ANALYSIS OF DIFFERENTIAL EMISSION MEASURE EVOLUTION FOR SELECTED SEP AND NON-SEP ASSOCIATED FLARES BASED ON HARD AND SOFT X-RAY OBSERVATIONS

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ABSTRACT

We present prompt results of analysis of differential emission measure distributions (DEM) for solar flares. The DEM describes the distribution of emitting plasma with temperature. For calculations of the DEM shape we use Withbroe - Sylwester (WS) multiplicative iterative algorithm. Our input data set consists of total flare fluxes as measured by the *Yohkoh* Soft X-ray Telescope (SXT) in most of available filters, the Hard X-ray Telescope data (HXT), the Bragg Crystal Spectrometer (BCS) line fluxes and *GOES* X-ray fluency as measured in 0.5 - 4 Å and 1 - 8 Å bands.

Reconstruction of DEM shape from observed X-ray fluxes constitute uneasy ill-defined inverse problem. Therefore, before applying the algorithm to real data we performed numerous tests of the inversion method using several synthetic DEM distributions. This has been done in order to better understand how to interpret the DEM as obtained from real measurements and understand limitations of the inversion procedure. In our tests, we have used a number of typical DEM distribution shapes (cf. Figure 2).

The overall stability of the WS reconstruction procedure led us to investigate DEM shapes for particular flare events selected. We have chosen to look for possible differences in DEM shape and behavior for flare events which have been associated and not associated with the (following) solar energetic particle (SEP) occurrence.

Key words: Sun; X-rays; SEP events; differential emission measure.

1. INTRODUCTION

The multi-temperature analysis of the X-ray data provides important information about physical conditions within flaring plasma. The knowledge of evolution of the DEM distribution allows to study the energy transport processes within flare in more details. One of the methods allowing to determine DEM from the observations is the Withbroe - Sylwester (WS) multiplicative algorithm (Withbroe, 1975, Sylwester et al., 1980) relying on the maximum likelihood approach.

In this paper we present again some details of WS method, show results of its tests and demonstrate the shape of calculated DEM for flares belonging to two classes: SEP-associated (SEP) and NOT- associated (N-SEP).

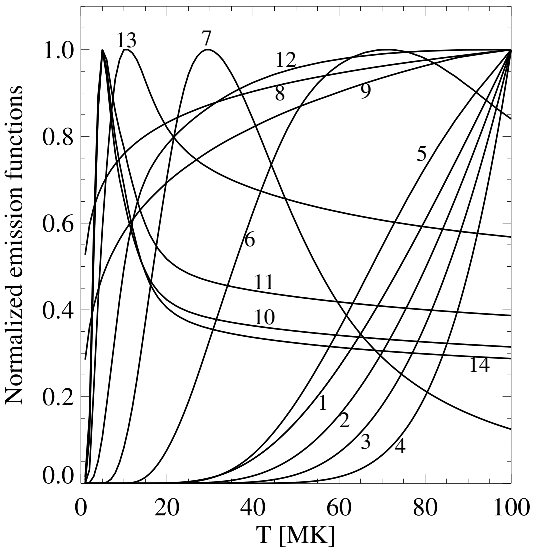

Figure 1. The emission functions used in the present study for the 14 lines or energy bands. Key numbers denoting the curves correspond to lines/bands given in Table 1.

Table 1. The set of lines/bands used in our DEM inversion

i	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Instr.*	HXT	HXT	HXT	HXT	BCS	BCS	BCS	GOES	GOES	SXT	SXT	SXT	SXT	SXT
Chan.	L	M1	M2	H	FeXXVw	CaXIXw	SXVw	1 - 8 Å	0.5 - 4 Å	Al01	AlMg	Be119	Al12	Mg3
Unc. [%]	15	19	15	21	3	2	2	1	10	1.2	1	1.5	1.3	2

**Instr.* ≡ *Instrument*, *Chan.* ≡ *Channel*, *Unc.* ≡ *Uncertainty*

2. THE WS ALGORITHM

The Withbroe-Sylwester (maximum likelihood) multiplicative algorithm is the iterative procedure in which the next approximation of the DEM distribution $\varphi_{j+1}(T)$ is calculated from preceding one $\varphi_j(T)$ using the following expression:

$$\varphi_{j+1}(T) = \varphi_j(T)\frac{\sum_{i=1}^{k} c_i w_i(T)}{\sum_{i=1}^{k} w_i(T)} \tag{1}$$

where:
c_i is the correction factor taken as $c_i = F_{oi}/F_{ci}$, F_{oi} and F_{ci} are the measured and predicted fluxes in particular line/band i ($i = 0, 1, 2 \ldots k$) and $w_i(T)$ is the weight function defined by the following relationship:

