Specifications for Including the APEC Model in CSC 2.1

Michael McCollough, Aneta Siemiginowska, Doug Burke, and Dale Graessle

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I. **Introduction:** The APEC model is a thermal plasma model which is used to fit many astronomical objects in which spectral lines may be present. APEC was not included in the CSC 2.0 version of the catalog. We performed tests of the APEC modeling to assess the overall performance and possibility of including the APEC fit results in the catalog. Below is a description of the APEC issues and the XMM catalog results.

A. ***Two Parameter Fits:*** The APEC model was initially tested for a two parameter fit (nH and kT) with the abundances and redshift (z) fixed at 1.0 and 0.0 respectively. It was apparent that many of the fits were bad because of incorrect lines strengths (different abundances) and the line positions (redshift).

B. ***XMM Thermal Fits:*** Information about the XMM treatment of the thermal models can be found at:

https://www.cosmos.esa.int/

This page contains most of the XMM catalog related links. The **Spectral Fit Catalogs** can be found at http://xraygroup.astro.noa.gr/ . There are three basic catalogs containing information related to the thermal model.

i. 3XMM-DR7 spectral fit catalogue XMMFITCAT : This is the 3XMM catalog spectral fit catalog. The thermal model used in this catalog is MEKAL. The abundances and z are fixed (1 and 0 respectively). This catalog contains 156,926 sources.

ii. 3XMM-DR6 photo Z catalogue XMMPZCAT : This is a catalog created from derive photometric sources for all X-ray extra-galactic sources with reliable optical counterparts in the SDSS or Pan-STARRS catalogues (XMMPZCAT). This catalog contains 30,816 sources.

iii. 3XMM-DR6 spectral fit Z catalogue XMMFITCAT-Z : In this catalog the X-ray spectral fits were obtained by taking into account the photometric redshift information (XMMFITCAT-Z). For these sources the redshift is allowed to vary (but appears that a lower limit on redshift fits is set at 0). The abundances were not allowed to vary.

The catalog(s) paper can be found at https://arxiv.org/pdf/1411.

For the 4XMM-DR10 for 23,007 sources a website allows interactive fitting (APEC models are available). This can be found at http://xmm-catalog.irap.omp.

II. **APEC Spectral Fit Runs:** To determine performance of the full APEC parameter fit (nH, kT, Ab, z) we ran a large number of fits. We performed both 2 parameter and full parameter fits for CSC 2.0 sources which had over 1000 counts, for a total of 5311 sources. We found the following results:

A. **rstat:** The full parameter fits provide a much better description of data than the 2 parameter fits. This is apparent in Fig. 1 & 2 in which the rstat distribution is shown to be shifted lower for the 4-parameter fit compared to the 2-parameter fit. As an example, 86% (4559) of 4-parameter fits have a reduced statistic below 2 whereas it is only 55% (2938) for the 2-parameter fits.. Fig. 3 also demonstrates how the individual fits are improved and show that very few sources with a good 2 parameter fit had worse results in a full parameter fit.

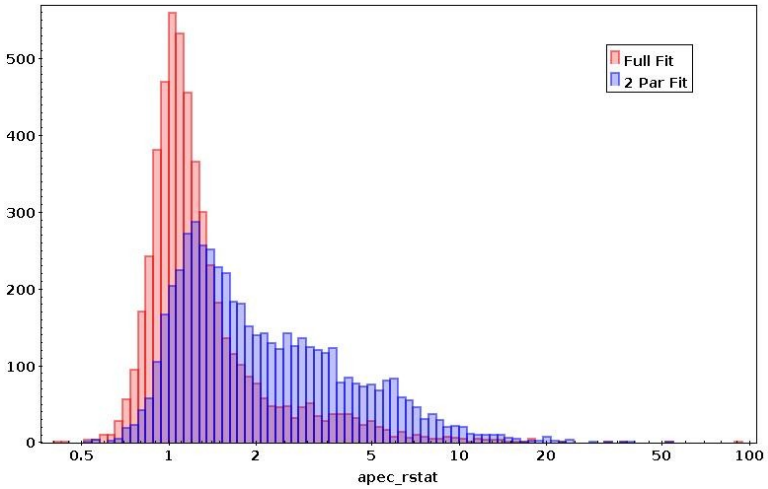

Fig. 1: The histogram plot of rstat with the values for the full parameter fit (red) and the 2 parameter fit (blue). Note the improvement for the full parameter fit with more source with rstat < 2.0.

