Chandra Source Catalog Energy Bands

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Abstract: Given below is the rational for deciding the energy bands and their associated effective energy (mono-energy used for exposure maps, etc.) to be used in Chandra Source Catalog. A brief discussion of the problems and issues that needed to be addressed are given.

I. Energy Bands

For the Chandra Source Catalog (CSC) we desire to find the optimal energy bands to use for source detection and flux measurements. For ACIS and HRC we need a broad bands which will cover the entire range in energy to which the telescope and detectors are sensitive. Additional for ACIS observations, for which there are spectral resolution capabilities, it is also desirable to have multiple narrow bands. Based on prior experience with the data it was decided that there was adequate spectral resolution and sensitivity for three additional bands (soft, medium, and hard) which would also be used for images, source detection, flux measurements and hardness ratios. An additional fourth band for super soft sources was also found to be desirable. Below is a review of how the energy boundaries of the various bands were determined.

A. Energy Bands for ACIS

For ACIS several issues need to considered in determining the bands to be used. Given below is a summary of the initial inputs, previous work, telescope and detector response information, and rational used in deciding the energy boundaries.

1. Initial Issues and suggestions:

Below are a list of initial issues and suggestions which were used to start the evaluation process for the energy boundaries to be used for ACIS CSC catalog entries.

a. Effective Area: There is a need to avoid large changes in the effective area (in the HRMA and detectors) in the middle of the bandpass whenever possible. Such changes can possibly have a negative impact on calculating such things as exposure maps. In some cases (the broad band and soft band) this may not be possible.

b. Signal vs. Noise: There is a need to avoid extending the bandpasses too low (soft) or too high (hard). Integrating the bandpass where there is no signal has the risk of adding noise to the measurement while not adding any signal.

c. Iridium Edge: There is an iridium M-edge in the 2-2.5 keV area. This would make a natural break between the medium and hard bands.

d. Chip Differences: The front illuminated ACIS chips have very little sensitivity below

0.3 keV and the back illuminated ACIS chips go down to about 0.1 keV. Possibly a compromise between the two is desirable.

e. High End: It is likely that the hard (and broad) band should go out to at least 7 keV (to include the Fe K lines). But by the time you get to 10 keV you have very little signal and are likely just adding noise. Some compromise between these energies is desirable.

2. Previously used bands:

In the table below is a summary of the bands that have been used at the CXC and were found in a brief survey (10 different articles in ApJ) of the literature.

Survey	***ChaMP***	***Antennae XRBs***	***Antennae Soft Diffuse***	***Most Common (Various ApJ)***
Soft	0.3-0.9 keV	0.3-1.0 keV	0.3-0.65 keV	0.3-1.0 keV
Medium	0.9-2.5 keV	1.0-2.5 keV	0.65-1.5 keV	1.0-2.0 keV
Hard	> 2.5 keV	2.5-7.0 keV	1.5-6.0 keV	2.0-7.0 keV
Broad		0.3-7.0 keV		

In the table below is the range of energy boundaries found in the various ApJ articles.

Soft (lower)	***Soft/Medium***	***Medium/Hard***	***Hard(upper)***
0.1-0.3 keV	0.5-1.1 keV	2.0 keV	6.0-8.0 keV

3. XMM bands:

For CSC it should be noted that the shape of the XMM effective area curve is very similar to Chandra's up to ~6 keV. The XMM mirrors has gold edges while Chandra has Iridium, but they are quite close in energy (e.g. 2.0 keV vs. 2.2 keV; the edges are quite complex and spread out). Thus similar energy bands to those used by XMM may expect and desirable for the CSC.

a. XMM current source catalog (Serendipitous Source Catalogue: 1XMM):

This catalog uses the following energy bands bands:

i. Basic energy bands:

0.2-0.5 keV
0.5-2.0 keV
2.0-4.5 keV
4.5-7.5 keV

7.5-12.0 keV

b. Broad energy bands:

0.2-2.0 keV
2.0-12.0 keV
0.2-12.0 keV
0.5-4.5 keV

(see http://xmmssc-www.star.le.ac.uk/newpages/UserGuide_1xmm.html#TabBands)

b. XMM's next version of a source catalog (2XMM):

Will uses the following energy bands bands:

i. Basic energy bands:

0.2-0.5 keV
0.5-1.0 keV
1.0-2.0 keV
2.0-4.5 keV
4.5-12.0 keV

b. Broad energy bands:

0.2-12.0 keV

(private communication: Clive Page)

