Temperature Reconstruction from SDO:AIA Filter Images

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Abstract

Spectral lines are emitted by excited atoms in a plasma due to a variety of temperature sensitive processes. Because different lines peak in intensity at different temperatures, it is possible to determine the temperature of a region on the sun by taking the ratios of various line intensities. In this work, images of the sun taken in 6 wavelengths by the AIA instrument on the SDO spacecraft were compared to emissivity curves as a function of temperature. Two modes were employed: 'Isothermal' mode, in which a single temperature was found for each pixel which best matched the spectrum in that pixel, generating a single image; and 'DEM' mode, in which an image was generated for each temperature model, indicating how strongly each pixel matched that temperature model. The program was applied to AIA images of the full disk from 04/11/2016, 23:59:50, in both modes, and two active regions were found and examined: one on the limb, and one near disk center.

The Atmospheric Imaging Assembly (AIA)

Instrumentation

The Atmospheric Imaging Assembly (AIA) is an instrument on the Solar Dynamics Observatory (SDO). It consists of four, 20cm normal-incidence telescopes, which observe a 41 arcmin field of view in 10 EUV and UV channels, with 0.6-arcsec pixels and a 4096x4096 CCD. [2] This is accomplished by rotating a filter wheel located in front of the focal plane of

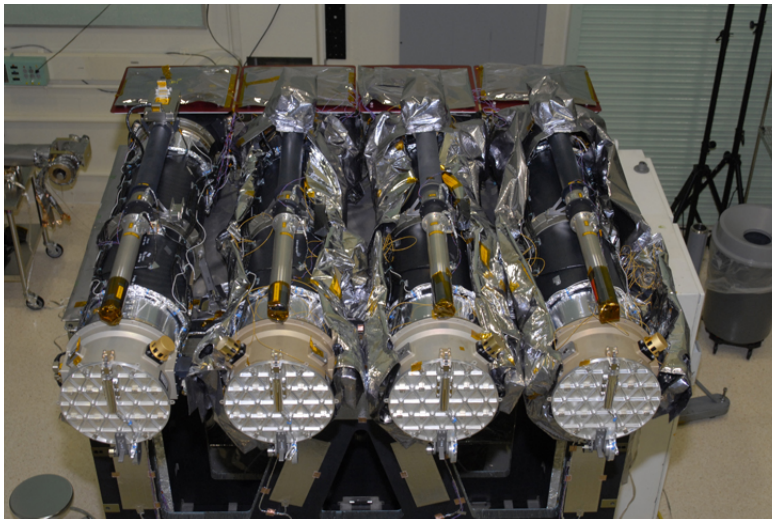
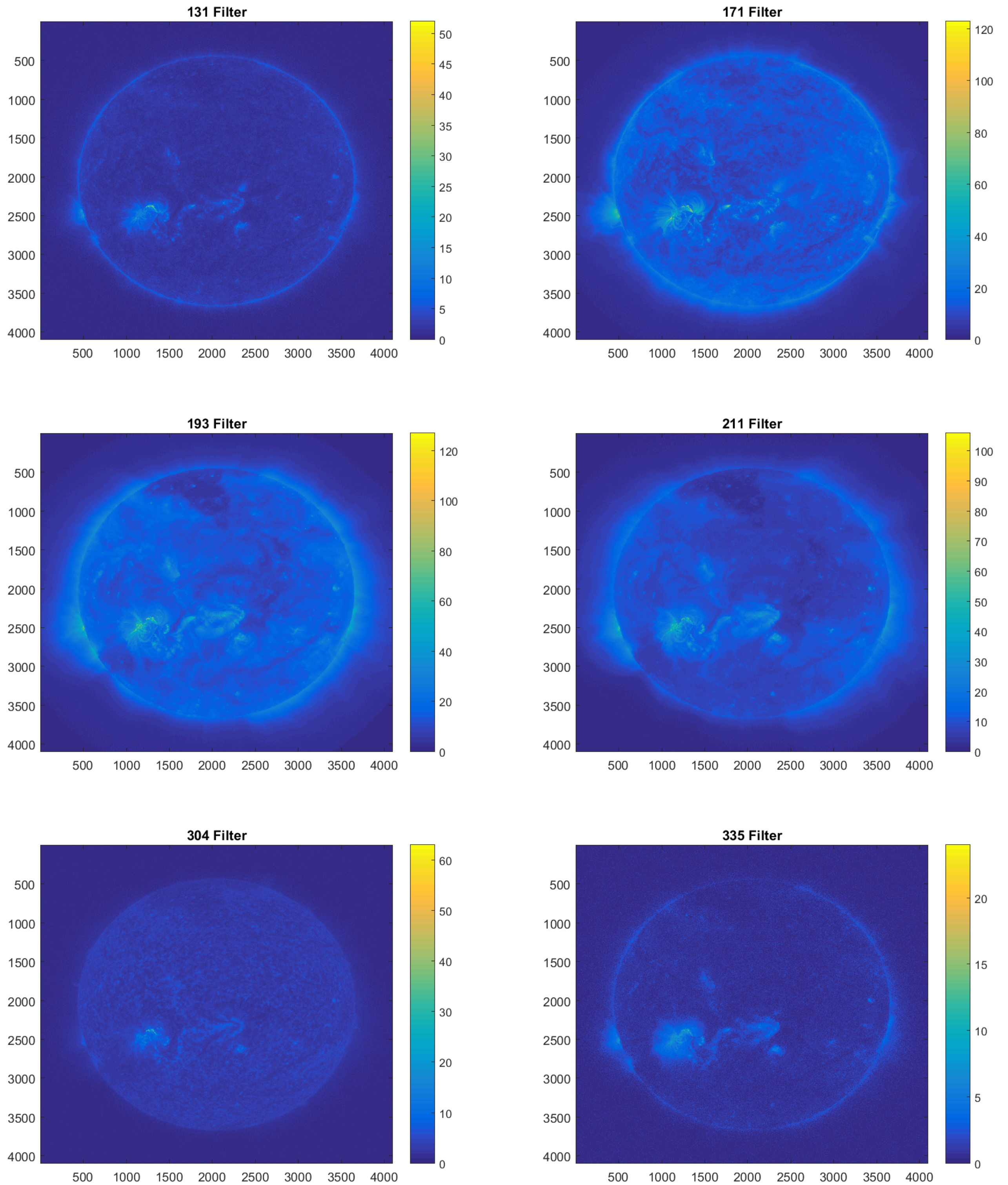