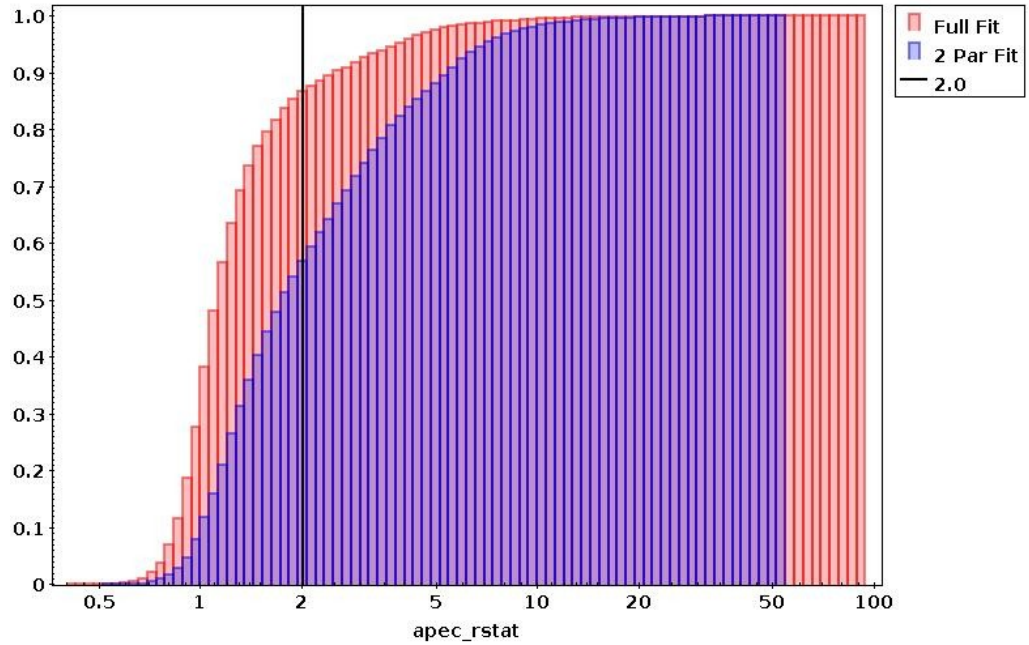

Fig. 2: A cumulative histogram distribution of rstat. With full parameter fits in red and 2 parameter fits in blue. The vertical line at 2.0 allows one to see what fraction of the sources of rstats below 2.0

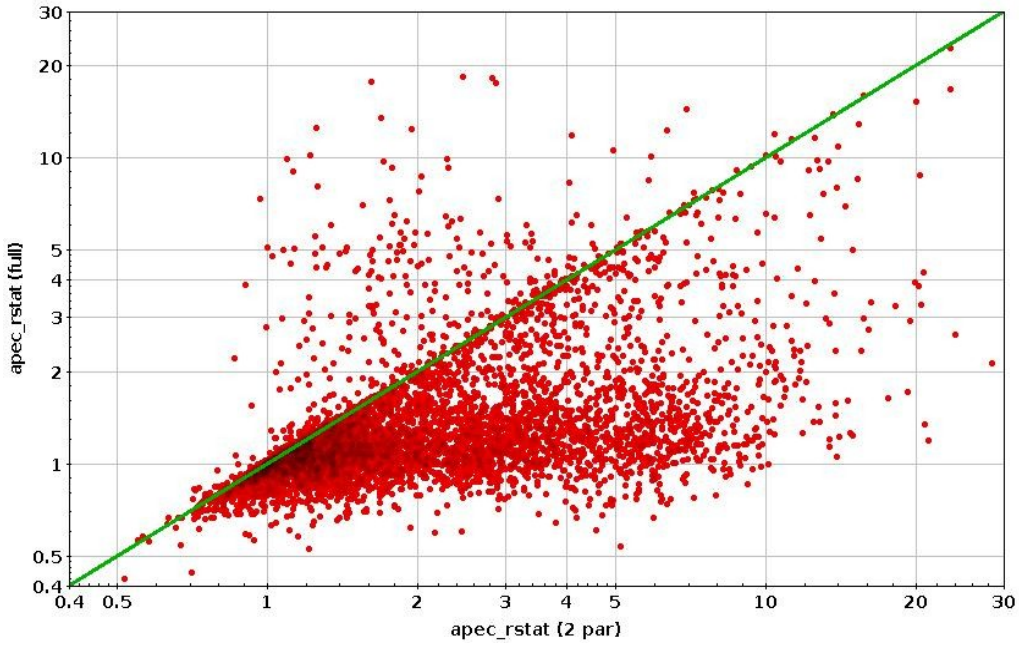

Fig. 3: A plot rstat (2 parameter) vs rstat (full parameter) for APEC fits. The green line is the one to one line. Note the improvement with the full parameter fits.

