Using SunPy for your research - Coronal temperature maps

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Python and SunPy

Why Python and SunPy?

Temperature maps
- Background and theory
- Implementation
- Validation
  - Against synthetic data
  - Against other methods

Switching from IDL to Python

Other research using SunPy

Python and SunPy

Python

- Interpreted, object-oriented language
- Free, open-source software
- Very flexible, general purpose language
    - Modular structure means it can be used for very specific tasks

Python for Science

- Numerous scientific libraries
  - NumPy, math - arrays and mathematical functions
  - SciPy - scientific functions
  - matplotlib - plotting and visualising data
  - astropy, spacepy, scikit-learn, scikit-image

SunPy for Science

- Uses various existing scientific libraries
  - NumPy, SciPy, matplotlib, astropy, suds, pandas, sqlalchemy, etc
- Aims to provide an alternative to SSWIDL

Why Python and SunPy?

Disadvantages of IDL and SSW

IDL

- Expensive
- Licences can be problematic
- Difficult for those with little coding experience to pick up
- Decent visualisation takes effort
- `http://phpmanualmasterpieces.tumblr.com/post/66992896812/language-field-trip-idl`

SSW

- Install is huge and takes ages
- 'Updating' often breaks things
- Unclear versioning and no documentation

Advantages of Python and SunPy

Python

- Free, open-source
- Syntax is made to be readable
- General purpose language, but with various scientific libraries
- Lots of routines available on-line
- Easy to call C or Fortran functions from Python for increased speed
- Powerful visualisation capabilities

SunPy

- Has all the advantages of Python - open-source, readable syntax, etc.
- Draws on many other mature scientific Python libraries
- Maintained by an active community
- Proper version control
- Continuous integration and testing
- Extensive documentation

Temperature maps

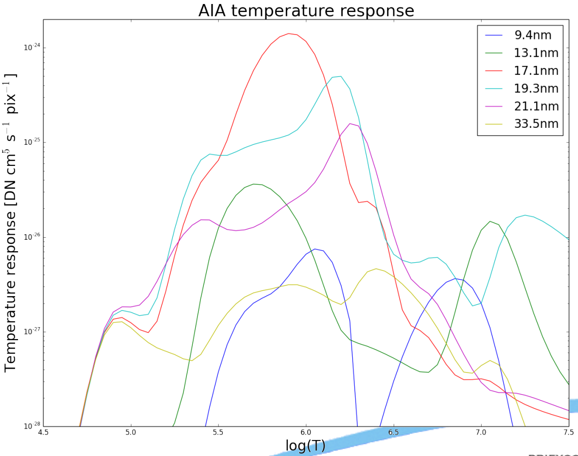
Background and theory

AIA data

- Atmospheric Imaging Assembly on the Solar Dynamics observatory (SDO)
- Images the corona in each of six Fe-dominated EUV wavelength bands with $\sim$1.2 arcsec per pixel resolution every $\sim$12 seconds
- AIA has very high spatial, temporal and thermal resolution - excellent data source for various coronal features
- Each channel corresponds to the formation temperature of the dominant ion (mostly)
- Coronal temperatures can be inferred from the relative brightness of each channel

Temperature response functions

- Obtained in IDL (currently), then loaded into Python



Defining the Differential Emission Measure

- Differential Emission Measure (DEM) describes the amount of plasma emitting along a given line-of-sight (LOS) as a function of temperature:

$$DEM(T) = n_e^2 \frac{\mathrm{d}z}{\mathrm{d}T}$$

- Width provides a measure of how multi-thermal the plasma is
- Peak temperature is the temperature of the majority of the plasma
- Integral of DEM over temperature gives the column electron density

Inferring the DEM

- Intensity measured by pixel x of a particular channel i on AIA is a convolution of the DEM and that channel's temperature response function:

$$I_i(x) = \int_0^\infty K_i(T)\, DEM(T; x)\, \mathrm{d}T \qquad (1)$$

- This is an ill-posed problem and there exists no unique solution without imposing physical constraints [Judge et al., 1997]
- Various schemes have been designed to invert this equation: Brosius et al. [1996], Kashyap and Drake [1998], Warren et al. [2008], Goryaev et al. [2010], Hannah and Kontar [2012], Plowman et al. [2012], Aschwanden et al. [2013]

Implementation

Data aquisition

- Level 1 data downloaded from the Virtual Solar Observatory
- VSO queried with appropriate SunPy wrappers - this will be covered in more detail tomorrow