$$w_i(T) = f_i(T)\varphi_j(T)\frac{\int_0^\infty f_i(T)\varphi_j(T)dT}{\int_0^\infty [f_i(T)\varphi_j(T)]^2 dT}\left[\frac{|F_{oi} - F_{ci}|}{\sigma_i} + 1\right]^a \tag{2}$$

where:
a - is the optimizing parameter (Sylwester et al., 1980), $f_i(T)$ is the emission function in line/band i and F_{c_i} is the flux calculated (in j^{th} iteration) as:

$$F_{ci} = \int_0^\infty f_i(T)\varphi_j(T)dT \tag{3}$$

In Figure 1 we present temperature dependences of all associated emission functions in the temperature range where DEM distributions have been calculated. The key numbers i denoting functions correspond to line/band numbers as indicated in the Table. The corresponding typical uncertainties (lowest row in the Table) were calculated in the following way:

- *Yohkoh* HXT - we fitted Gaussian to the histogram of the shot noise in each channel and we took σ of this Gaussian distribution as representative relative uncertainty;
- *Yohkoh* BCS - the uncertainties were calculated as square root of the integral over the wavelength and time of the count rate in the resonance line (taken above continuum);
- *Yohkoh* SXT - the uncertainties in all "filters" were taken equal to the square root of total photon counts in the area covering entire flare;
- *GOES* - we used the same method as for *Yohkoh* HXT.

Preparing for the test we used the assumed synthetic DEM model and calculated (from Eq. (3)) fluxes in the set of basic lines/bands shown in Table 1. Then these fluxes were treated as observed ones ($F_{oi} = F_{ci}$) and used as input data. In Figure 2 we present the results of our tests. In the left panels in the Figure we present "ideal" situation when no errors are allowed in the input data. In the right panel we plotted results as obtained for 100 cases which were calculated using the input fluxes randomly perturbed according to the typical uncertainty values from the Table.

Performed tests of WS algorithm indicate, that it is possible to determine an overall shape of the differential emission measure from observations in the selected set of X-ray measurements. Especially well the algorithm restores smooth shapes of DEM. In case of isothermal sources, the location of the peak on the restored DEM distribution is placed exactly at the corresponding temperature. For two-temperature sources, the algorithm resolves the components if only their separation is large enough compared to the "width" of the emission functions at the corresponding temperature (i.e. few MK in the 10 - 20 MK range and several MK in the range above 30 MK). For the set of selected 14 X-ray fluxes, the T-range, where reliable estimates of DEM shape can be calculated covers the range between 3 and $\sim$ 50 MK. It is worth to note that the algorithm detects easily cases, when an abrupt discontinuity (drop) in the DEM shape is present. This property would allow to detect high temperature cut-offs in DEM distribution (if present). Results of application of WS algorithm to noisy data confirm that the inverse problem being solved is ill-posed, and presence of uncertainties substantially limit the confidence in derived DEM distributions however only in areas where DEM level is relatively low.

3. THE RESULTS

In this prompt research we selected a typical pair of SEP and N-SEP flare events with a purpose to look for possible differences of DEM distributions between the two classes. As an example of the N-SEP flare we have chosen 13 January 1992 flare ("Masuda event"). This flare was of *GOES* M2.0 class and it occurred at the western limb. It has reached maximum phase around 17:34 UT. This flare has been well observed by *GOES*, *Yohkoh* BCS and HXT and also using four

SXT filters: Al01, AlMg, Be119 and Al12. We excluded from the analysis the SXV line flux of BCS (McTiernan, 1997) and H channel of HXT because the fits to the DEM are no good when that data are included. In Figure 3 (upper panel) we present calculated DEM distributions for two selected times (the rise phase - left panel and decay phase - right panel). In the lower part of the Figure we present resulting observed to calculated flux ratios in particular line/band. Numbers on X-axis correspond to key numbers in Table 1. In Figure 3 the solid line represents our results while the dash-dotted line represents the shape of DEM calculated by McTiernan (1997) using the Maximum Entropy method.

As an example of SEP event we have chosen 20 October 1995 flare. It was a *GOES* M1.5 class event arising from AR 7912 located at S09W95. The maximum phase was reached around 06:07 UT. The flare has been observed by *GOES*, *Yohkoh* BCS and HXT and also through four of *Yohkoh* SXT filters: Al01, AlMg, Be119 and Al12. In Figure 4 we present the DEM distributions calculated for the four selected times during the rise phase of this event.