Figure 1: The AIA instrument aboard the SDO spacecraft

each telescope. Six of these channels observe lines of ionized iron, and one observes ionized Helium. They are Fe XVIII (94 Å), Fe VIII, XXI (131 Å), Fe IX (171 Å), Fe XII, XXIV (193 Å), Fe XIV (211 Å), He II (304 Å), and Fe XVI (335 Å), and each filter has a FWHM of about 10 Å. The instrument is capable of taking images in all channels once every 10-12 seconds, with a typical exposure time of 0.5 - 3 seconds per image. This high cadence allows for the study of rapidly evolving events such as solar flares and coronal mass ejections. These channels were chosen because they coincide with strong emission lines formed at different temperatures ranging from 500,000K to 20,000,000K.

Images from each of these filters can be seen in Figure 2. These images are “Level 1.5” data. Level 1 means that the images have been corrected for inherent instrumental effects. The bias and dark frames have been subtracted, and has been corrected with the instrument flat field. Level 1.5 data has additionally been rotated/translated such that a given pixel in any image will always be located at the same point on the solar disk, regardless of which filter/telescope the image came from. Of course, as the sun rotates, a location on the solar disk will not correspond to the same part of the surface, and the image would have to be “de-rotated” to account for that if images taken at different times were to be compared.

Figure 2: Images of the Sun in 6 wavelength bands from the AIA instrument aboard SBO. Images are scaled to their max value for visibility. Timestamp: 04/11/2016, 23:59:50



Filter Temperature Response Functions [1]

For each channel, the intensity in a given pixel is given by

$$p_i(x) = \int_0^\infty d\lambda \int_{pixel} d\theta \; R_i(\lambda) I(\lambda, \theta)$$

where $R_i(\lambda)$ is the wavelength response function of the i-th channel of the telescope. This can be recast in terms of temperature as

$$p_i(x) = \int_0^\infty dT \; K_i(T) DEM(T, x)$$

where $DEM(T, x)$ is the differential emission function, and represents the actual emission at a given temperature.

$K_i(T)$ is the temperature response function of the instrument, which is given by

$$K_i(T) = \int_0^\infty d\lambda \; G(\lambda, T) R_i(\lambda)$$

where $G(\lambda, T)$ is the plasma emissivity.

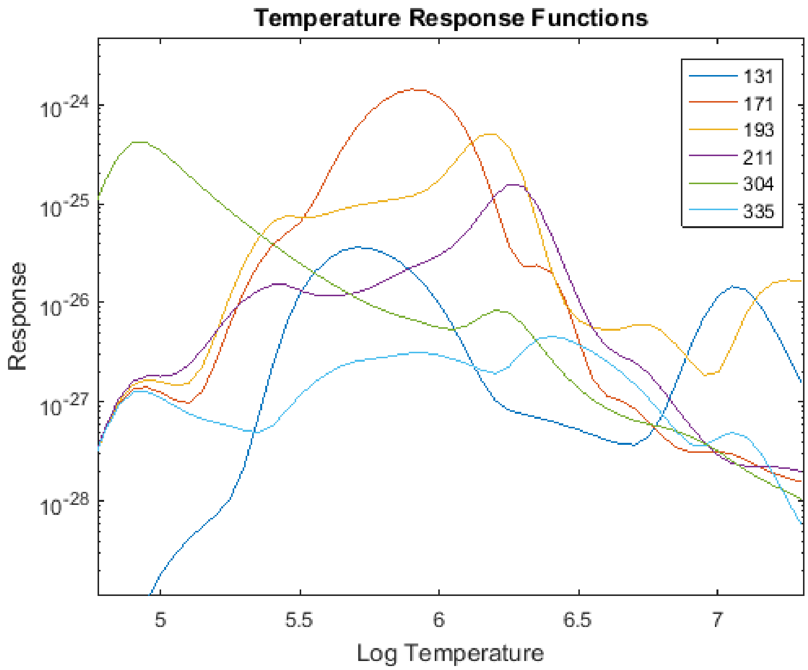
The temperature response functions represent the amount of incident radiation that the instrument would read as a function of temperature of the emitting plasma, taking into account the differential sensitivity of the instrument as a function of wavelength, R, and the actual temperature dependent emissivity of the plasma, G. The emissivity is a description of the plasma and atomic physics that govern how material at a given temperature emits radiation. This is determined by a combination of factors, including the relative abundance of various elements in the solar atmosphere, ionization equilibrium states as a function of temperature, and the oscillator strengths of the emission lines known to lie within the filter passbands. This information was drawn from the CHIANTI database, and was used to create the temperature response functions shown in Figure 3(a). This was done by Boerner (2011), before the launch of SDO, and sent to us in a personal communication from Steven Cranmer. Note that data was provided for a broader range of temperatures than the AIA instrument is actually sensitive to, and so it was truncated above and below at 200MK and 50,000K, respectively. Boerner has since updated the response function with in-flight calibrations [1], but that data was not available in tabulated form for the purposes of this work.

