Solar X-ray Spectrometer (SOXS) mission: Observations and new results

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Abstract. We present the observations and recently obtained new results from the "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 state-of-the-art solid state detectors viz. Si PIN and Cadmium-Zinc-Telluride (CZT) were employed that operate at near room temperature (-20 ^{0}C). The dynamic energy range of the Si PIN and CZT detectors are 4-25 keV and 4-56 keV, respectively. The Si PIN has sub-keV energy resolution while the CZT has about 1.7 keV energy resolutions throughout the dynamic range. The high sensitivity and sub-keV energy resolution of Si PIN detector allows for measuring the intensity, and equivalent width (w) of the Fe-line and Fe/Ni-line complexes at approximately 6.7 and 8.0 keV as a function of time. We present the results related to the Fe-line complex obtained from the study of 10 M-class flares observed by the SOXS mission. We found that the equivalent width (w) of the Fe-line feature increases exponentially with temperature up to 25 MK but later it increases very slowly up to 35 Mk and then it remains constant up to 45 MK. We compare our measurements of w of the Fe line feature with calculations made earlier by various investigators and propose that these measurements may improve theoretical models. We interpret the variation of 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.

Index Terms. Equivalent width, Fe-line feature, solar flares, X-ray emission.

1. Introduction

The "Solar X-ray Spectrometer (SOXS)" instrument (Jain et. al., 2000a, b, 2005) was launched onboard an Indian geostationary satellite namely GSAT-2 on 08 May 2003 by the GSLV-D2 rocket. The SOXS Low Energy Detector (SLD) (Jain et. al., 2000a, b, 2005) aims to study X-ray spectra from solar flares with high energy and temporal resolution. It employs solid -state detectors viz. a Silicon PIN detector for 4 - 25 keV (area 11.56 sq. mm); and a Cadmium Zinc Telluride (CZT) detector for the 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 was 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. In order to improve our current understanding of the X-ray line emission characteristics, synoptic observations at energies below 10 keV are of utmost importance since they may reveal the temperature enhancement during flares of different magnitude. Iron lines (Fe XXV, XXVI) at 6.7 keV and Fe/Ni complex lines at 8 keV appear only during solar flare activity (Phillips, 2004). Understanding their emission characteristics requires high spectral and temporal resolution observations that may resolve the problem with the solar standard model that evolved after the precise abundance measurements from helioseismology observations (Antia and Basu, 2005) and from coronal neon measurement in solar type stars by Jeremy et al. (2005). The high sensitivity and sub-keV energy resolution of the 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 high temperature flares.

This line complex is due mostly to the 1s-2p transitions in He-like and H-like iron, 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; Landi et al., 2006). 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 ~6.7 keV, the intensity of the Fe/Ni line complex at ~ 8 keV, and the line-to-continuum ratio are functions of the plasma temperature and can be used to limit the range of possible plasma parameters. The BCS instruments onboard SMM and YOHKOH spacecrafts were successful in measuring the high resolution spectra of a few lines including Fe line complex but they could not succeed in obtaining them at very high temporal resolution as well as above 7 keV for Fe/Ni line feature. However, detailed studies of such features of the Fe and Fe/Ni line complexes have not been carried out 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 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 a study of solar flare thermal spectrum using RHESSI, RESIK and GOES mission data and determined the absolute elemental abundances, which however may have been 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 sub-keV spectral and high temporal resolution. Therefore the purpose of this paper is to study the X-ray emission characteristics of the Fe-line features in solar flares using the high sensitivity and sub-keV energy resolution capabilities of the Si PIN detector of the SOXS instrument.

2. Observations

The instrumentation of the SLD/ SOXS payload, its in-flight calibration and operation has been described by Jain et al. (2005). 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 than the earlier detectors used for solar flare research in this energy range. However, the spectral resolution achieved by the 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 (~1 ms) but we designed for 100 ms resolution during flare mode in order to record energy spectra with sufficient counts.

The temporal data i.e., intensity (counts/s) as a function of time, is revealed in four energy bands viz. 6-7 keV (L1), 7-10 keV (L2), 10-20 keV (L3) and 4-25 keV (T) by the Si detector, and in five energy bands by the 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 the Fe-line feature in the flare plasma. For the current investigation we use data from Si detector only and selected ten flares of *GOES* importance class M.