The comparison of derived DEM shapes for SEP and N-SEP events indicates that no substantial differences can be noted, at least at times (later on) during the rise phase. In order to place the above conclusion on firm base it is necessary to make similar comparison for a statistically significant set of flare events. For both analysed flares, derived DEM shape resembles the case of two-temperature distribution (with the maxima around $T \sim 6$ MK and $T \sim 20$ MK). Later on, after flare maximum, the role of the higher temperature component systematically decreases. Our results obtained using WS algorithm compare well with the result of similar analysis by McTiernan (McT). McT applied Maximum Entropy DEM restoration algorithm and therefore (cf. Fludra and Sylwester, 1986) their derived DEM shapes are smoother than WS-determined shapes. Otherwise, the shapes compare quite well. In case of the 20 Oc-

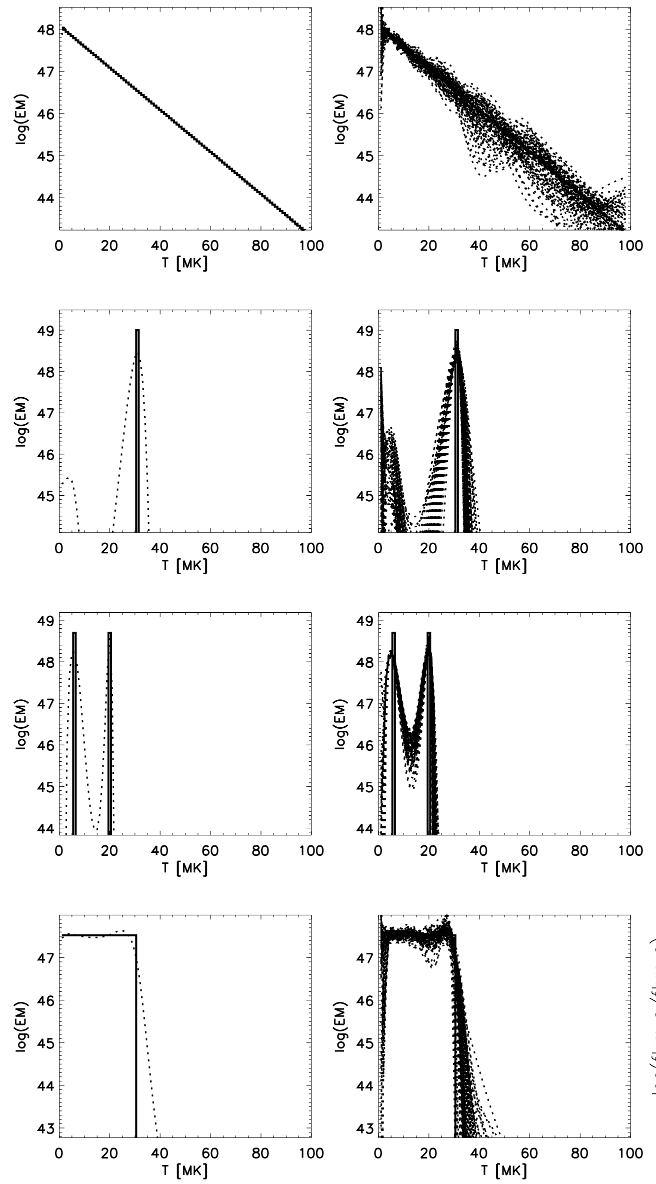

Figure 2. Left row: comparison of assumed (solid line) with calculated (dashed line) model in case the data does not contain errors. In the right row each of hundred calculated models was computed using perturbed lines fluxes. The perturbations have been taken according to average uncertainty values from the Table.

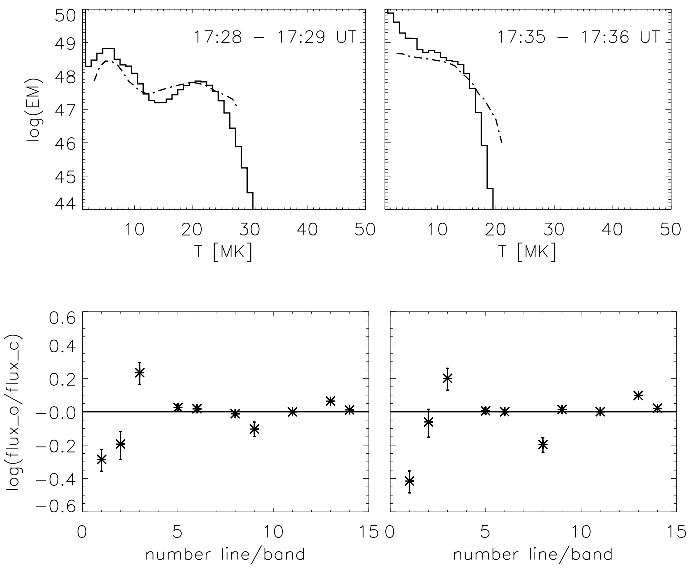

Figure 3. DEM distributions calculated for 13 January 1992 flare. The lower panel show the ratio of observed to calculated fluxes in the particular line/band. In the upper panel the solid line represent results of present study while the dash-dotted line represents the shape of DEM as calculated by McTiernan (1997) using Maximum Entropy method.