Methodology

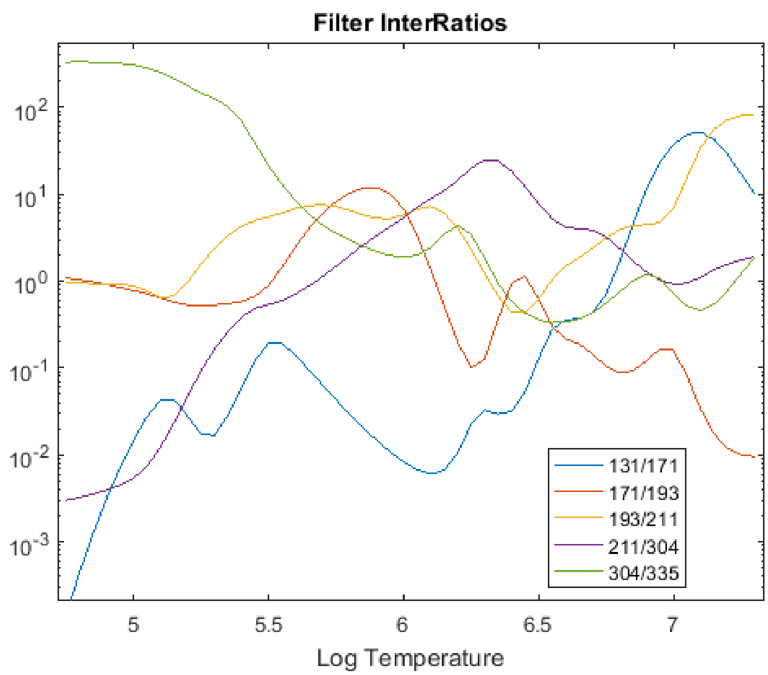
Temperature Discrimination

A given parcel of gas will emit light in different wave bands with an intensity that is modulated by the local gas density. The intensity in a single channel is thus insufficient for determining temperature. In order to determine the temperature in a given pixel, the ratios of the intensities in several filters must be examined. For this work, six channels were used, and therefore there are 15 possible ratios to consider. For simplicity and speed, only the ratios of adjacent-in-wavelength filters were examined. Figure 3(b) shows the ratios of adjacent temperature response functions. For every possible temperature, there are thus five model parameters that describe the expected relative intensities of each of the six images taken at different wavelengths. The ratios of the raw images from each filter were calculated for every pixel of the images, such that a new object was created where each pixel was assigned the five ratio parameters which could them be compared to the temperature models.

Figure 3: Analysis of each filter's temperature response functions.



(a) Temperature Response function for each wavelength



(b) Ratios between adjacent filters

Model Matching

For each pixel, the line ratios were compared to each of the temperature models using the following statistic:

$$S(T) = \frac{1}{N}\sum_{n}^{N}\left(1 - \frac{(P_n - R(T)_n)^2}{P_n^2 + R(T)_n^2}\right)$$

where $P_n = \frac{I(\lambda_n)}{I(\lambda_{n+1})}$ are the line ratios of the pixel and $R(T)_n$ are the same ratios for a given temperature model. This statistic is bounded such that, if the pixel matches a model perfectly, $S = 1$, and if it is a poor match, $S \to 0$. If n line ratios were to match perfectly, but all the others were extremely poor, we would get $S = n/N$. The statistic therefore gives a quantitative measure of how closely the pixel matches the expected spectrum for a particular temperature.

Modes of Visualization

Once the values of S has been calculated for each pixel for each temperature model, there are two ways of looking at the result.

Isothermal

Figure 4 shows a single image, where the color of each pixel represents the model which had the highest value of S. This represents the temperature of the pixel if we assumed that there were only one temperature of gas contained within the pixel. Of course, this is a poor assumption, which motivates another method of investigation.

Differential Emission Measure

In this mode, a picture is made for each of the temperature models, and the value of S for every pixel for that temperature is shown. In this mode, we can examine the sun in temperature space, allowing us to see that many of the features of the sun actually contain plasma at multiple temperatures. We can also examine in more detail how the temperature of different features varies across their spatial extent. Examples of DEM images of the full disk can be seen in Figure 5.

