

Differential Emission Measures from the Regularized Inversion of Hinode & SDO data

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Introduction

Observations from Hinode and SDO provide an unprecedented view of plasma in the solar atmosphere. However the inference of how much material is emitting at each temperature - the Differential Emission Measure, DEM - from these data sets is an ill-posed inverse problem. Normally an isothermal assumption or model forward-fitting is employed to recover the DEM but such methods force a model form on the data and can be computationally slow. In this poster we present a model independent regularization algorithm that makes use of general constraints on the form of the DEM. This method uses Tikhonov regularization (also used to recover electron spectra from RHESSI observations) and provides both vertical and horizontal errors.

Assuming optically thin emission in thermal equilibrium the DEM $\xi(T)$ is related to the observations via:

$$g_i = \int_T K_i \xi(T) dT + \delta g_i$$

where g_i is the observable in the i^{th} filter/line intensity, with associated error δg_i , and K_i is the corresponding temperature response/contribution function. The uncertainties associated with these observations results in an ill-posed inverse-problem with any direct attempts at a solution resulting in amplification of the errors and spurious solutions. Additional constraints are therefore required to recover a solution. One way of constraining the problem is to make an assumption about the form of the emission and then forward fit this model to the problem. However if the chosen model is inappropriate then the solution is meaningless.

The regularization approach adopted here is to add linear constraints to the DEM resulting in the problem being recast as

$$\left\| \tilde{\mathbf{K}} \xi(T) - \tilde{\mathbf{g}} \right\|^2 + \lambda \left\| \mathbf{L}(\xi(T) - \xi_0(T)) \right\|^2 = \min$$

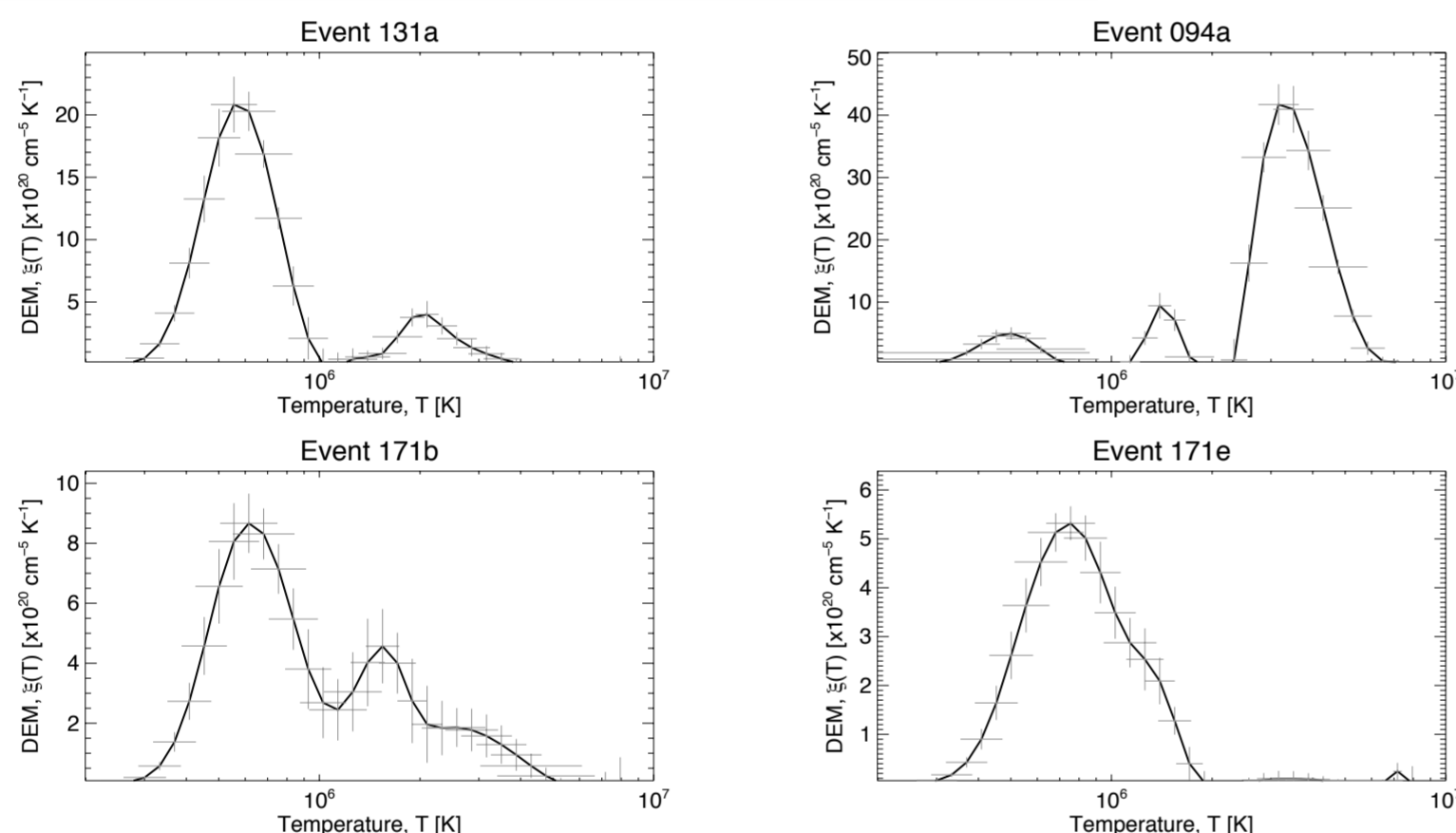
where the tilde represents normalization by the error, λ is the regularization parameter (which controls the χ^2 , and optionally the positivity, of the final solution), \mathbf{L} is the constraint matrix (normally taken as the identity matrix \mathbf{I}) and $\xi_0(T)$ is a possible guess solution. This is quickly solved using General Singular Value Decomposition (GSVD) and also provides a way of estimating both the vertical and horizontal (temperature resolution) errors on the regularized DEM.

