Using SunPy for your research - Coronal temperature maps

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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

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Temperature maps

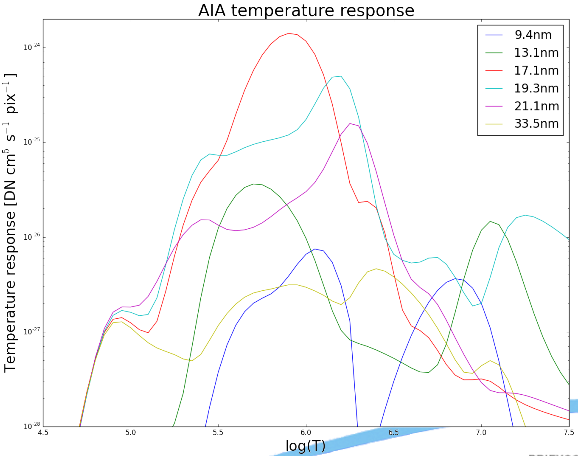
Background and theory

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:

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

- This is an ill-posed problem and there exists no unique solution without imposing physical constraints [Judge et al., 1997]
- Multiple schemes have been designed to invert this equation and infer the DEM by applying various physical assumptions

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 [Warren2008] and [Aschwanden2013], 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 ~2 minutes

Disadvantages:

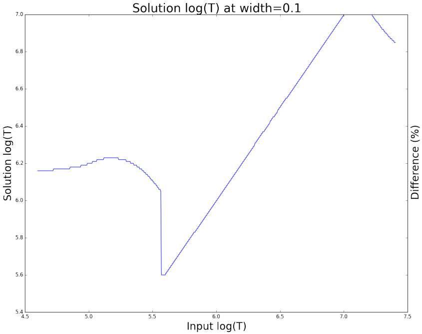
- May be less accurate than a full parameter search would be
- Does not provide a full DEM which could be used to estimate the emission measure

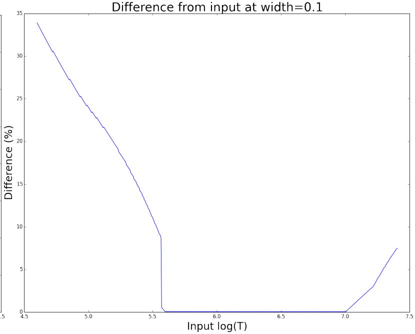
Validation

Model DEMs

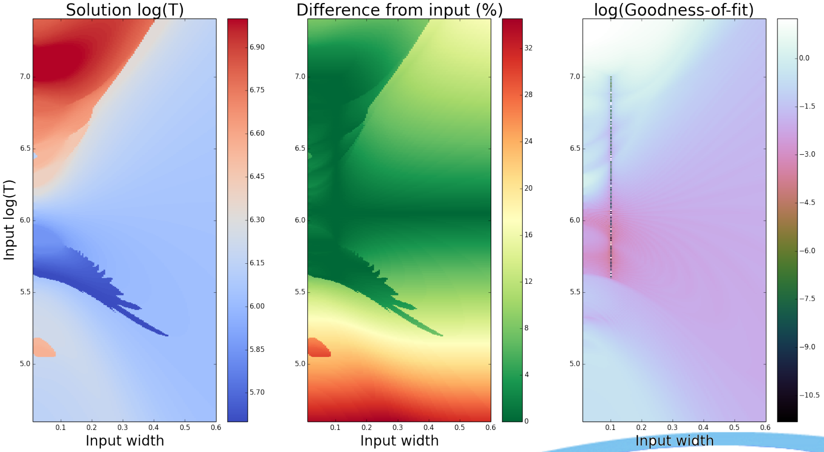
- Accuracy of DEM solutions will not necessarily be the same for all plasma DEMs
- The method was tested on synthetic AIA emission calculated from a variety of model Gaussian DEMs
- Model DEMs had:
  - peak temperatures between 4.6 and 7.4 in increments of 0.005
  - width between 0.01 and 0.6 in increments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