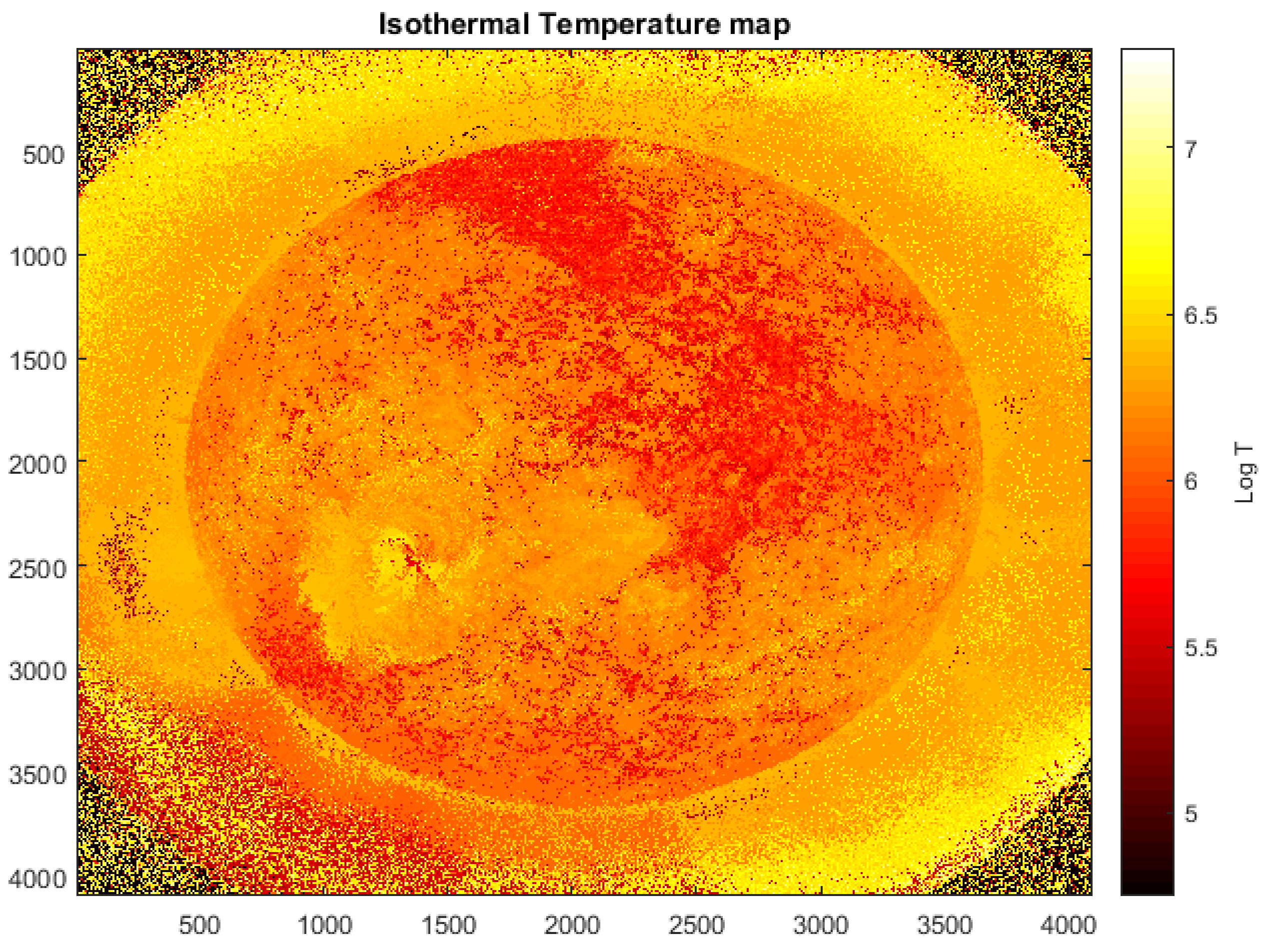
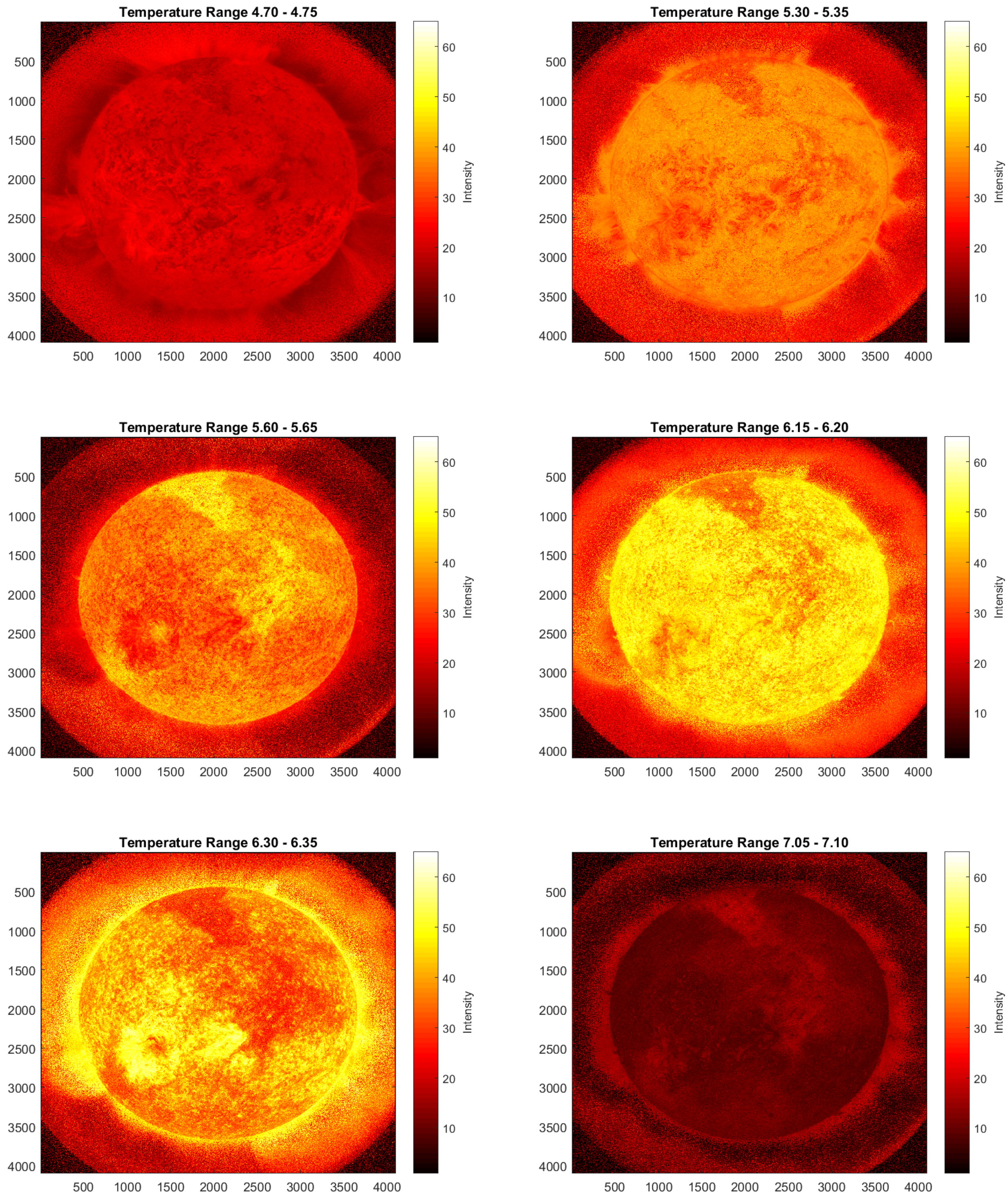