Image preprocessing

- Level 1.0 data corrected for exposure time and processed to level 1.5 with aiaprep()
- aiaprep() is equivalent to SSWIDL's aia_prep function:
  - Rotates the images so that solar north points to the top of the image
  - Scales the images so that each pixel is exactly 0.6 arcsec across
  - Recentres the images so that solar centre coincides with the centre of the image.
- Images were normalised by dividing the intensity of each pixel by the intensity in the corresponding 17.1nm pixel

Form of the DEM

- This method systematically tests a range of possible DEMs - a general DEM profile must be assumed
- A Gaussian profile is selected because:
  - It can be fully described by only three parameters
  - Other studies have found multithermal DEMs with relatively narrow widths
  - Using the same shape as other studies allows a more direct comparison between the methods

Gaussian parameters

- To save time and memory, the problem is simplified by finding only the DEM peak temperature
- Model DEM width is set to 0.1
  - A wider model DEM will be less accurate for narrow AND wide plasma DEMs [Guennou et al., 2012b]
  - A narrower model DEM would not necessarily provide meaningful results [Judge, 2010]
- Model DEM peak temperatures considered were between $\log(T) = 5.6$ and 7.0 in increments of 0.01 in log temperature
  - The temperature is well constrained by the response functions within this range [Guennou et al., 2012a]

Testing the Gaussians

- Each DEM is used to produce synthetic pixels value for each channel (i)
- For every DEM, synthetic and measured values are compared for each pixel (x)

$$fit(x) = \frac{1}{n_i} \sum_i |I_{measured}(x, i) - I_{synth}(i)|$$

- Synthetic emission is constant for a given temperature response, so they are saved and reused for efficiency
- The DEM with the lowest fit(x) approximates the plasma thermal distribution

Evaluation of method

This method is very similar to the methods used by Warren et al. [2008] and Aschwanden et al. [2013], but only one parameter is varied.

Advantages:

- Calculation is much more efficient - full AIA resolution temperature maps (4096 x 4096 pixels) can be obtained within $\sim$2 minutes

Disadvantages:

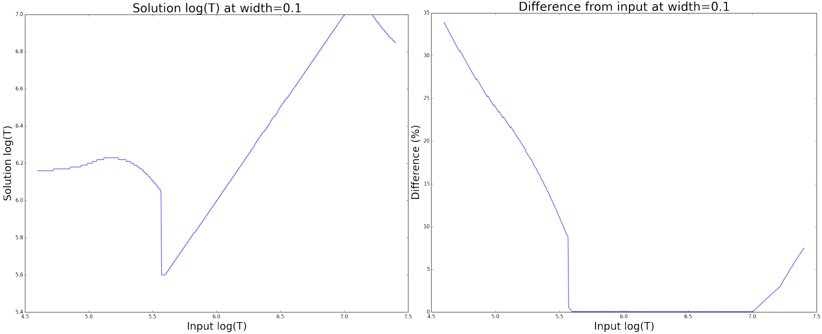
- May be less accurate than a full parameter search would be
- Does not provide a full DEM which could be used to estimate the emission measure

Validation

Model DEMs

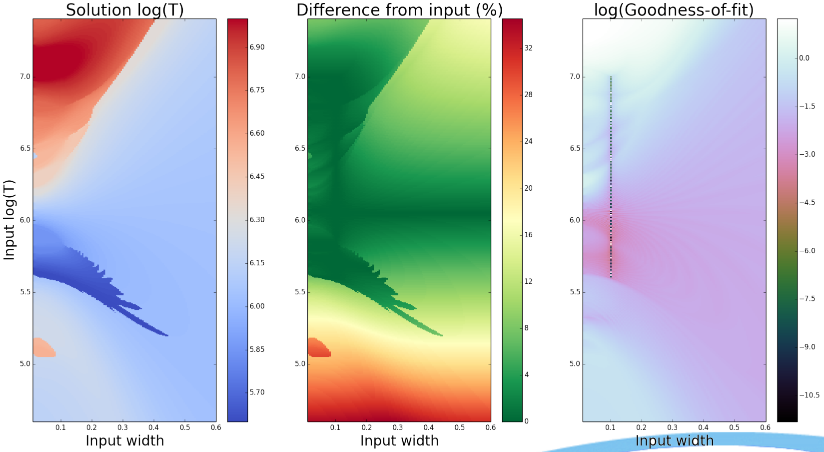
- Accuracy of DEM solutions will not necessarily be the same for all plasma DEMs
- The method was tested on synthetic AIA emission calculated from a variety of model Gaussian DEMs
- Model DEMs had:
  - peak temperatures between 4.6 and 7.4 in increments of 0.005
  - width between 0.01 and 0.6 in increments of 0.005
  - height values of 15, 25 and 35