2.1 Temporal mode

In Fig. 1 we show the temporal mode observations i.e. light curves of 31 October 2004 flare in four energy windows of the Si detector. The time resolution for temporal and spectral mode observations during quiet periods is 1 s and 3 s respectively but during the flare mode, it is 100 ms for both temporal and spectral modes. It may be noted that the flare is gradually rising and long enduring.

Table 1: SLD/SOXS Flare Events Considered for Investigation.

S. No.	Date	Time UT Begin	Peak	End	SOXS (Si) Peak Int. (counts/sec)	GOES Class	Active Region Location	NOAA
1.	30 Jul 2003	0407	0409	0428	2420	M2.5	N16 W55	10422
2.	13 Nov 2003	0454	0501	0510	1292	M1.6	N04 E85	10501
3.	19 Nov 2003	0358	0402	0419	1190	M1.7	N01 E06	10501
4.	07 Jan 2004	0355	0400	0433	2243	M4.5	N02 E82	10537
5.	25 Mar 2004	0429	0438	0507	1740	M2.3	N12 E82	10582
6.	25 Apr 2004	0528	0536	0558	1918	M2.2	N13 E38	10599
7.	14 Jul. 2004	0518	0523	0525	4093	M6.2	N12W62	10646
8.	14 Aug 2004	0537	0544	0604	7474	M7.4	S11 W28	10656
9.	31 Oct 2004	0526	0531	0546	2062	M2.3	N13 W34	10691
10.	25 Aug 2005	0436	0439	0452	4705	M6.4	N07E78	10803

2.2. Spectral mode

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 Si detector's count spectra at the peak time of 31 October 2004 flare is shown in Fig. 2. The low intensity below 6 keV is due to aluminum plus kapton filter mounted on the detector head to absorb 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 Fe and Fe/Ni lines are visible at ~6.7 and ~8 keV respectively very strongly in the flare relative to background.

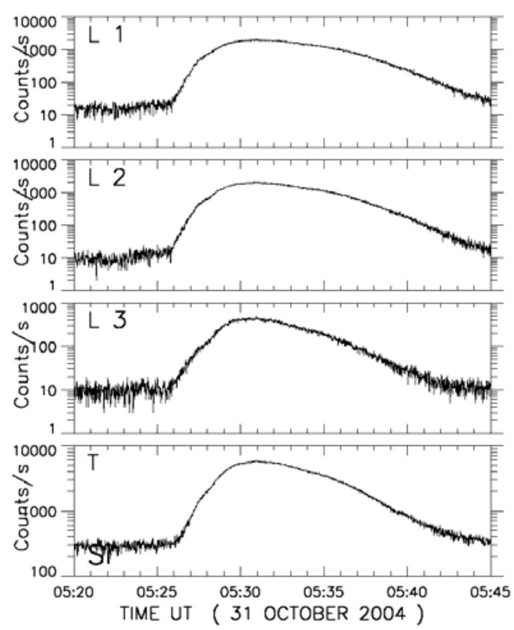

Fig. 1. Light curves of 31 October 2004 solar flare as recorded in L1, L2, L3 and T energy bands (see text) of Si detector of SLD/ SOXS mission.

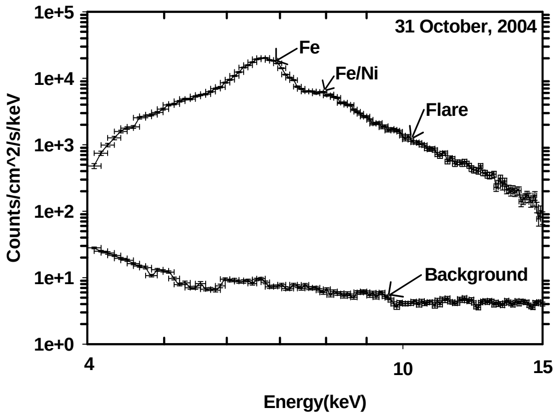

Fig. 2. Count Spectra from Si PIN detector for 31 October 2004 flare at 05:30:59 UT. Note Fe and Fe/Ni line features.