4. Effective area, quantum efficiency, and contamination:

In determining the energy bands it is important to examine how the effective area and quantum efficiency of the detector vary as a function of energy. One also has to address the issue of contamination of ACIS and how it impacts the sensitivity of the the detector as a function of energy and time. A secondary issue is the role the spectrum of the observed sources may play in determining the bands to be used.

a. Effective area and quantum efficiency: In Fig. 1 is a plot of the product of the effective area with the quantum efficiency of a back illuminated chip (S3: solid line) and a front illuminated chip (I3: dashed line). One can note the following:

i. One can see the edges due to Iridium with the largest drop occurring around 2 keV.

ii. There is a strong C-K edge at around 0.3 keV.

iii. One can see the marked difference to response between the back illuminated and front illuminated chips below 1 keV.

b. Contamination: In Fig.2 are the same curves as Fig.1 except they have been multiplied by a transmission factor which is determined by the amount of contamination on a given chip. The important things to note are the very deep C edge and the large overall lost in response below 1 keV (especially in the back illuminated chip). One should keep in mind that the L3 catalog will span the entire range of contamination from none to the most recently measured value.

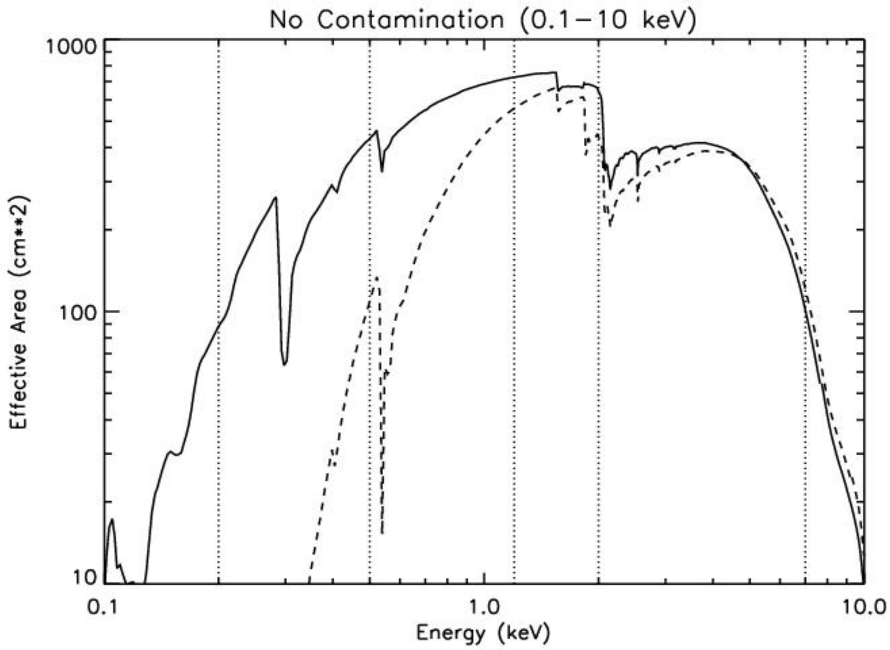

Fig. 1: This is a plot of the product of the effective area of the telescope with quantum efficiency of the detector. The solid line is the back illuminated chip (S3) and the dashed line is the front illuminated chip (I3). The dotted lines are the energy boundaries of the

c. Spectral weighting: In Figs.3 and 4 are the same curves as Fig.1 and 2 respectively, except they have been multiplied by a spectral weighting function of the form:

$$\left(\frac{E}{E_0}\right)^{-\alpha}$$

where E is the energy, E_0 is the normalization energy (taken to be 1 keV here), and α is a power law index which is taken to be 1.0 for typical objects observed with Chandra. This weighting will give a better sense of the contribution of Chandra sources various regions of the spectrum. The most notable effect is increase the effective areas at low energy and decrease the high energy cutoff to around 7.5 keV.

CSC bands.