B. kT: The kT histogram for the two parameters has two peaks with the lower peak being mostly bad fits. The histogram for full parameter fits is more centrally peaked. For the fits with rstat < 2.0 the full parameter fits have a median value of 3.54 keV versus the higher value of 6.56 keV for only the two parameter fits. This can be seen in Fig. 4 & 5.

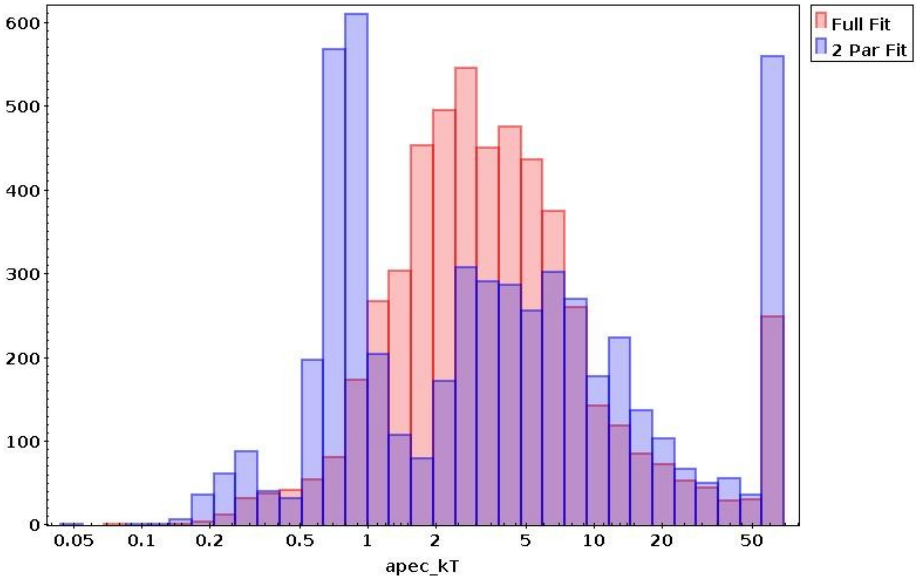

Fig. 4: A histogram plot of the kT distribution for the full (red) and 2 parameter (blue) fits. Note that 2 parameter has two peaked (excluding those at the high kT limit). The full parameter fits have a

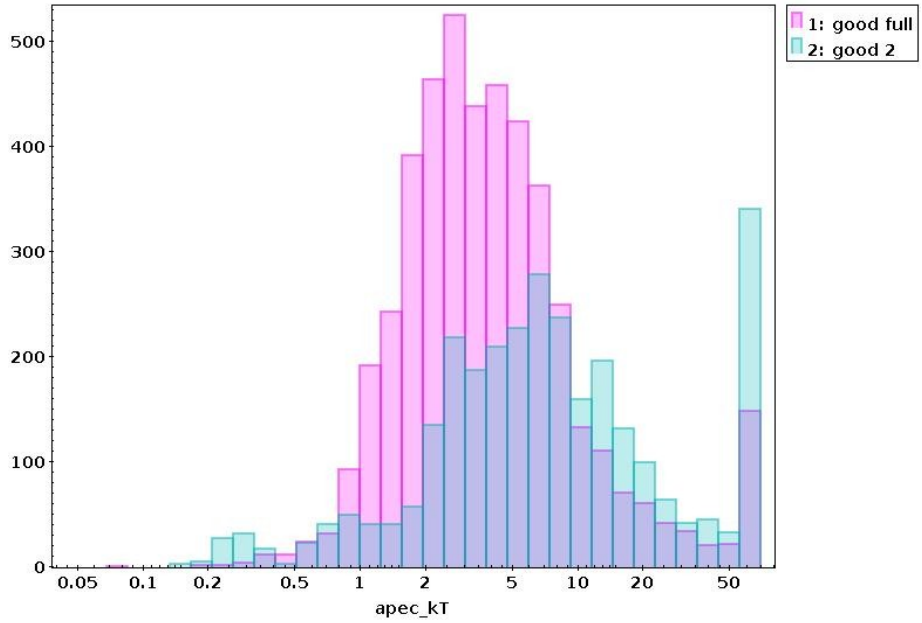

Fig. 5: The same plot as Fig. 4 for those fits with rstat < 2.0. Note that for the full parameter fits there are more good fits and peak at a lower kT.