3. Analysis and results

The raw data for temporal and spectral mode observations are first corrected for any spurious counts in a single channel 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. The instrumental response is diagonal matrix as described earlier by Jain et al. (2005) and therefore simple division of count spectra at a given time by response matrix provides the photon spectra. The photon spectra are used to study the evolution of Fe and Fe/Ni lines in a given flare as a function of time.

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 Fig. 3 is a sequence of photon spectra of 31 October 2004 flare in the energy range 5 to 10 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 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 control the shape of the line. However, the non-thermal contribution might also play a role (cf. Fig. 4).

The Fe line feature is here defined as the excess above the continuum, as observed by the Si spectrometer with spectral resolution (FWHM) $\leq$ 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 Fig. 3 that Fe-line feature i. e intensity varies over the flare evolution. We analyzed 10 to 27 spectra for each flare 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 are formed (cf. Fig. 4), we undertake their analysis for deriving plasma parameters such as temperature, emission measure, and spectral index using the SOXSoft spectra fit program. This program takes its main routine from Solarsoft where Mewe and Chianti codes can be used to derive the plasma parameters. We do reverse fit i.e., fitting the model on the photon spectra. Further our analysis is based on two-temperature model, i.e. first we derive the temperature of the plasma by continuum fit, and secondly while fitting the line feature. In order to fit the spectra in the energy range between 5 and 15 keV, and particularly the Fe-line feature, by an isothermal plasma function, we use the Chianti code because the 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 χ^2 (difference counts). In order to derive the line parameters such as the net area and gross area under the curve and equivalent width we subtracted the continuum contribution to the spectrum. The temperatures are derived from the continuum in the energy range 9.5 to 16 keV using Chianti best-fit code. The spectra in this energy range are better fitted by thermal function instead of only non-thermal function.

3.1.1 Evolution of temperature and emission measure

In Fig. 4 we show a best-fit of photon flux from the Chianti code for a multi-thermal plus break energy power law functions. In multi-thermal function the differential emission measure (DEM) has power law dependence on temperature, while break power law is with/ without discontinuous derivatives. We have fitted the spectrum in the energy range 4.2 to 20 keV at one time with these two combined functions to achieve the best fit based on reduced chi-square. Fig. 4 is such best fit for the flare spectrum at 05:31:00 UT on 31 October 2004. The emission measure at 14 MK is 4.99e49 cm^{-3}. The best-fit is projected by residual as shown in Fig. 5. In this way, we obtain temperature and emission measure values for each photon spectra of a given time of the flare.

3.1.2 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_{flare}(Fe). 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 (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 a large number and 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 us to determine the abundance of Fe in flare plasma.