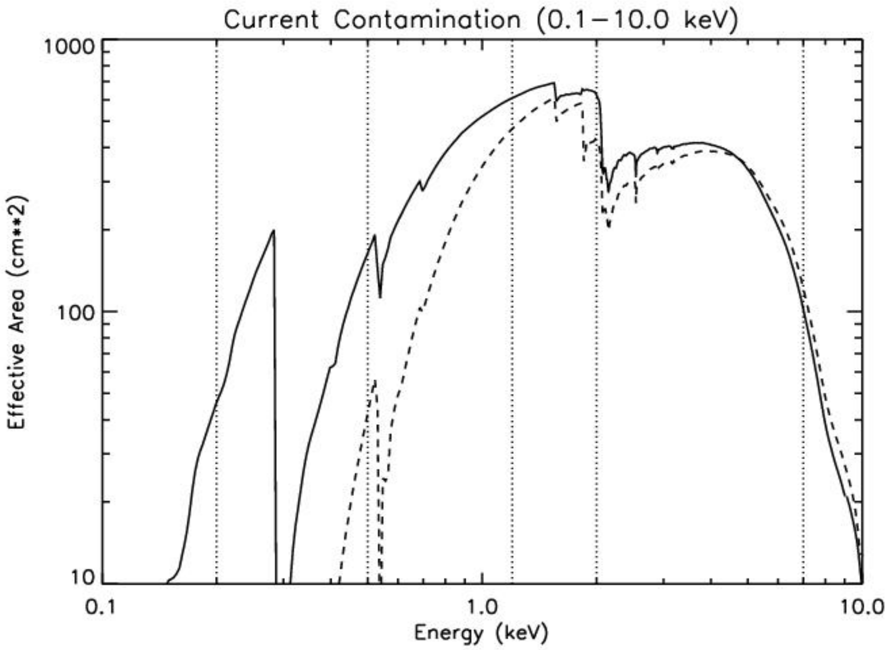

Fig. 2: This is a plot of the product of the effective area of the telescope with quantum efficiency of the detector with the current reduction due contamination included. The solid line is the back illuminated chip (S3) and the dashed line is the front illuminated chip (I3). The dotted lines are the energy boundaries of the CSC bands.

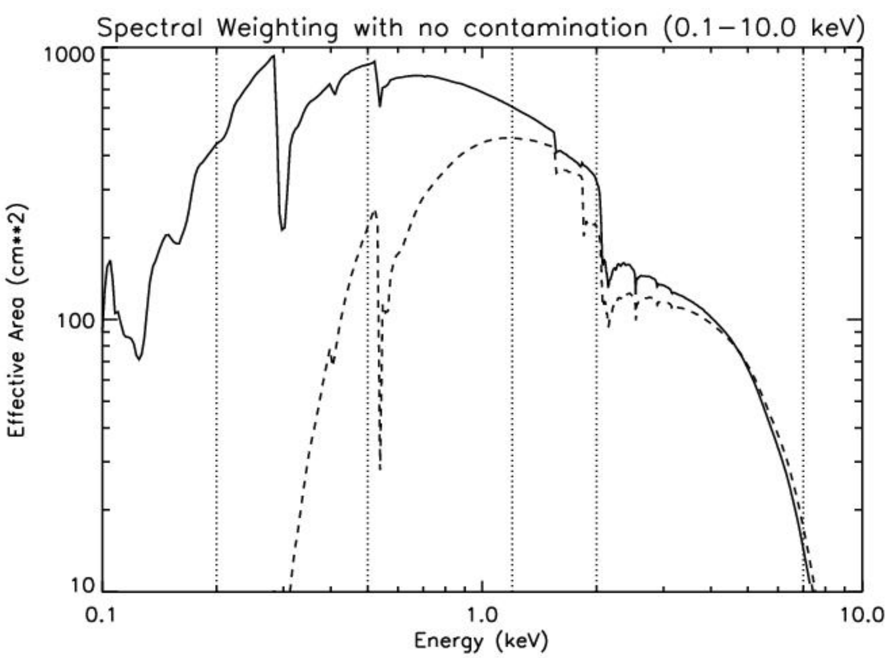

Fig. 3: This is a plot of the product of the effective area of the telescope with quantum efficiency of the detector times a spectral weighting function (see text). The solid line is the back illuminated chip (S3) and the dashed line is the front illuminated chip (I3). The dotted lines are the energy boundaries of the CSC bands.