Figure 4: The best matching temperature for each pixel on the full solar disk.

Figure 5: A selection of images showing how different regions of the Sun match various temperature models. They are on an absolute scaling of 64*S. Temperatures are log space.



Analysis of Features

Full disk

Figure 5 shows several DEM images of the entire solar disk. There are a few features of note here. The chomosphere shows up strongly in the 1.5 MK (logT = 6.15) image, and there is a clearly evident coronal hole that more closely matches a temperature of about 0.5 MK (5.6). At about 200,000K (5.3) its easy to see gas flowing along magnetic field lines off the solar limb. At 1.5MK (6.15) you start to see some gas in the lower corona, and at about 2MK (6.3) coronal gas is dominant. There is almost no gas that has a temperature near or above 10MK (7).

Sunspot

There is one primary active region in these images, near the bottom left of the image. Figures 6 and 7 show the original AIA images and the a selection of the computed DEM slices, respectively. The gas inside the coronal loops seems to be mostly around 1MK (6.05)m but with some clear indication of gas at around 200,000K (5.35). I was interested to discover that the tops of the loops seem to be much hotter,and strongly match gas of around 2.2MK (6.35). The surrounding gas is just a bit cooler than that, between 1.25-1.75MK (not pictured) so it seems that the loops are definitely heating their surroundings. There is also a small feature that shows up best at around 10MK (8), that is likely to be a twisted magnetic flux tube or rope. Surrounding that rope is gas at about 300,000K, similar to the temperature at the base of some of the coronal loops.

Off Limb Activity

Just to the left of the active region, off the limb, there is another mildly active region. See Figures 8 and 9. The bottom right image of Figure 9 shows the isothermal mode image. Notice that it is not particularly informative. The DEM method really shows its value here.

Here, the the structure of the field lines above the region can be seen most easily at around 200,000K (5.35), but with some significantly cooler components at around 15,000K (4.15), and some hotter components at 2.5MK (6.4). The gas surrounding the loops shows up most clearly at around 2MK (6.3).

Conclusion

AIA images of the sun were analyzed to determine the temperature of various solar features by comparing the ratios of spectral line intensities to those expected from models of stellar plasma at a range of temperatures. The method used here is a relatively simple algorithm that requires a lot of computation. Other methods exist which are able to perform the inversion at much greater speeds and with higher accuracy. Still, this method is the most intuitive way of determining temperatures, and this project has provided good insight into the ranges of temperatures of various structures on the sun.

References

[1] P. F. Boerner, P. Testa, H. Warren, M. A. Weber, and C. J. Schrijver. Photometric and Thermal Cross-calibration of Solar EUV Instruments. *solphys*, 289:2377–2397, June 2014.

[2] J. R. Lemen, A. M. Title, D. J. Akin, P. F. Boerner, C. Chou, J. F. Drake, D. W. Duncan, C. G. Edwards, F. M. Friedlaender, G. F. Heyman, N. E. Hurlburt, N. L. Katz, G. D. Kushner, M. Levay, and et. al. The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). *solphys*, 275:17–40, January 2012.