C. nH: In Fig. 6 & 7 show the histograms of the nH distributions for the two types of fits. Overall they are similar with the 2 parameter fits having a peak of high nH value with poor fits.

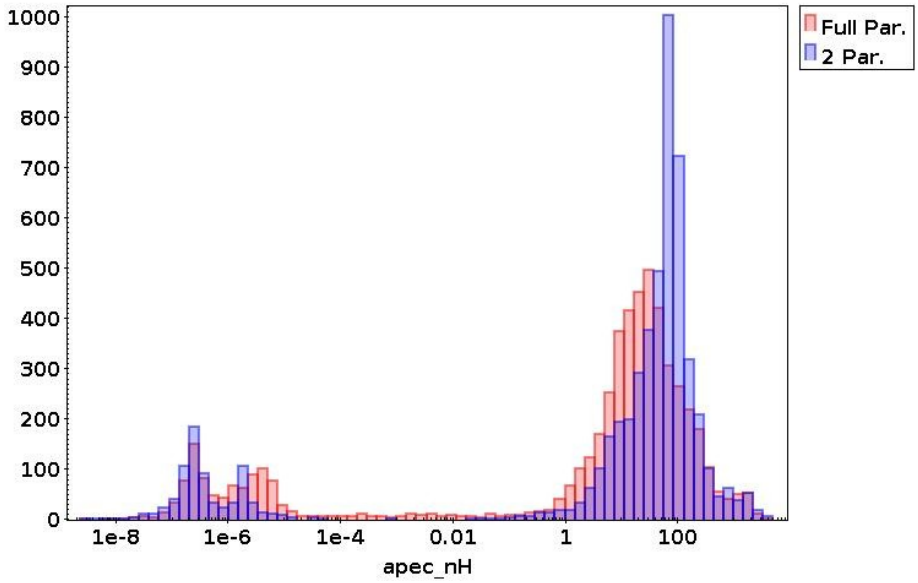

Fig. 6: This is a comparison of result nH values from the full (red) and 2 parameter (blue) fits. They are similar with the 2 parameter showing a tendency to be driven to slightly lower and higher values.

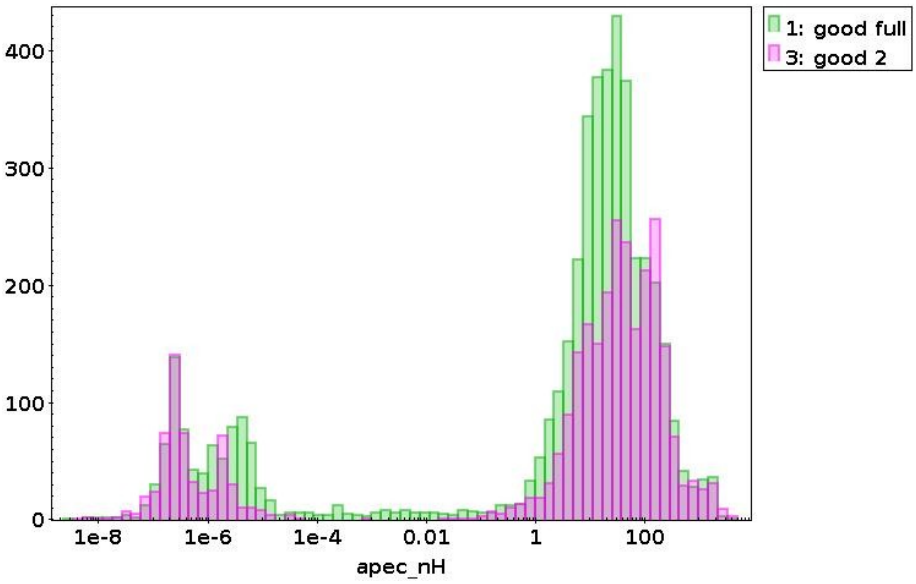

Fig. 7: The nH distributions shown in Fig. 6 for fits with rstat < 2.0. This shows the same trends as seen in all of the fits.