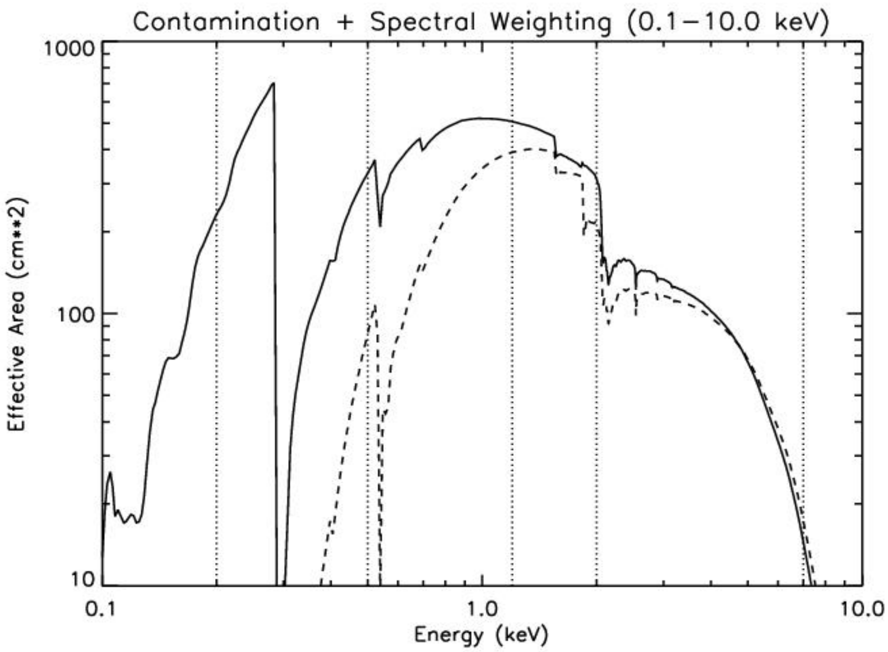

Fig. 4: This is a plot of the product of the effective area of the telescope with quantum efficiency of the detector times a spectral weighting function (see text) with the current reduction due contamination included. The solid line is the back illuminated chip (S3) and the dashed line is the front illuminated chip (I3). The dotted lines are the energy boundaries of the CSC bands.

5. Synthetic Color-Color Plots:

To better access which energy bands should be used, for the CSC, synthetic color-color plots were created using PIMMS. (The initial scripts for these simulations were provided by A. Tennant.) Three models were used:

(1) absorbed Power Law;

(2) absorbed Raymond-Smith;

(3) absorbed Blackbody.

What was sought was a set of bands which, for a reasonable range of parameters, would fill the color-color plot and hence serve as a useful diagnostic in understanding the nature of the sources being detected. This also would allow one to differentiate between various spectral models. For the color-color plots three bands were used: hard (H); medium (M); and soft (S). There was also a total (T) band which corresponds to the broad band to be used. The colors were defined as:

$$\frac{(M-S)}{T} \quad \text{(soft color)}$$

$$\frac{(H-M)}{T} \quad \text{(hard color)}$$

For the simulations runs both the I3 and S3 chip were run so that differences of the front and back illuminated chips could be evaluated.

a. Simulation Results: Several different sets of bands were run and the results examined. The following conclusions were reached:

i. An initial set of bands which include a very soft band (0.2 – 0.5 keV) were a poor diagnostic for most of the likely sources to found in the CSC. There were questions about the calibration in this soft band as well. For this reason the lower bound was taken to be 0.5 keV. But see section b. below for a further discussion of this issue.
ii. Because of the strong change in effective area at 2.0 keV this was a natural break for the M to H band.
iii. To determine break between the S to M we did several different simulations. The results were a break at 1.2 keV which tends to optimization the desire to fill the color-color plot (as a function of parameter space) while still having close to an equal amount of effective area in each band. See section 6 for more of a discussion of this point.

iv. We also did several simulations to evaluate the high energy cutoff. It was desirable to go up to at least 7.0 keV to include the Fe complex found in many X-ray sources in 6.4 - 6.9 keV region. There were some concerns that other lines above 7.0 keV might contribute to the hard band. But various simulations showed any such contribution was negligible. Thus an upper bound of 7.0 keV was chosen.

The simulated color-color plots of the chosen bands are shown in Figs. 5-7 for the ACIS-S detector.