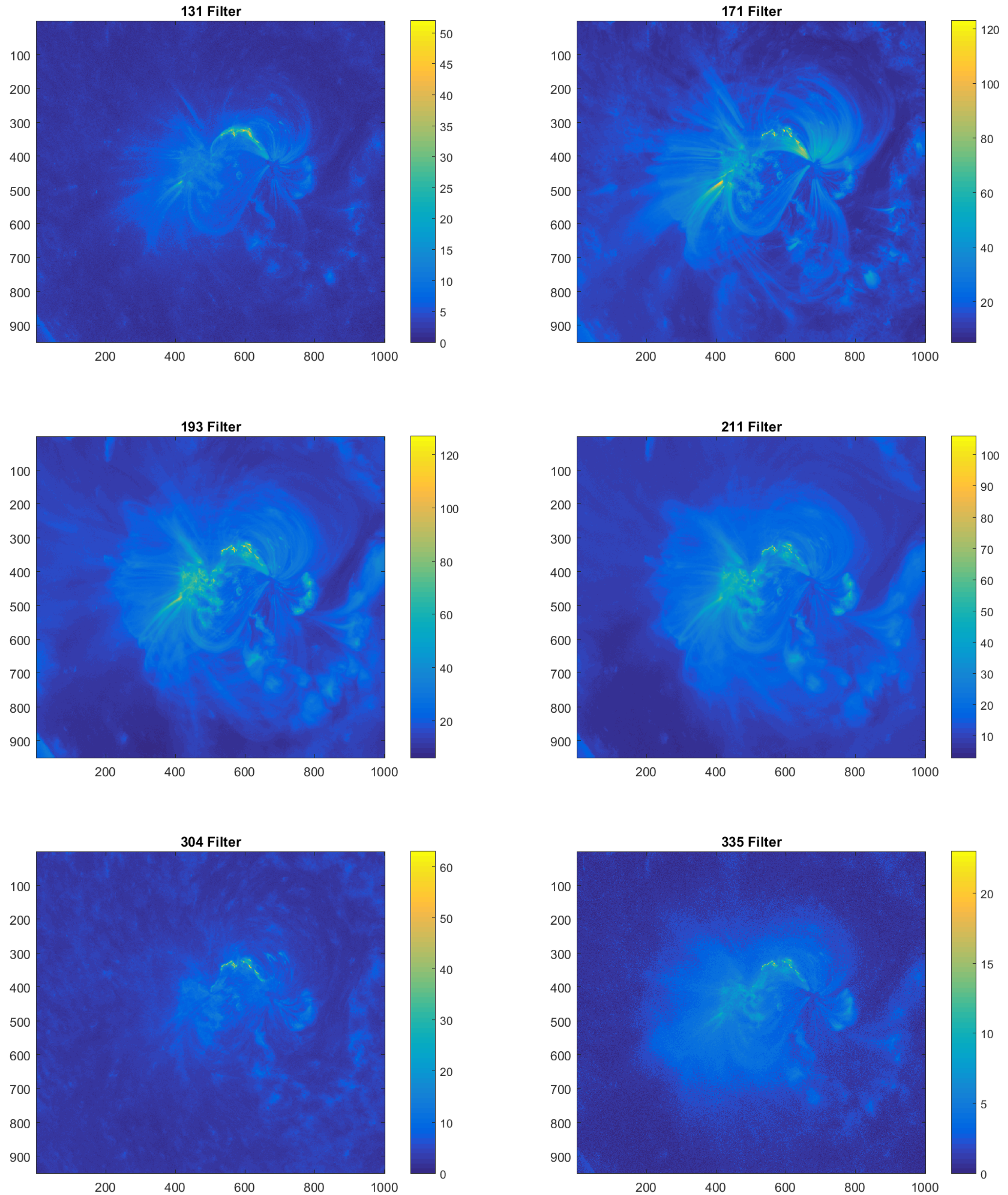


Figure 6: Images of a sunspot in 6 wavelength bands from the AIA instrument aboard SBO. Images are scaled to their max value for visibility.