Full explanation of the method is given in Hannah & Kontar, A&A 2011 and the regularization software and test examples are available to the solar community.

Below we demonstrate the capabilities of our regularized inversion technique applied to various published observations:

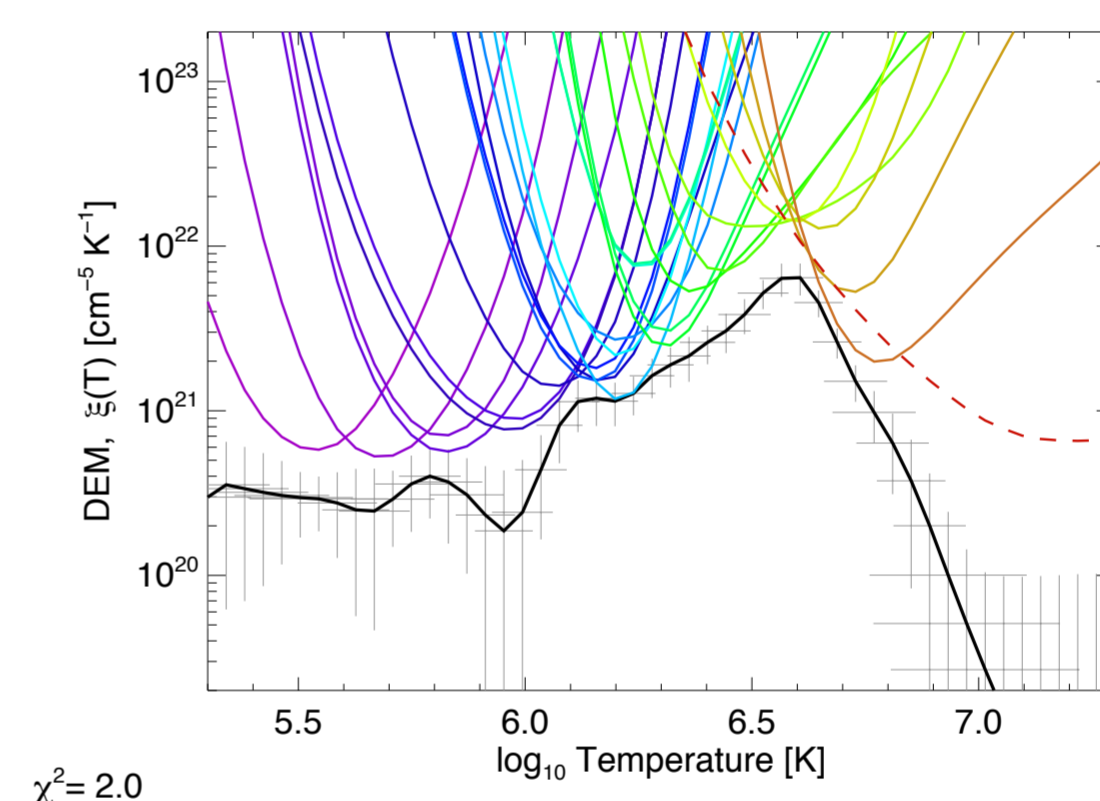
1. SDO/AIA coronal loops (Aschwanden & Boerner ApJ 732, 2011)
2. Hinode EIS & XRT active region core (Warren et al. ApJ 734, 2011)
3. SDO/AIA flare loops (Foullon et al ApJ 729, 2011/Reeves & Golub ApJ 727, 2011)