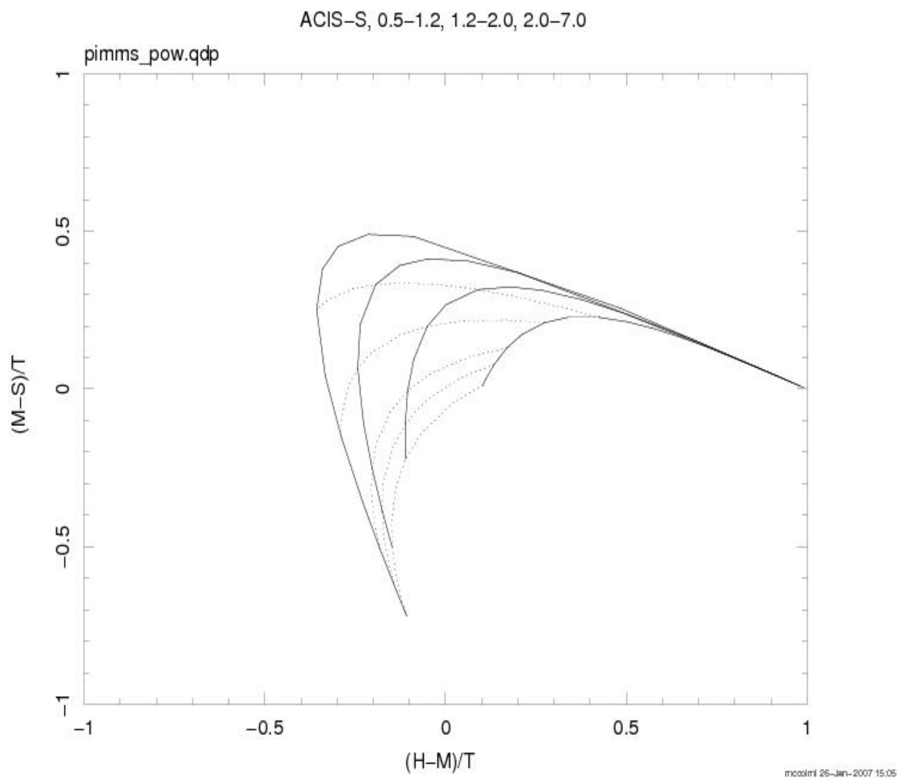

Fig. 5: This a synthetic color-color plot made for an absorbed power law model using PIMMS for the chosen CSC energy bands. The fixed spectral Index values used were 1, 2, 3, and 4. The fixed values of N_h *used were* $1.0\times10^{20}\,cm^{-2}$ *,* $1.0\times10^{21}\,cm^{-2}$ *,* $2.0\times10^{21}\,cm^{-2}$ *,* $5.0\times10^{21}\,cm^{-2}$ *, and* $1.0\times10^{22}\,cm^{-2}$ *. The solid lines represent lines constant spectral index and the dotted lines are lines of constant* N_h *.*

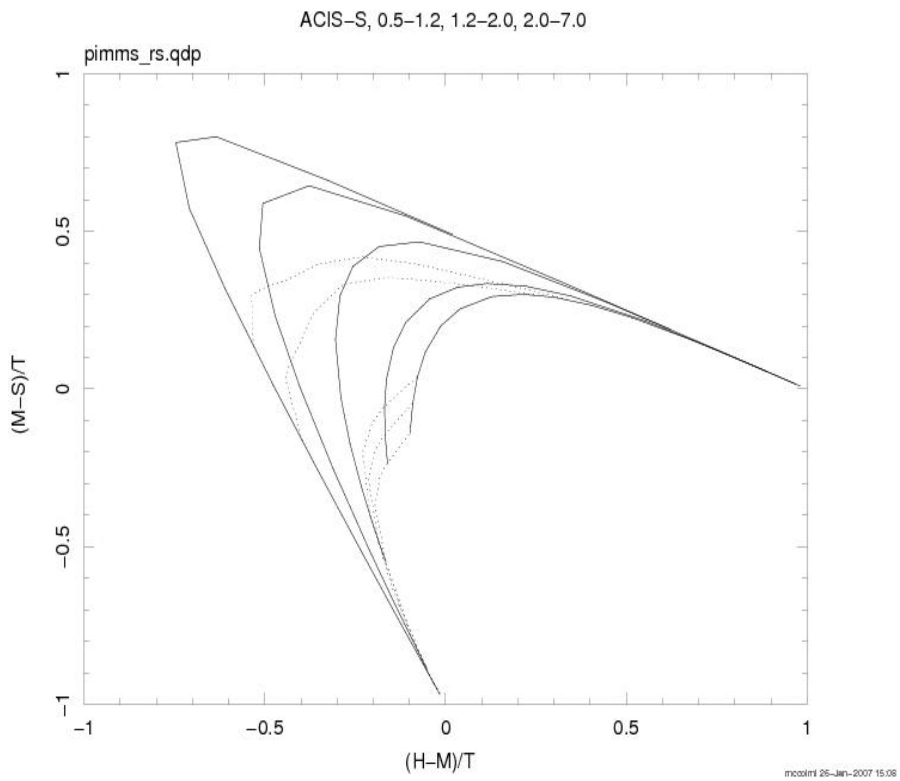

Fig. 6: This a synthetic color-color plot made for an absorbed Raymond-Smith model using PIMMS for the chosen CSC energy bands. The fixed temperature values used were 0.25, 0.5, 1, 2, and 4 (in keV) . The fixed values of N_h used were $1.0\times10^{20}\,cm^{-2}$, $1.0\times10^{21}\,cm^{-2}$, $2.0\times10^{21}\,cm^{-2}$, $1.4\times10^{22}\,cm^{-2}$, and $1.75\times10^{22}\,cm^{-2}$. The solid lines represent lines constant temperature and the dotted lines are lines of constant N_h .