D. Abundances: The abundances from the full parameter fits show two peaks (not considering the values pegged at the 5.0 upper limit). The lower broad peak at around 10^{-7} corresponds to sources which do not show lines (described by just a continuum model) and a significant peak at 0.225 for the majority of sources (Fig. 8).

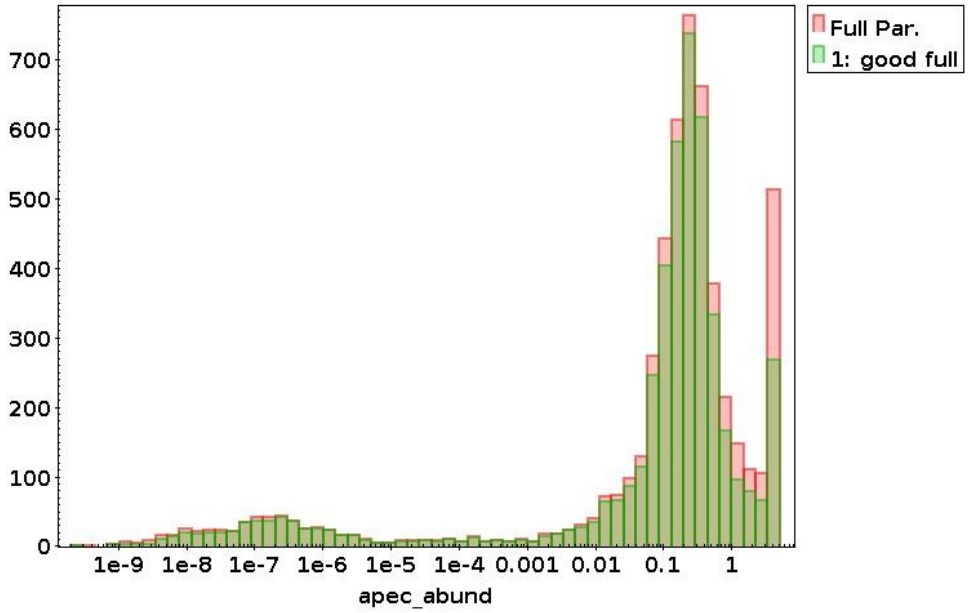

Fig. 8: A histogram plot of the abundance distribution from the full parameter APEC fits. The red is all and the green is are those that have rstat < 2.0.

E. Redshift: The redshift distribution has a narrow peak at a redshift of ~0.04 with a very rapid drop off by 1.0 which can be seen in Fig. 9. There are a few sources which show a higher redshift which may or may not be physical. There are also sources with negative redshift values. Many, but not all, are consistent (within the errors) of being zero. We did test runs where there was a soft limit of 0 on the redshift. But these appear to create a bias in the temperatures.

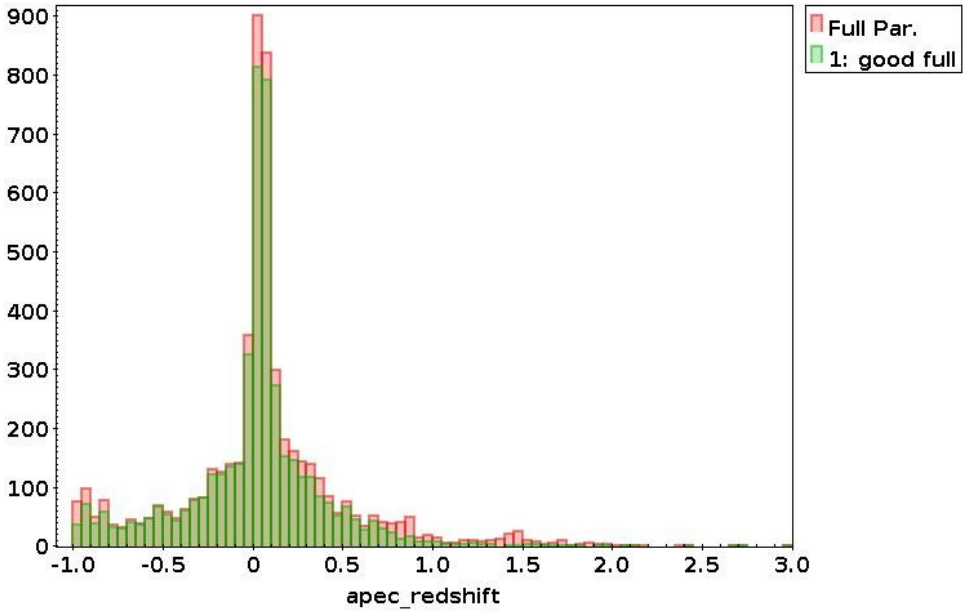

Fig. 9: A histogram plot of the redshifts from the full parameter APEC fits. The red is all the fits and the green are those that have rstat < 2.0.