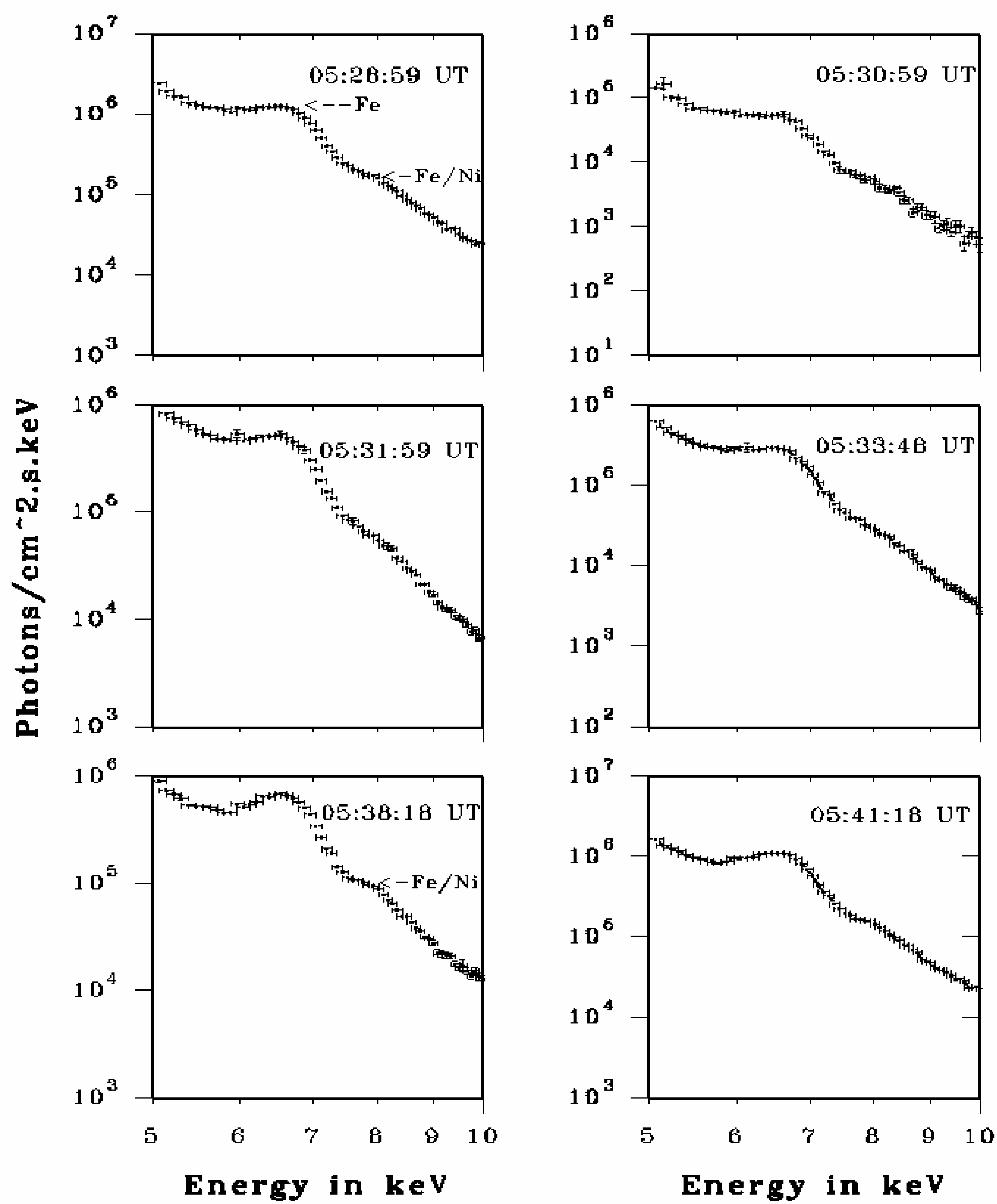

Fig. 3. Sequence of X-ray photon spectrum in the energy range 5 – 10 keV of 31 October 2004 flare showing evolution of Fe and Fe/Ni line features. X-axis error bar is channel width of 0.082 keV, while Y-axis error bar is ± 1σ of the photon flux in the given channel.

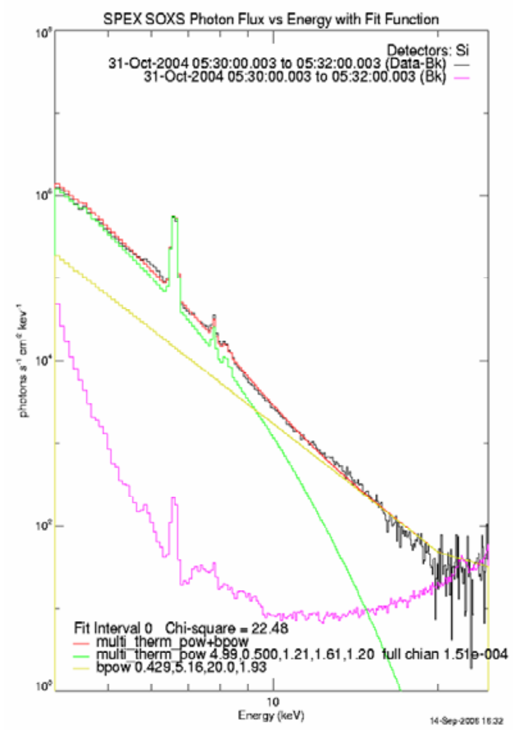

Fig. 4. The X-ray photon spectra of 31 October 2004 at 05:30:59 UT in 4 – 25 keV. The spectrum is fitted with multi-thermal power law plus non-thermal break power law. Differential emission measure, temperature of the plasma and the photon index are measured from the fit. X-axis error bar is channel width of 0.082 keV.