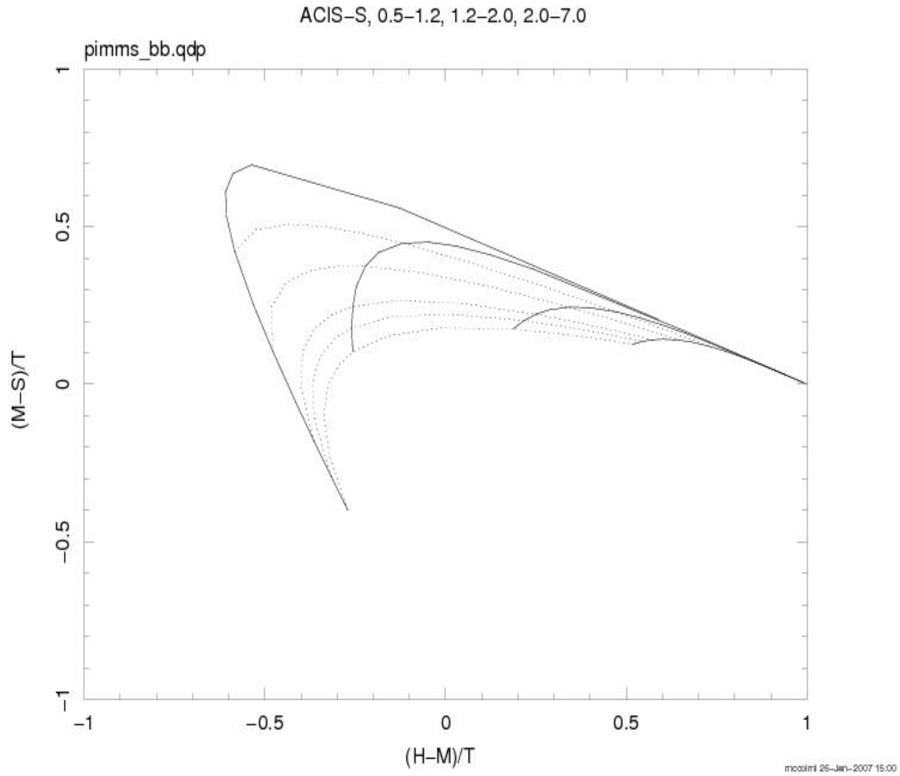

Fig. 7: This a synthetic color-color plot made for an absorbed Blackbody model using PIMMS for the chosen CSC energy bands. The fixed temperature values used were 0.25, 0.5, 1, and 2 (in keV) . The fixed values of N_h *used were* $1.0\times10^{20}\,cm^{-2}$, $1.0\times10^{21}\,cm^{-2}$, $2.0\times10^{21}\,cm^{-2}$, $5.0\times10^{21}\,cm^{-2}$, and $1.0\times10^{22}\,cm^{-2}$. The solid lines represent lines constant temperature and the dotted lines are lines of constant N_h .

b. Super Soft Sources: There was still a concern about the detection and analysis of Super Soft Sources. For this reason simulations were run for a low temperature Blackbody using the 0.2-0.5 keV band along with the new S and M bands. In this case the total (T) band is from 0.2-2.0 keV. The results for ACIS-S are shown in Fig. 8. It appears that this band could be used in the search and analysis of Super Soft Sources. It was decided that this Ultra-Soft (U) band would be useful and should be kept.