F. Negative Redshifts: About 20% (1041/5311) of the APEC fits are good (rstat < 2.0) with an upper redshift limit of that is negative. The majority (54%, 560/1041) of these fall into two categories of low abundances (< 0.05) or high temperature (kT > 7.0 keV). In these cases the lines in the model are either very weak or not present. That indicates that there are no heavy elements present or that the temperature is so high that any heavy elements are ionized to the extent that no line emission would be present in the X-ray spectrum. In these cases the lines are at the noise level and hence their fitting (via the abundance and temperature) has no physical meaning. In the case with higher abundances and lower temperature many spectra were a combination of weak lines and lines which were not compatible with the APEC CEI model. An example is a spectrum with lines at lower temperatures (~2-3 keV) along with Fe Kα. (~6.4 keV) which may indicate a more complex model is needed. See Fig. 10 for an example of this type of spectrum.

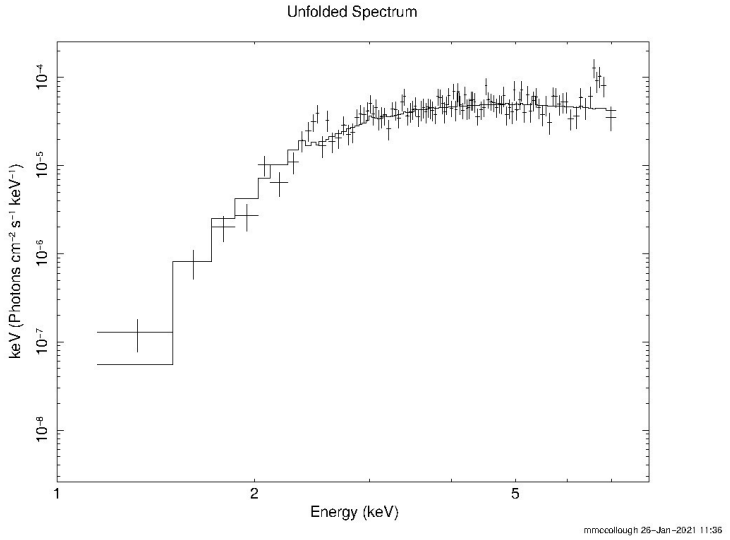

Fig. 10: This is a source (obsid: 13440, obi: 0, region: 0753) which has a negative z (-0.51) and a rstat of 1.0. One see evidence of line emission between 2-3 keV and line emission from Fe lines (~6.4 keV). From a CEI model such as APEC one can not produce the lower energy lines with the Fe lines from a single component.

G. Individual Fits: To check the good APEC fits we check individual spectra. As can been seen in Fig. 11 these spectra are overall soft and show evidence of lines. These sources also tend to have poor fits in the other spectral models being used. Thus confirming that the full parameter APEC fits will be important for certain sources.

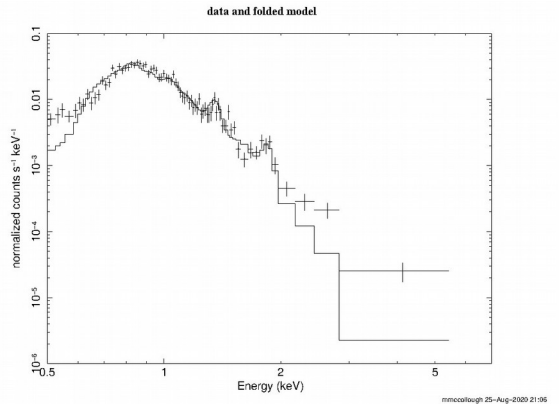

Fig. 11: An example of a spectrum that show strong spectral lines (obsid: 13814, obi: 0, region: 0788).

