

This document contains the method for creating a temperature map for given chandra data.

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1 Temperature Maps

Before we can get to the temperature map (I promise I'm getting there...), we first have to actually use the data we got from the Weighted Voronoi Tessellation Algorithm; we need the pixels binning information.

1.1 Intermediate Step: Binning the Data

As this subsection's title suggests (look up), we must first go through the process of binning the data (our fits file) based on the recommendation of our WVT algorithm.

Instead of describing this in great detail, I will simply include an algorithm outlining the process and point the reader toward the python file (*Bin_data.py*) for more in depth analysis.

Data: WVT Bins and Fits File

Result: Binned PHA files

initialization -- > read in WVT bin information;

```
for bin do
    for pixel in bin do
        Create fits file for pixel;
        Generate PI/PHA file;
    end
    Combine Pixel's PI/PHA files;
end
```

Algorithm 1: Binning Algorithm

Clearly the implementation is a little more complicated and uses several *CIAO* tools such as *specextract* and *dmextract*. For more information on these wonderful tools, check out the *CIAO* website:

<http://cxc.harvard.edu/ciao/>

1.2 Generating Temperature Maps

We can now (FINALLY) use our combined pixels to generate a temperature map assuming you have already created a binning of some sort – I would suggest my Weighted Voronoi Tessellations algorithm¹. We will be employing *XSPEC*² for our modeling needs.

There are two main types of models:

- Additive: Source of emission i.e. producer of photons
- Multiplicative: Modifies spectrum i.e. acts on photons

Let's examine the major components of our model...

¹<https://github.com/crhea93/WVT>

²<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

1.2.1 zpow

zpow is a simple photon power law taking into account redshift. This is just classic blackbody goodness...

$$A(E) = K[E(1+z)]^{-\alpha} \quad (1)$$

where α is the dimensionless photon index of the power law, z is our objects redshift, and K is a normalization factor at $1keV$ in units of *photons/keV/cm²*. Photon indices of AGN are typically between $1.5 - 2.5$; this value needs to be determined from the literature.

Its worth noting that **zpow** is an additive model.

1.2.2 zphabs

zphabs is a model for hydrogen column density. Hydrogen column density is the "number of units of matter observed along a line of sight that has an area of observation"³. Basically, it takes into account all the stuff in between us and the object we are looking at (though it could be missing things such as a warm absorber like a galactic cluster which would require another model component – wabs in this instance). **zphabs** has a very simple equation:

$$M(E) = e^{-n_H \sigma(E(1+z))} \quad (2)$$

where n_H is the equivalent column density in $10^{22} \text{ atoms cm}^{-2}$, $\sigma(E)$ is the electron cross section – not Thompson – where z is the redshift.

All we specify are n_H and z .

zphabs is a multiplicative model

1.2.3 apec

apec is a wonderful model to handle the emission spectrum of a collisionally-drive optically-thin plasma (think AGN). Hence we use it to constrain the temperature of the object. For real details please check out the following website:

<http://www.atomdb.org/physics.php>

The most important thing to know is that it does in fact model thermal bremsstrahlung.

We need only specify T (*KeV*), as a guess, and z which is our redshift.

Apec is a multiplicative model

³https://en.wikiversity.org/wiki/Column_densities

1.2.4 χ^2 statistic

The χ^2 is defined as the following:

$$\chi^2 = \sum_{i=1}^{N_{el}} \left(\frac{x_i - \mu_i}{\sigma_i} \right)^2 \quad (3)$$

Where x_i is the data value at point i , σ_i is the corresponding error, and μ_i is the model value.

By calculating the χ^2 we can get a decent guess on how well our fit is. Optimally, our χ^2 will equal the number of **degrees of freedom**. We call this ratio the **Reduced Chi-Squared Statistic**. Hence we can very easily calculate the reduced chi-square if we know the number of degrees of freedom for a model:

$$\chi_{red}^2 = \frac{\chi^2}{N_{dof}} \quad (4)$$

So an optimal fit using a reduced χ^2 -statistic means $\chi_{red}^2 = 1$. Hence for our algorithm, we will try to hit a $\chi_{red}^2 = 1$... or as close as we can get ...

1.2.5 C-statistic

For low counts (in my opinion most X-ray observations are relatively starved in the photon department), we should instead use the *Cash-statistic*, *c-stat*, beacuse at low counts the variance approaches 0 and thus the χ^2 -statistic fails. We define the *c-stat* in the following manner:

$$c = 2 \sum_{i=1}^n s_i - N_i + N_i \ln(N_i/s_i) \quad (5)$$

where s is the number of counts according to the model, N_i is the number of observed counts, and n is the number of bins. In addition, we are able to calculate a “goodness of fit” for this statistic, C_R :

$$C_R = \frac{C}{n - p} \quad (6)$$

where p represents the number of free parameters.

In XSPEC we simply need to set `fit.statistic = 'cstat'`.

2 The Algorithm

Data: Binning Map

Result: Temperature Map and Graphic

Step 1: Bin data using *Bin_data.py* ;

Step 2: Run XSPEC Model on binned data by "simply"^a running *XSPEC.py* ;

Step 3: Create Visual Map in ParaView using *Cones_Paraview.py* ;

Algorithm 2: Temperature Map Pipeline

^aLike fitting a model is simple..... But seriously this is where a mistake could be made resulting in incorrect Temperature Profiles so play around with the model on a *single* observation to ensure it is a descent fit...

Oh yes, you need to have paraview installed. If you are a linux user, its a simple command `sudo apt-get install paraview`. ParaView is an amazing tool for data rendering. Take a look at the associated website: <https://www.paraview.org/>.

3 Dealing with Merged Data Set

How do we create temperature maps for merged data sets? As documented on the CIAO site ⁴, we are not able to create spectra from merged observations. Thus we have to be very careful in the creation of temperature maps for merged data sets.

The basic steps are as follows:

1. Merge Observations (Don't worry! We are just going to use the event file and exposure map).
2. Create a bin map using your favorite binning algorithm; I suggest using Weighted Voronoi Tessellations.
3. For each individual observation do the following:
 - (a) Create individual event files for each bin
 - (b) Extract spectrum for each bin
4. Run fitting software on each bin by fitting all datasets simultaneously

In following these steps, we are able to reconstruct a temperature map for a merged observation while avoiding the inherent drawbacks of merging data.

⁴http://cxc.harvard.edu/ciao/caveats/merged_events.html

Bibliographies

References