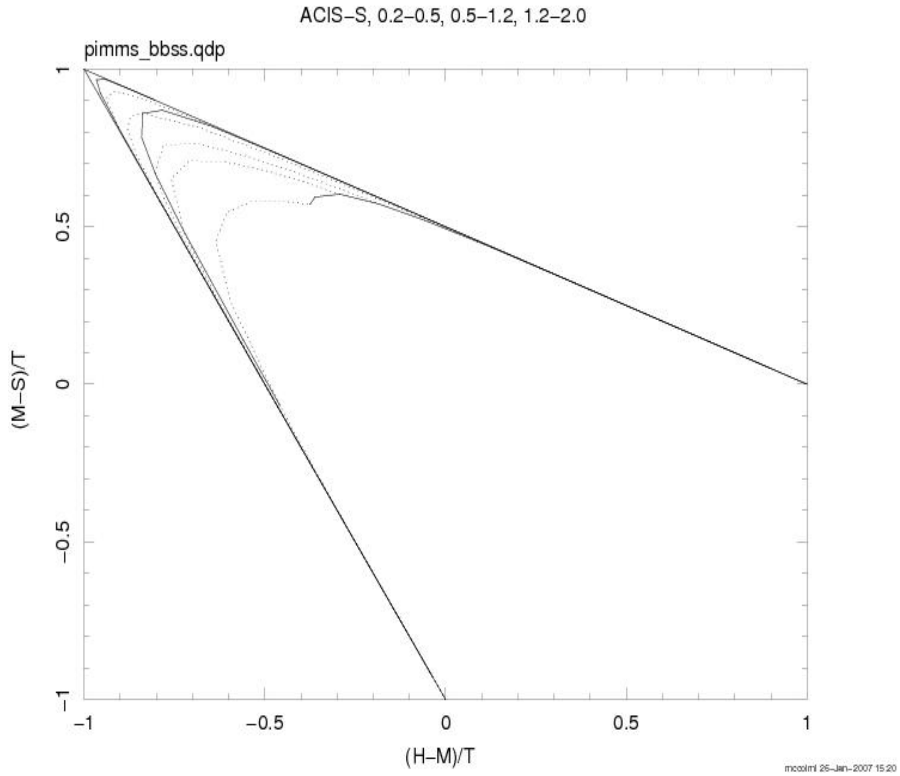

Fig. 8: This a synthetic color-color plot made for an absorbed Blackbody model using PIMMS using the Ultra-Soft, Soft, and Medium CSC bands. The fixed temperature values used were 20, 50, 100, and 250 (in eV) . The fixed values of N_h used were $1.0\times10^{20}cm^{-2}$, $1.0\times10^{21}cm^{-2}$, $2.0\times10^{21}cm^{-2}$, $5.0\times10^{21}cm^{-2}$, and $1.0\times10^{22}cm^{-2}$. The solid lines represent lines constant temperature and the dotted lines are lines of constant N_h.

6. Equal Effective Area:

To access where to put the break energy for the S to M bands it was found desirable that each band have roughly the same effective area. To estimate the energy for this we summed QE weighted effective area for the 0.5-2.0 keV band. We then created two bands (low and high) for which summed QE weighted effective area was calculated and divided by the total for the 0.5-2.0 keV band. This is plotted in Fig. 9 as a function of break energy between the two bands for both ACIS-I and ACIS-S. The break energy of 1.2 keV fits the criteria of have relatively equal effective areas between the two bands.

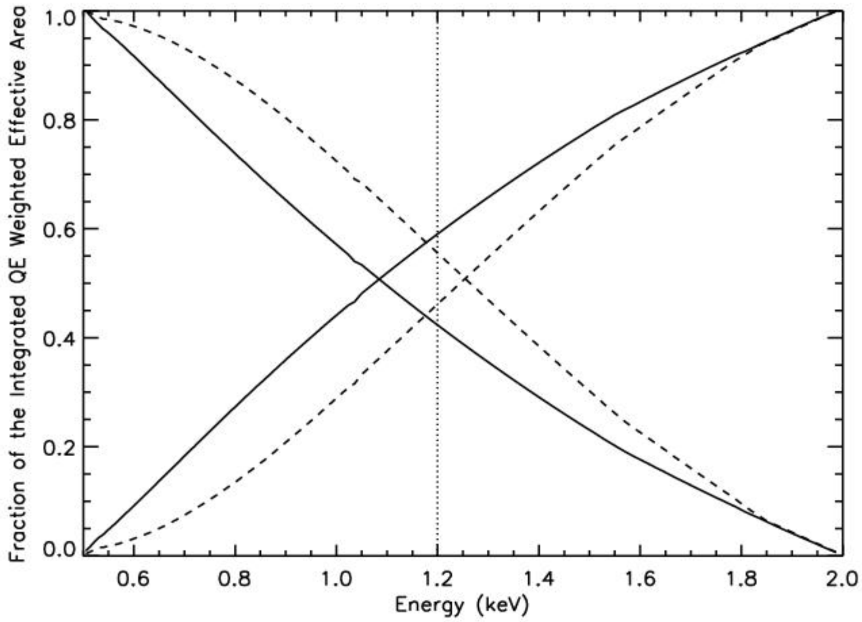

Fig. 9: To estimate the Soft to Medium band break energy for the 0.5-2.0 keV band the QE weighted effective area was summed for the band. Then two bands (low and high) were created for which summed QE weighted effective area was calculated and divided the total for the entire band. This represent the fraction of the total effective area for the band contained in each of these sub bands. These bands are plotted as function of break energy. The solid lines are for an ACIS-S chip and the dashed lines are for an ACIS-I chip. The dotted line represents the Soft to Medium break energy chosen for the CSC.