H. Low Counts Sources: To verify that sources with lower counts would also be reasonably fit by a full parameter APEC model a group of 450 sources whose net counts were between 150-1000 counts was fit. The results matched what we found (in terms of distributions of fit parameters) in sources with over 1000 counts. Thus we do not expect any problems with fitting the lower count sources.

I. Joint Fits: We have performed tests of the joint fits and individual fits to the spectra of the joint fits. The results between the various fits appear to be in agreement. We did joint fits in the same manner as the way the other spectral model fits are done will be acceptable.

J. Run Times: Our current estimates of run times for the full parameter fits is ~8 times longer than the current run times for the other spectral models currently being run.

III. **Recommendations:** Based on our testing we find that the full APEC model results in better fits. The initial two parameter fit test (which is similar to what is done for the XMM catalog) gives a poorer fit. Hence we recommend that for CSC 2.1 we include the APEC model in the spectral fitting of catalog data. This should be a full parameter (nH, kT, Abundance, z) fit of the data.

A. ***Changes to Specfit:*** The pipeline version of specfit should be updated and be replaced with a version of specfit which allows APEC to be run with a full parameter (nH, kT, Ab, z). This is a change that Dan has already put into specfit that updated specfit so that the abundance and redshift parameters in the APEC model are thawed and allowed to be fitted.

B. ***Default Mode:*** A full fit of all the fit parameters should be used for the APEC model computation.

C. ***APEC Version:*** We recommend using the most recent version of the APEC model (August 2020):

i. Using the new 201 tabulated temperatures v3.0.9 AtomDB files for APEC models. These CEI files reduce potential interpolation problems (see http://atomdb.org/interpolation/index.php).

IV. Operational Implementation of Changes: We would recommend the following operational implementation:

A. ***Fitting Criteria:*** The same criteria used for fitting the other specfit models for individual observations should be used for the APEC model. This is the minimum number of nets counts (150) and the energy range (0.5-7.0 keV) should be used.

B. ***Database Fields:*** The database fields for the full APEC model fits are currently in the catalog database filled with null values. So the APEC results should be incorporated into the prop3 files and then transferred into the database as appropriate.

C. ***Negative Redshifts:*** The full APEC fits for which the redshift upper limit (apec_redshift_hi) is negative represent fits that have no physical meaning and would likely confuse users of the catalog. As such these values should be made null values in the catalog.

D. ***Joint Fitting:*** The same criteria for the joint fitting of the other models should be used for the full APEC model.

E. ***CSC 2.1 Data:*** For going forward with CSC 2.1 the fitting APEC model should be a default fit for new runs of the catalog data.

F. ***CSC 2.0 Data:*** For data currently in the CSC 2.0 there should be a plan put in place to do an APEC fit to the data in the catalog. This work can be done as a separate release with a lower priority than the CSC 2.1 release. But should be done in the future.

V. Aperture Model Energy Fluxes: From our test run of full APEC fits there is a need to give a list of default spectral parameters which will be used in calculating the APEC aperture model energy fluxes. From our test run we have taken the median value of the good (rstat < 2.0) full APEC spectral fits. The values to use are:

A. ***Recommended Parameter Values:***

i. ***nH:*** Determined from *colden* (as done for the other spectral models).

ii. ***kT:*** 3.5 keV

iii. ***Abundance:*** 0.2

iv. ***z:*** 0.0

B. ***Implementation Plan:*** Given that the CSC 2.0 has values populated using a kT of 6.5 keV we do not believe this change should be implemented in the CSC 2.1 release since this would result with APEC flux values with mixed parameters used to calculate them. What we are recommending are:

i. ***Test Run:*** We will rerun a subset of the CSC 2.0 data using the new values for a full fit and compare with the values that are currently in the catalog. This way we can assess how big the change will be.

ii. ***Change of APEC Flux Values:*** We propose that at a later date to do a bulk replacement of the APEC aperture model energy fluxes for all of catalog data. This does not have to be done at the time of CSC 2.1 release.

VI. Software Test Cases: The following will be provided:

A. ***High Count Fits:*** A fits file containing all of the APEC fit results for CSC 2.0 sources with > 1000 counts.

B. ***Low Count Fits:*** A fits file containing all of the APEC fit results for a select group of CSC 2.0 sources with lower count (150-1000 counts).

C. ***Select Spectra:*** A select list (obsid, obi, region) will be provided for spectra to be tested. Also a list of master sources for joint fit test will be provided.