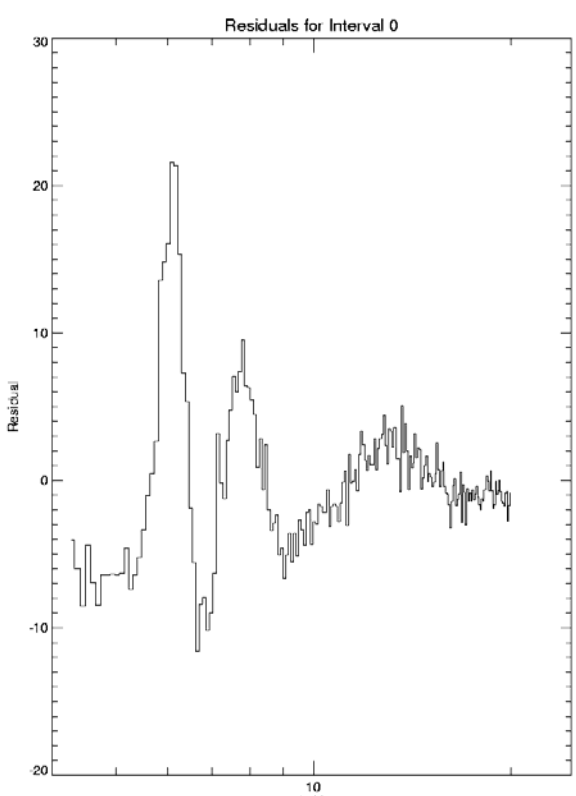

Fig. 5. The residual (difference) counts of multi-thermal power law plus non-thermal break power law fit (cf. Fig. 4).

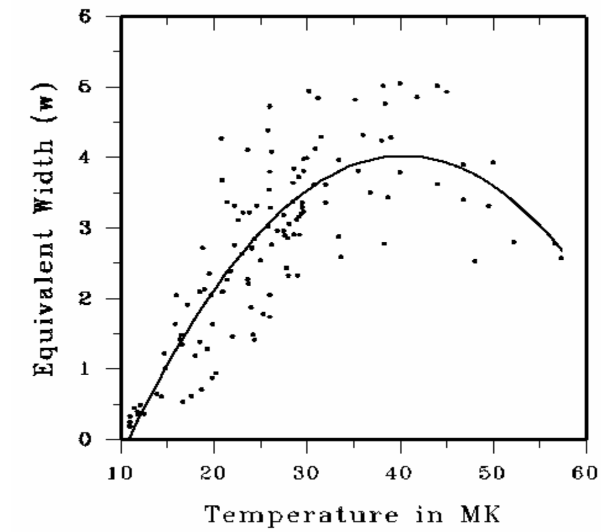

Fig. 6. Variation of equivalent width (*w*) as a function of temperature when combined for all ten flares under study.

A measure of the Fe-line feature's intensity with respect to the continuum is provided by the equivalent width (*w*), measured in keV, which can be determined from Si/SLD spectra. In order to get better statistical confidence we carried out a detailed study of the equivalent width (*w*) by analyzing all 10 M-class flares under current investigation. We derived *w* from each photon spectra of a given time of the flare for which temperature was measured from continuum. A total 140 photon spectra from 10 flares were analyzed to measure the *w*. Shown in Fig. 6 is the variation of the *w* with temperature. We found that w rises exponentially until 25 MK and later more slowly up to 35 MK. However it may be noted from this figure that *w* remains between 2 and 4 keV in the temperature range 20 – 35 MK but peak is around 40 MK, which remains until 45 MK. A decreasing trend in *w* begins after 45 MK. The decreasing trend towards higher temperature is seen for the maximum temperature 54 MK that was measured by us in the flares under current investigation.