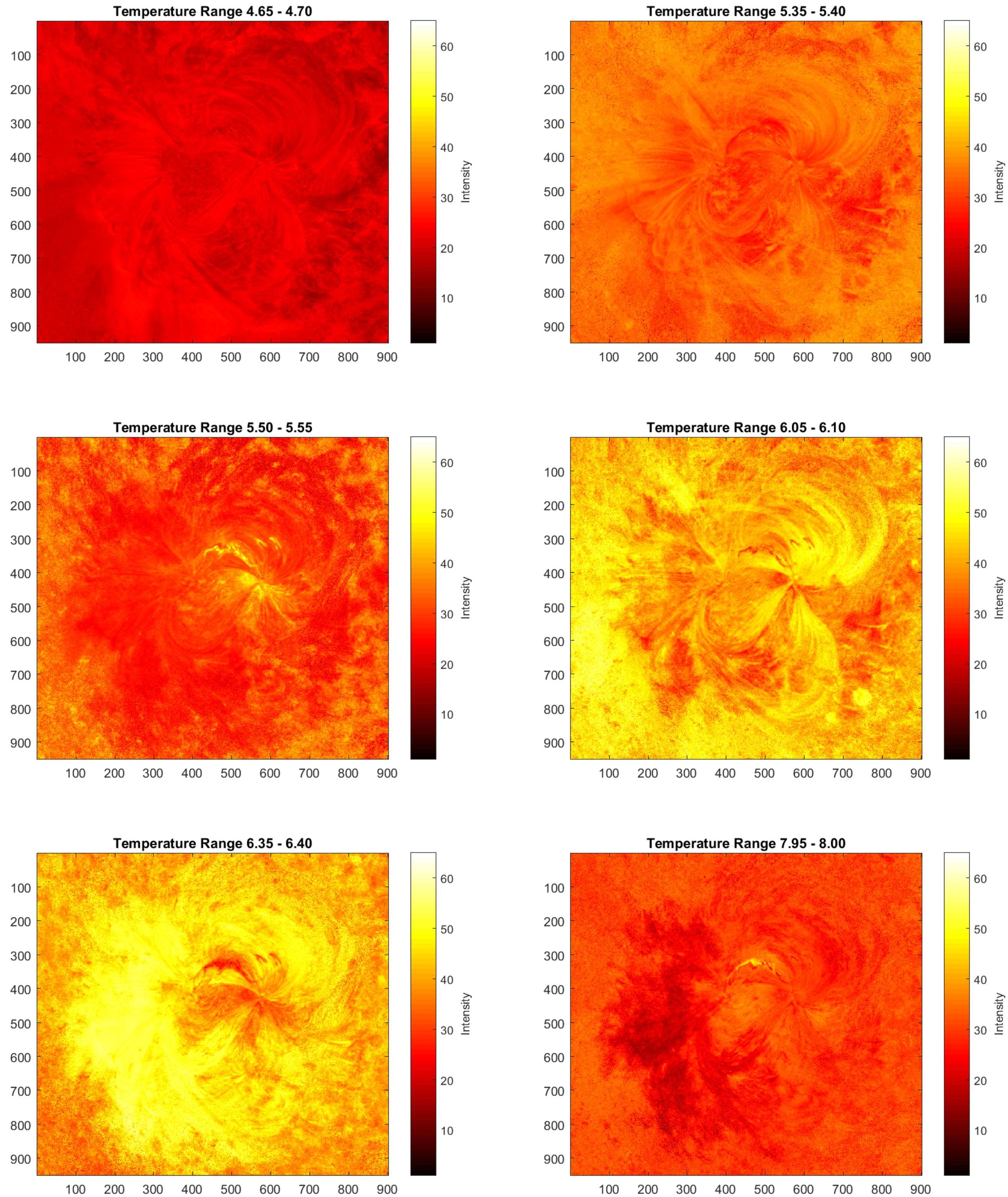


Figure 7: DEM Calculated in each pixel for the Sunspot. Images are on an absolute scaling of 64*S. Temperatures are in log space.