Output



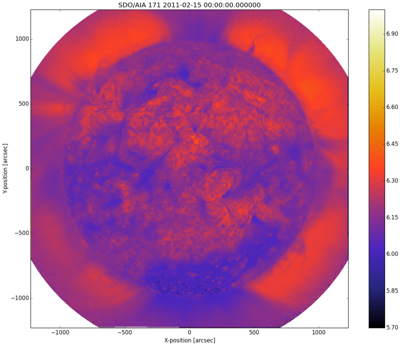
Solution log(T) at width=0.1
Solution log(T)
Input log(T)
Difference from input at width=0.1
Difference (%)
Input log(T)

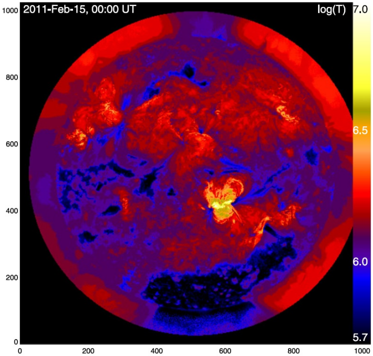
Output



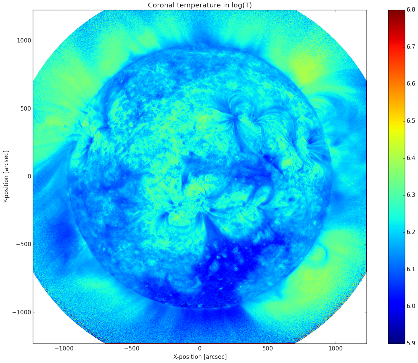
Solution log(T)
Difference from input (%)
log(Goodness-of-fit)
Input log(T)
Input width
Input width
Input width
7.0
6.5
6.0
5.5
5.0
0.1
0.2
0.3
0.4
0.5
0.6
6.90
6.75
6.60
6.45
6.30
6.15
6.00
5.85
5.70
32
28
24
20
16
12
8
4
0
0.0
−1.5
−3.0
−4.5
−6.0
−7.5
−9.0
−10.5

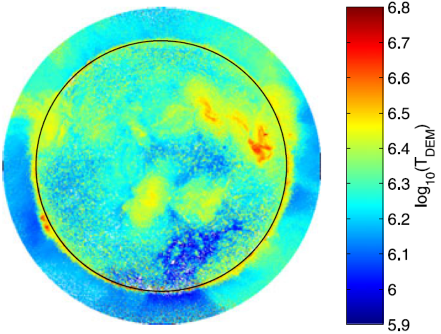
Comparison to Aschwanden et al. [2013]



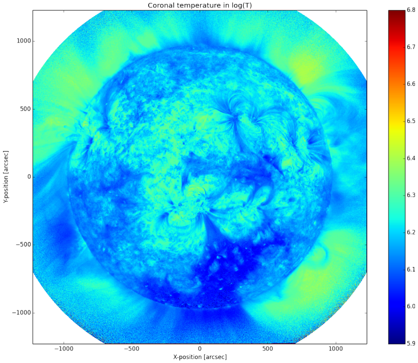


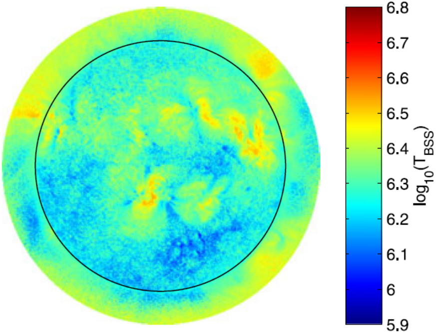
Comparison to Dudok de Wit et al. [2012] (DEM)





Comparison to Dudok de Wit et al. [2012] (BSS)





Switching from IDL to Python

Translating the code

- Didn't take very long
- Python code is similar length to IDL version but with more functionality
- IDL routines can still be called if necessary, and data can be loaded from IDL .sav files

How the code has improved

- TemperatureMap class is easier and more intuitive than everything being in functions, and has access to Map functionality:
  - easily cropped using Map.submap()
  - easily displayed with Map.plot()
- SunPy's access to VSO and HEK make it easy to search for events and regions of interest
- Coordinate information from HEK also allows easy 'tracking' on the solar disk

Other research using SunPy

Recent papers

- Preflare active region dynamics [Korsos et al., 2015]
- Quasi-periodic pulsations in flares [Inglis et al., 2015]
- Coronal Fourier power spectra [Ireland et al., 2015]
- Local correlation tracking [Campos Rozo and Vargas Dominguez, 2014]
- https://www.zotero.org/groups/sunpy_-_python_for_solar_physicists

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