tober 1995 SEP associated event, the input fluxes were available from the very onset of the event, and it was possible to look for DEM distributions early during the rise phase. In Figure 4 (upper panel) we see that initially DEM shape is rather smooth, with the high-temperature shoulder extending up to 30 MK. As time progress, development of two component shape takes place, with the high-temperature cut-off moving to lower temperatures.

The study of DEM shape evolution will be continued in order to increase statistics of our SEP vs. N-SEP samples. We also plan to incorporate several modifications to the WS algorithm in order to speed-up the calculations and increase robustness of the results. There are present a number of problems with fitting of the HXT fluxes. We observe that the disagreement between the observed and calculated fluxes for this instrument is systematically the largest. Part of the observed discrepancy can possibly be associated with the assumption (we made) of the thermal character of emission in the range observed by HXT. This assumption is probably an oversimplification, and we will (in the future) allow for presence of non-thermal plasma component in DEM shape modeling.

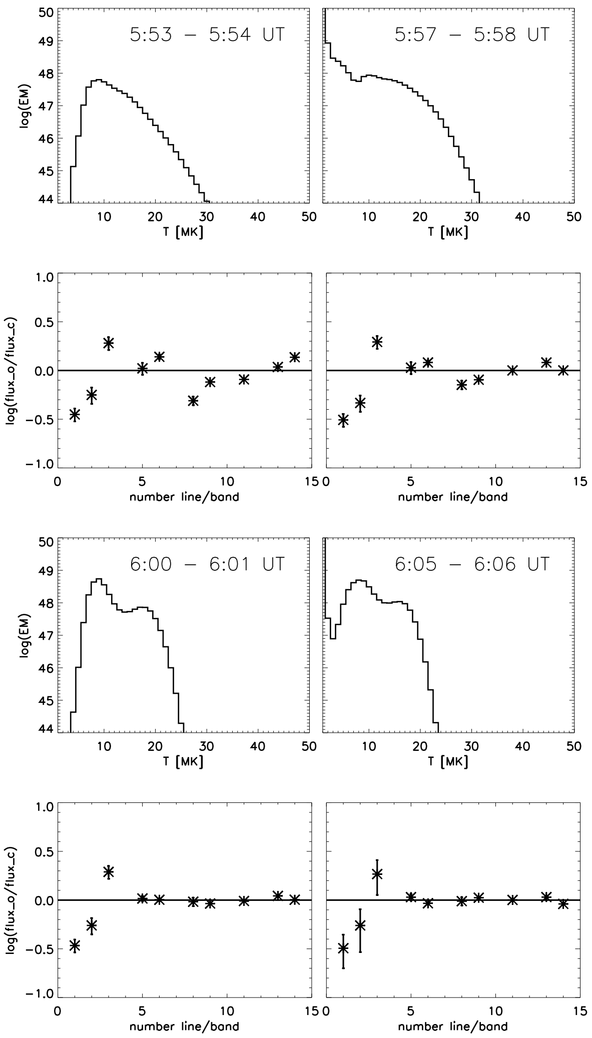

Figure 4. As in Figure 3. DEM distributions for 20 October 1995. The lower panel presents ratios of the observed to calculated flux in the particular line/band.

4. SUMMARY

In this paper we describe results of application of the Withbroe-Sylwester maximum likelihood iterative differential emission measure code to the interpretation of *Yohkoh* BCS, SXT, HXT and *GOES* flare observations. We performed extensive tests of this algorithm based on a set of the line and broadband X-ray fluxes. Result of the performed tests indicate that:

- The WS algorithm adequately restore input test DEM distribution in case of isothermal and power-law sources.
- By using the WS algorithm it is possible to detect presence of high-temperature cut-offs in the DEM distribution.
- Presence of uncertainties in the data substantially limit the accuracy of DEM inversion which reflects the ill-posed nature of the problem. However, it is still possible to determine overall shape of DEM even from the noisy set of data.
- In both SEP and N-SEP class flares the solar flare plasma is not isothermal. The shape of DEM has a humps in the temperature range around 6 and 20 MK during the main flare phase.

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