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 earlier study showed temperature does not vary smoothly but rather fluctuates in general during the whole flare interval and rapidly in particular during the rise phase (Jain et. al., 2006). This fluctuation in flare plasma temperature (T_e) affects the ionization state and thereby as a consequence of it we observe variation in 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. With increase in temperature viz. $9 < T_e < 30$ MK He-like Fe-lines and satellite (6.4 – 6.7 keV) are most intense. The strength of the Fe-line feature above the continuum i.e. equivalent width (*w)* was also found to be varying with T_e of the flare plasma. However, an exponential rise in *w* is seen up to 25 MK and then later it rises more slowly to remain between 2 and 4 keV. The equivalent width measured by us is in close agreement to Phillips (2004) though significant deviation exists in the temperature range of 25 – 50 MK. This motivated us to compare with that calculated earlier by Raymond and Smith (1977), Sarazin and Bahcall (1977), Rothenflug and Arnaud (1985) and Phillips (2004) as shown in Fig. 7. It may be noted from this figure that our measured values of *w* are significantly higher than Raymond and Smith (1977), referred as RS77, and Sarazin and Bahcall (1977), referred as SB77, and Rothenflug and Arnaud (1985) referred as RA85 in the temperature range 14 to 54 MK. Calculations of *w* from Phillips (2004), referred as P04, appear close to our measurements.

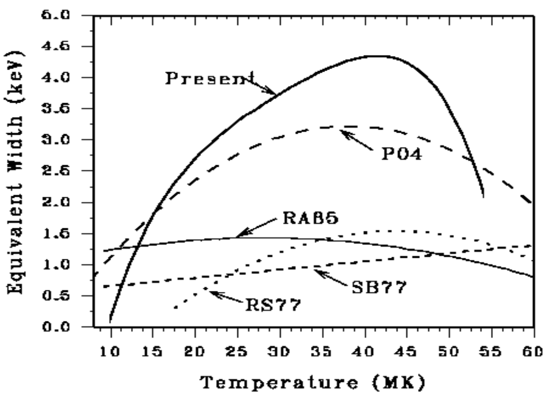

Fig. 7. Comparison of our measured values of equivalent width (*w*) with previous results from RS77 (Raymond and Smith, 1977), SB77 (Sarazin and Babcall, 1977), RA85 (Rothenflug and Arnaud, 1985) and P04 (Phillips, 2004).

Rothenflug and Arnaud (1985), Phillips (2004) and Oelgoetz and Pradhan (2004) calculated equivalent width (*w*) of the different ionic participations of Fe-line feature and showed how it varies with temperature for each individual ionic line. The *w* of FeXXV line is higher than FeXXIII, FeXXIV and FeXXVI up to 100 MK. Emission from FeXXVI above 100 MK becomes stronger and the total *w* is dominated by this emission. However, contribution to *w* from FeXXII, FeXXIII and FeXXIV almost stops around 21, 35 and 115 MK respectively. Therefore, in the temperature range of 9 – 44 MK for the flares studied in this investigation, the major contribution for *w* may be considered from these ionic emissions and FeXXV. However, a little contribution from FeXXVI may be considered when temperature exceeds 30 MK. The difference in calculations by earlier investigators with our measurements may be due to their consideration of different ionic contributions of Fe and their magnitudes. Our experimental measurements of equivalent width and its variation over temperature may help to improve theoretical calculations. Further improved understanding of Fe abundance may help in resolving the problem of elemental abundances in solar standard model.

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 detail. In this paper we carried out a study of the Fe-line feature in order to investigate the variation of equivalent width (*w*) as a function of temperature of the flare plasma. The equivalent width (*w*) rises exponentially up to 25 MK and then more slowly to reach a peak of ~4 keV at 40 Mk. We interpret the variation of *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 calculations carried out previously by many investigators 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 in general and elemental abundances in solar standard model in particular.

