of SLD/SOXS mission. Middle panels: variation of temperature ($T_e$), and, Bottom panels: variation of $(dT_e/dt)/T_e$ as a function of time in both flares.

Figure 11b: Top panel: light curve of 25 August 2005 (left) and 14 August 2004 (right) flares in 10 – 20 keV energy band as observed by Si detector of SLD/SOXS mission. Middle panels: variation of temperature ($T_e$), and, Bottom panels: variation of $(dT_e/dt)/T_e$ as a function of time in both flares.

Figure 12: Comparison of our measured values of equivalent width ($w$) with previous results from RS77 (Raymond and Smith, 1977), SB77 (Sarazin and Bahcall, 1977), RA95 (Rothenflug and Arnaud, 1985) and P04 (Phillips, 2004).