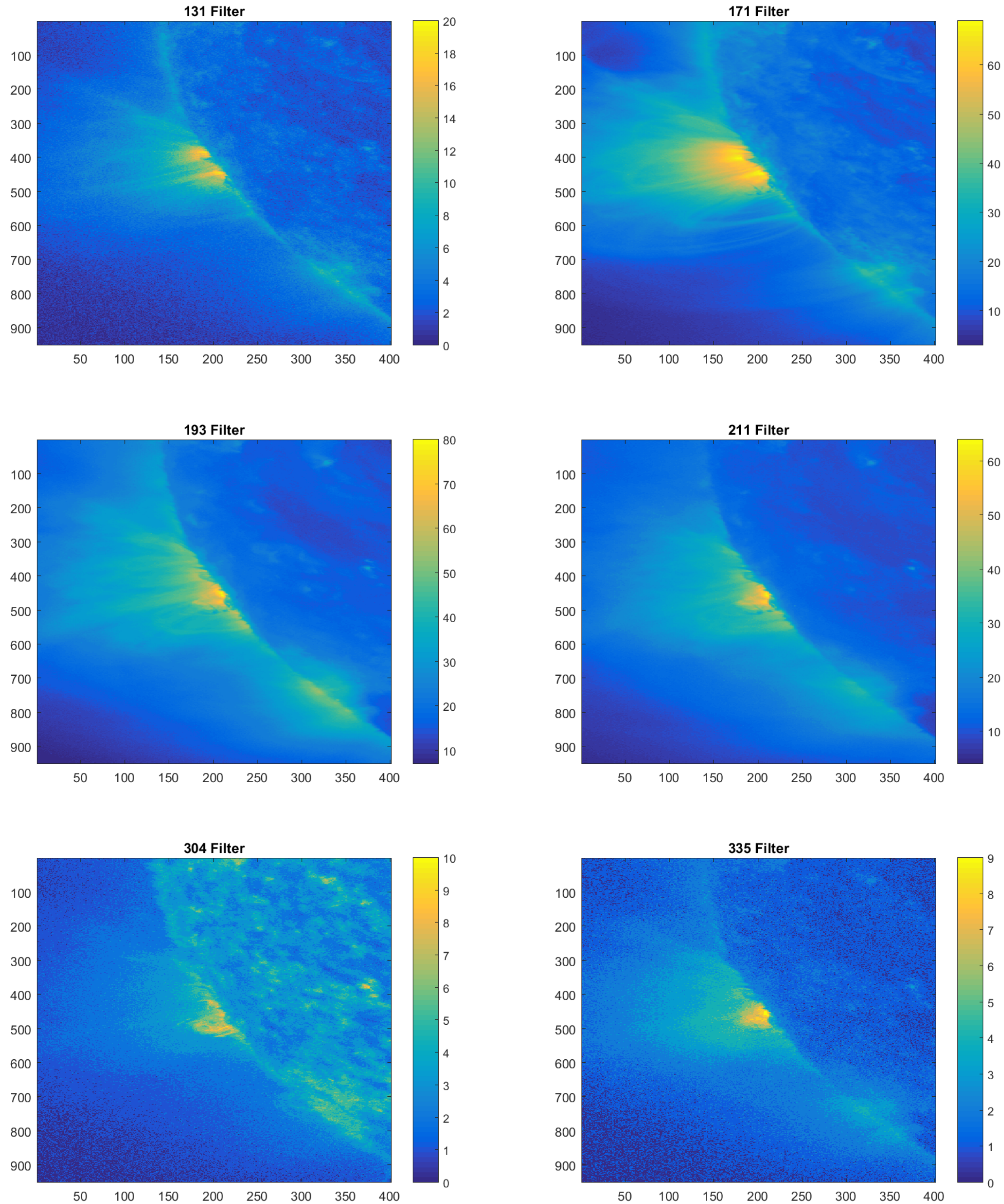


Figure 8: Images of an active region on the limb in 6 wavelength bands from the AIA instrument aboard SBO. Images are scaled to their max value for visibility.

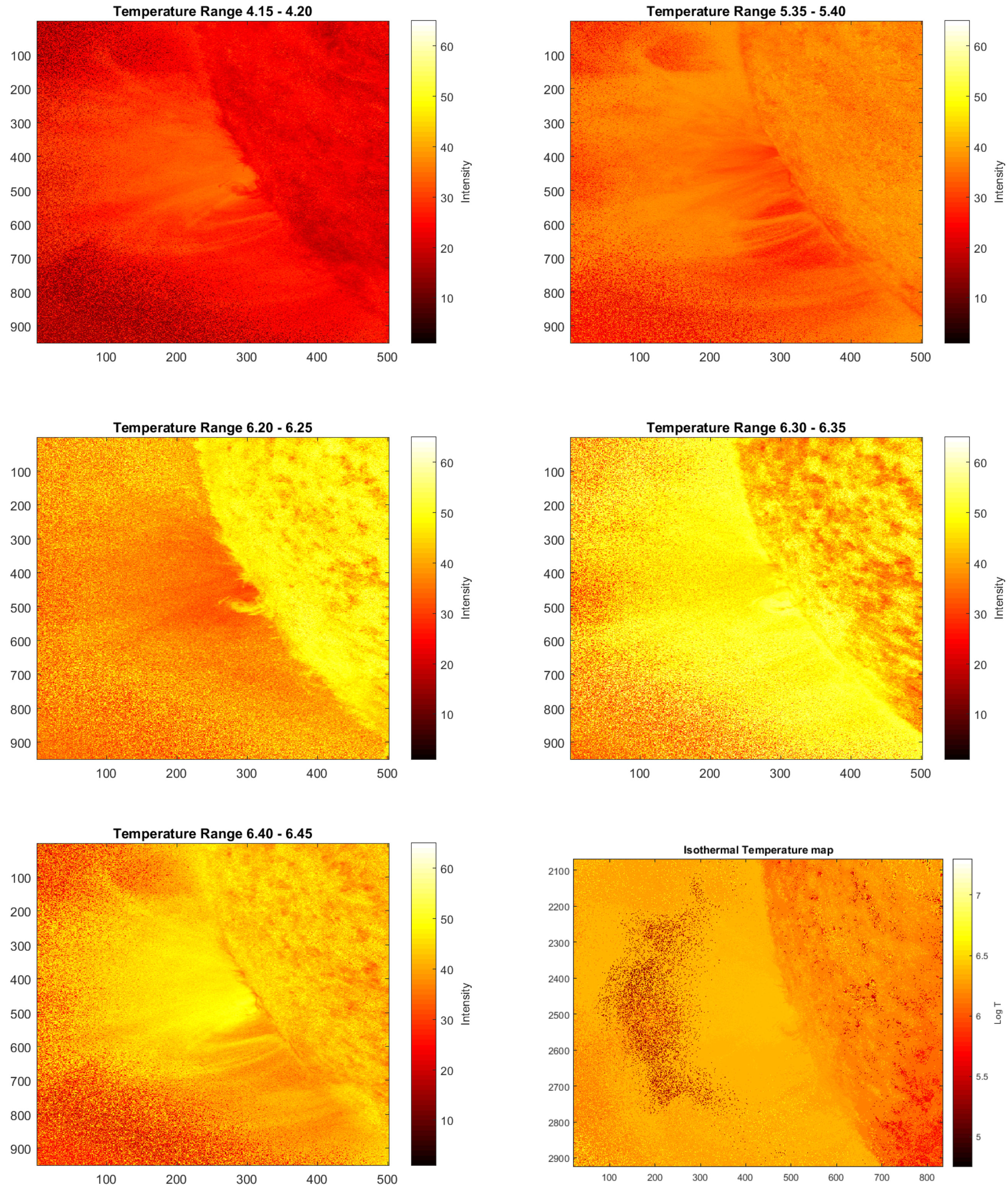


Figure 9: DEM Calculated in each pixel for the Active Region. They are on an absolute scaling of 64*S. The final image is the isothermal map, for comparison. Temperatures are in log space.