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References

H. M. Antia and S. Basu, *Astrophys. J.*, vol. 620, p. L129, 2005.

V. A. Boiko, S. A. Pikuz, U. I. Safronova and A. Ya. Faenov, *Mon. Not. R. Astron. Soc.*, vol. 185, p. 789, 1978.

J. L. Culhane, *Mon. Not. R. Astron. Soc*., vol. 144, p. 375, 1969.

K. P. Dere, E. Landi, H. E. Mason, B. C. Monsignori Fossi and P. R. Young, *Astron. Astrophys*., vol. 125, pp. 149-173, 1997.

G. A. Doschek, U. Feldman, P. B. Landecker and D. L. McKenzie, *Astrophys. J.*, vol. 245, p. 315. 1981.

J. J. Drake and P. Testa, *Nature*, vol. 436, p. 525D, 2005.

U. Feldman, G. A. Doschek, J. T. Mariska and C. M. Brown, *Astrophys. J*, vol. 450, p. 441, 1995.

A. Fludra and J. T. Schmelz, *Astron. Astrophys*. vol. 348, p. 286, 1999.

A. H. Gabriel, *Mon. Not. R. Astron. Soc.*, vol. 160, p. 99, 1972.

R. Jain et al., *Bull. Astrn. Soc. India*, vol. 29, p. 117, 2000a.

R. Jain et al., PRL Technical Document "Pre-flight Characterization and Response of the SLD/SOXS Payload", *PRL-GSAT-2-SOXS-0185*, 2003.

R. Jain et al., *Solar Phys.,* vol. 227, p. 89, 2005.

R. Jain et al., *Solar Phys*., (accepted for publication), 2006.

R. Jain and P. Sreekumar, Technical Document – "GSAT-2 Spacecraft – Preliminary Design Review (PDR) Document for Solar X-ray Spectrometer", *ISRO-ISAC-GSAT-2-RR-0155*, 2000b.

I. T. Kato, U. I. Safronova, A. D. Shlyaptseva, M. Cornille, J. Dubau and J. Nilsen, *Atomic Data & Nuclear Data* Tables, vol. 67, p. 225, 1997.

E. Landi, G. D. Zanna, P. R. Young, K. P. Dere, H. E. Mason and M. Landini, *Astrophys. J.*, vol. 162, p. 261, 2006.

R. Mewe, E. H. B. M. Gronenschild and G. H. J. van den Oord, *Astron. Astrophys*., vol. 62, p. 197, 1985a.

R. Mewe, J. R. Lemen, G. Peres, J. Schrijver and S. Serio, *Astron. Astrophys.*, vol. 152, p. 229, 1985b.

J. Oelgoetz and A. K. Pradhan, *Mon. Not. R. Astron. Soc.* vol. 354, p. 1093, 2004.

A. F. Patel and N. Jain, *SOXS/PRL Technical document, "Software Development for Data Processing and Analysis of Data from Solar X-ray Spectrometer (SOXS) Mission Onboard GSAT-2 Spacecraft*", 2005.

K. J. H. Phillips, *Astrophys. J.*, vol. 605, p. 921, 2004.

K. J. H. Phillips, W. M. Neupert and R. J. Thomas, *Solar Phys.*, vol. 36, p. 383, 1974.

K. J. H. Phillips, J. A. Rainnie, L. K. Harra, J. Dubau, F. P. Keenan and N. J. Peacock, *Astron. Astrophys.*, vol. 416, p. 765. 2004.

K. J. H. Phillips, J. B. Sylwester, B. Sylwester and E. Landi, *Astrophys. J.*, vol. 589, p. L113, 2003.

J. C. Raymond and B. W. Smith, *Astrophys. J. Suppl.*, vol. 35, p, 419, 1977.

R. Rothenflug and M. Arnaud, *Astron. Astrophys.*, vol. 144, p. 431, 1985.

C. L. Sarazin and J. N. Bahcall, *Astrophys. J. Suppl*., vol. 34, p. 451, 1977.

B. Sylwester, J. Sylwester, M. Siarkowski, K. J. H. Phillips and E. Landi, "Multi-Wavelength Investigations of Solar Activity", in *IAU Symposium, No. 223*, Alexander V. Stepanov and Elena E. Benevolenskaya and Alexander G. Kosovichev, Eds. Cambridge, UK: Cambridge University Press, 2004., pp. 671-674.