1. SDO/AIA Coronal Loops



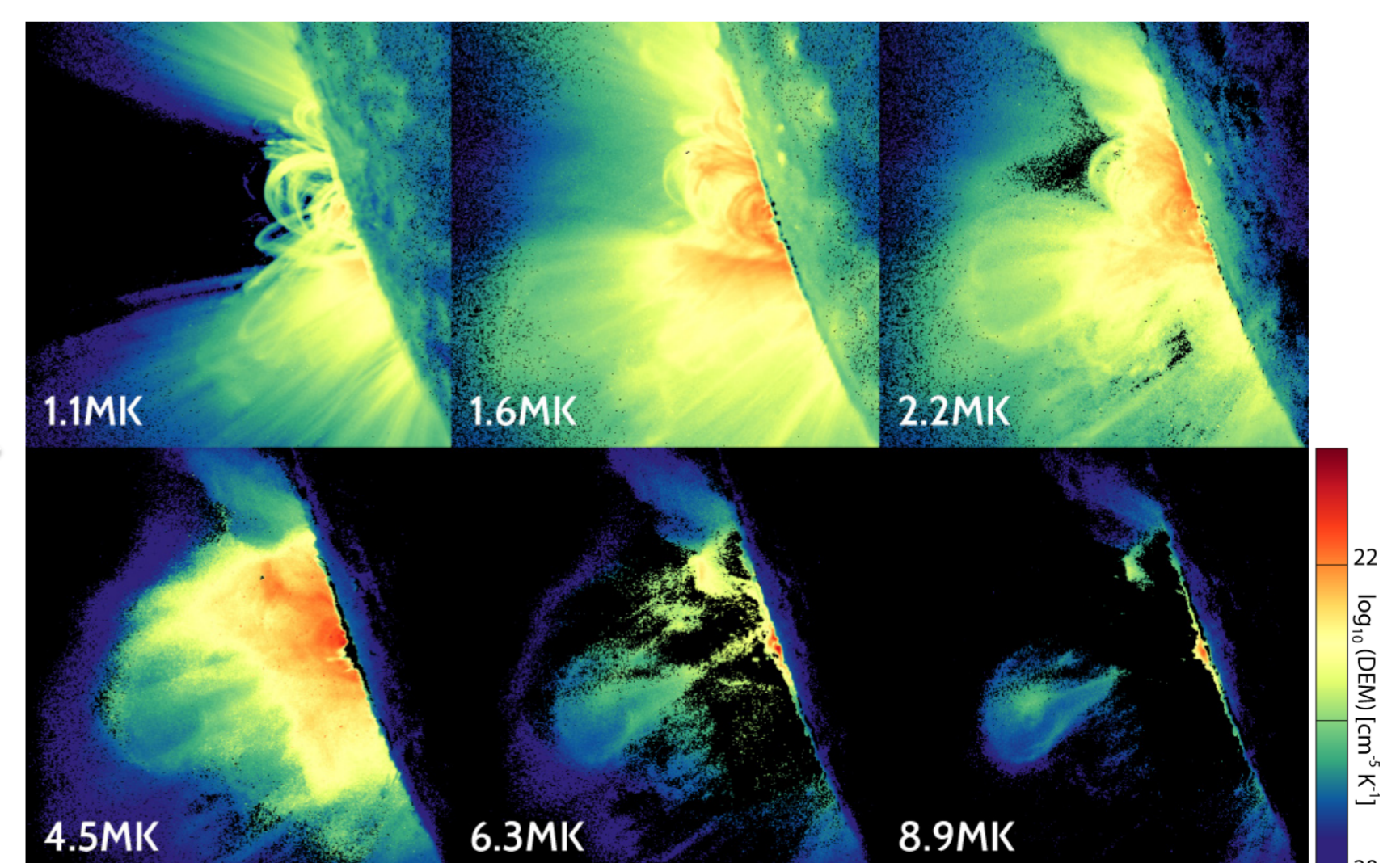
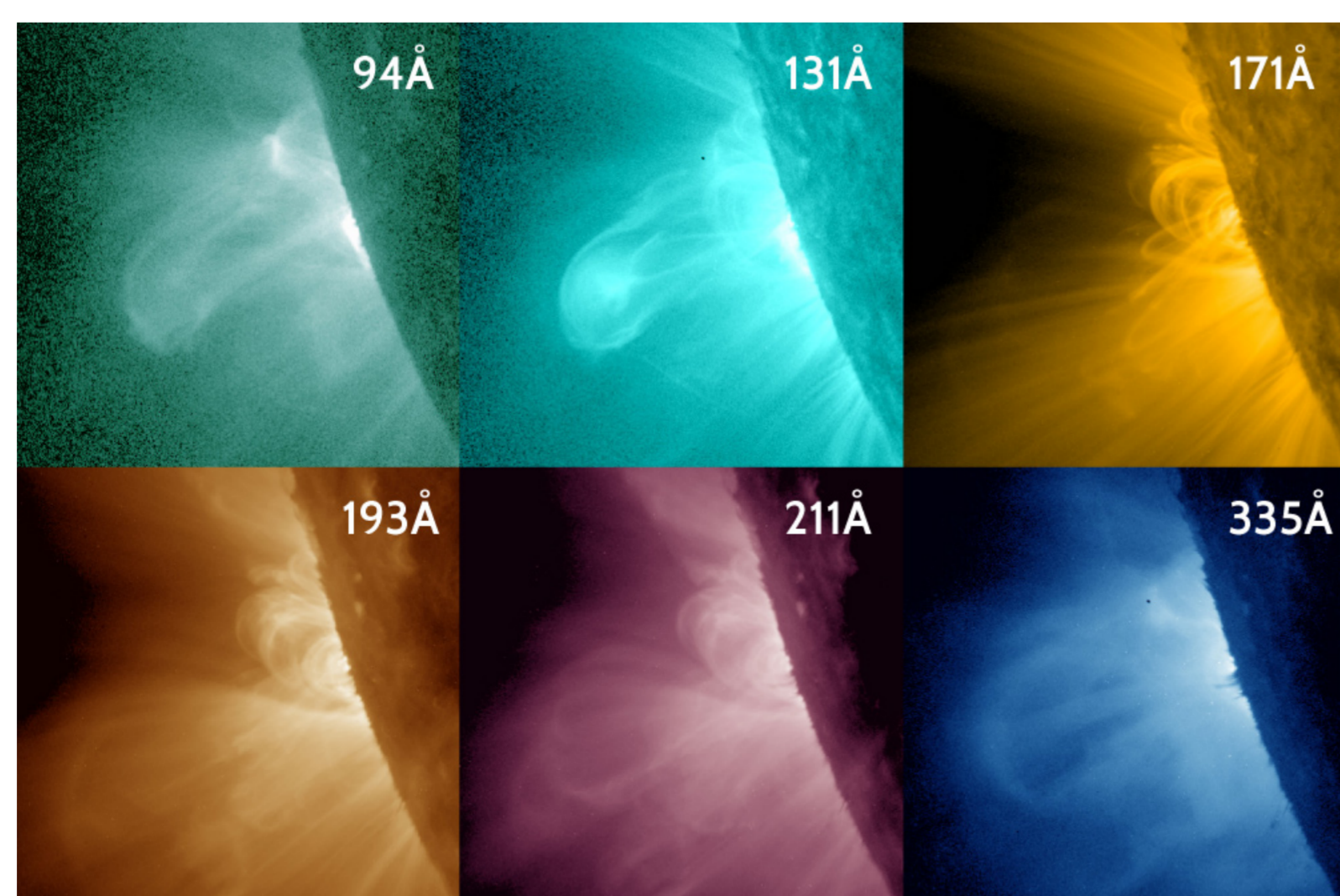
The DEM of coronal loops from ARI 1089 24-Jul-2010 were found from SDO/AIA observations by forward-fitting a multiple Gaussian model (Aschwanden & Boerner ApJ 732, 2011). Using their background subtracted data we used our regularized inversion method to recover the DEM of these loops, the results shown above. Our method does not assume any model for the DEM and we do recover some narrow Gaussian structures but also broader and more complicated DEMs. The errors obtained for the regularized solution help determine how much confidence to have in each DEM feature.

2. Hinode Active Region Core



The DEM of the "inter-moss" from the core of ARI 1089 23-Jul-2010 was produced using Hinode EIS and XRT observations by Warren et al. ApJ, 734, 2011. They used the MCMC method from PINTofALE (Kashyap & Drake 1998, 2000) whereas we applied our regularization method to their data, recovering a positive DEM with $\chi^2=2.0$ (black line & errors bars). The colour lines are the EM loci curves for the different EIS lines (solid) and XRT image (dashed). We are able to produce a very similar DEM, peaking at the same temperature, but considerably quicker (~ 1 sec) than the MCMC method and also with the associated vertical and horizontal errors bars.

3. SDO/AIA Flare/CME Loops & Eruption



SDO/AIA images (left) of the occulted C4.9 flare from 03-Nov-2010 about the time of peak SXR/HXR emission (12:14:36). Reeves & Golub ApJ 727 2011 discussed the hot plasmoid erupting over the course of this event. Using our regularized inversion method we are able to produce a full DEM for each pixel of the AIA images allowing us to construct temperature maps (right), the colour scale indicating DEM value for each temperature range. The hot erupting material is clearly visible in the 8.9MK map.