Output

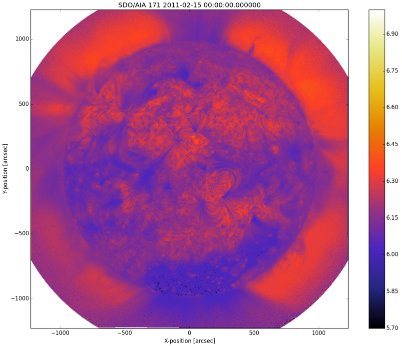

Solution log(T) at width=0.1
Solution log(T)
Input log(T)
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
4.5
5.0
5.5
6.0
6.5
7.0
7.5

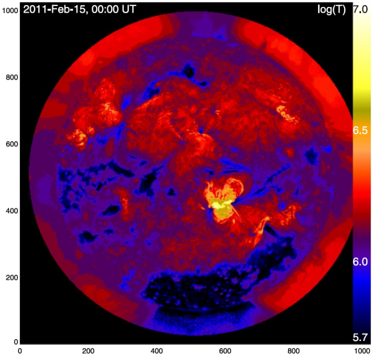

Difference from input at width=0.1
Difference (%)
Input log(T)
35
30
25
20
15
10
5
0
4.5
5.0
5.5
6.0
6.5
7.0
7.5

Output

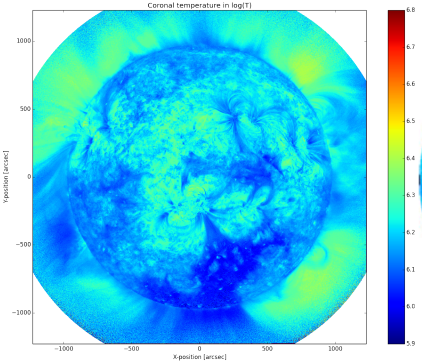

Solution log(T)
Difference from input (%)
log(Goodness-of-fit)
Input log(T)
7.0
6.5
6.0
5.5
5.0
0.1
0.2
0.3
0.4
0.5
0.6
Input width
6.90
6.75
6.60
6.45
6.30
6.15
6.00
5.85
5.70
32
28
24
20
16
12
8
4
0
0.0
−1.5
−3.0
−4.5
−6.0
−7.5
−9.0
−10.5

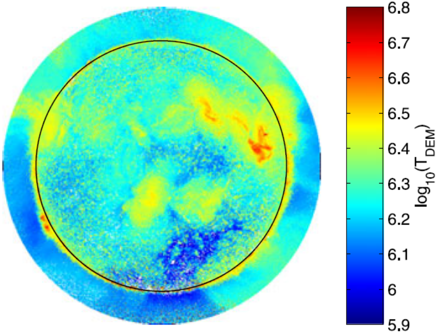
Comparison to Aschwanden et al. [2013]



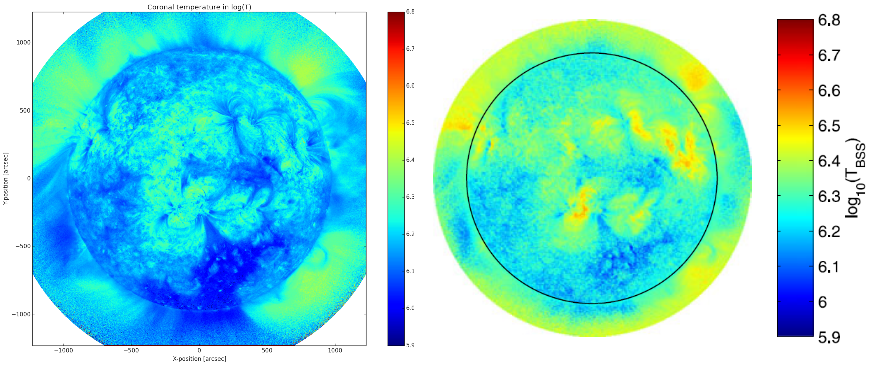


Comparison to Dudok de Wit et al. [2012] (DEM)





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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