7. CSC Energy Bands:

Based on the above sections we have chosen the bands given in the table below to use for CSC. The rational follows:

Bands	***Broad***	***Ultra-Soft***	***Soft***	***Medium***	***Hard***
Energies	0.5-7.0 keV	0.2-0.5 keV	0.5-1.2 keV	1.2-2.0 keV	2.0-7.0 keV

a. Broad (0.5-7.0 keV): The simulations indicate that bands going below 0.5 keV does not sever as a useful diagnostic for most sources likely to be found in the CSC. As a result a value of 0.5 keV is recommend for the low end of the broad band. At the high end there is a rapid fall off. One needs to go to at least 7.0 keV to get the Fe K lines. Simulations indicate that very little if any useful information is gained by going about 7.0 keV. In fact increased background included in the band by going to higher energies may prove detrimental. As a result the upper cutoff was chosen to be 7.0 keV.

b. Ultra-Soft (0.2-0.5 keV): It was felt that for very soft sources that an additional low energy band was needed. For the front illuminated chips there is virtually no response below 0.3 (contamination only makes this worse). For the back illuminated chips there is response out to 0.1 keV but this is also greatly curtailed by contamination. Thus a compromise value of 0.2 keV was chosen. Since this band will be used to search for soft sources we do not want to go too high in energy and a value 0.5 keV was chosen to match the soft band boundary. This value will be just below the O-K edge. The only real issue with this band is that the C-K edge will be in the middle of this band and will be deep in contaminated observations.

c. Soft (0.5-1.2 keV): The lower bound is set as noted above. The break between was chosen to be an optimization between equal effective area and fill the color-color plot as a function of parameter space. As a result a value of 1.2 keV was chosen.

d. Medium (1.2-2.0 keV): The low bound is set as noted above. The natural upper boundary is a 2.0 keV. One could make arguments for going 0.5 keV either side of this value. But making it 2.0 keV appears a reasonable natural boundary.

e. Hard (2.0-7.0 keV): The limits discussed in *a*. and *d*. set the limits of this band.

B. Energy Band for HRC

Since the HRC has limited spectral resolution a single broad band from 0.1-10 keV was chosen. All images, source detections, and fluxes are based on this band pass. The effective area ($HRMA \times quantum efficiency$) for HRC-I and HRC-S is shown in Fig. 10. In Figs.11 is the same plot multiplied by the spectral weighting function given in section **A.**

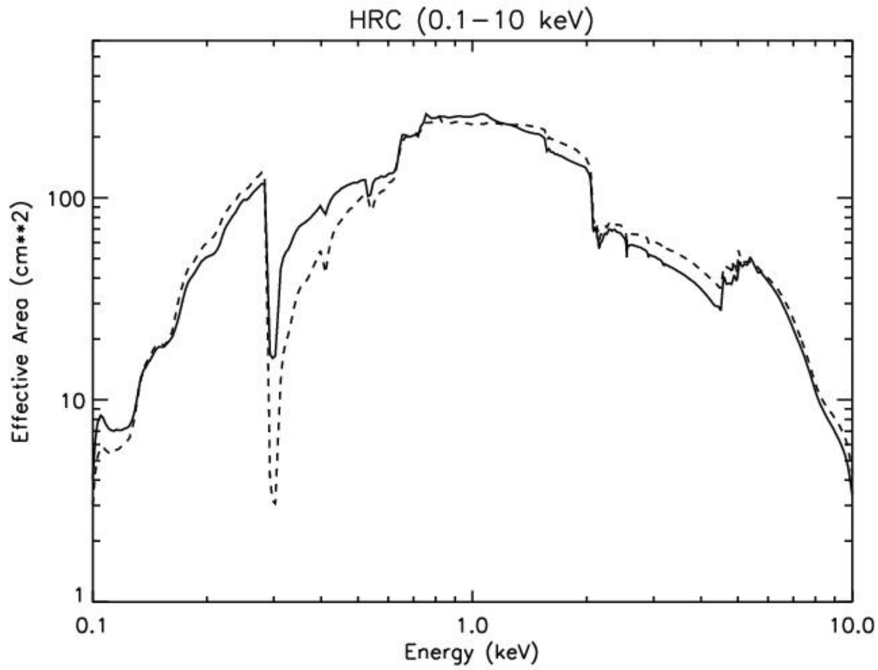

Fig. 10: This is a plot of the product of the effective area of the telescope with quantum efficiency of the detector. The solid line is the HRC-S detector and the dashed line is the HRC-I detector.

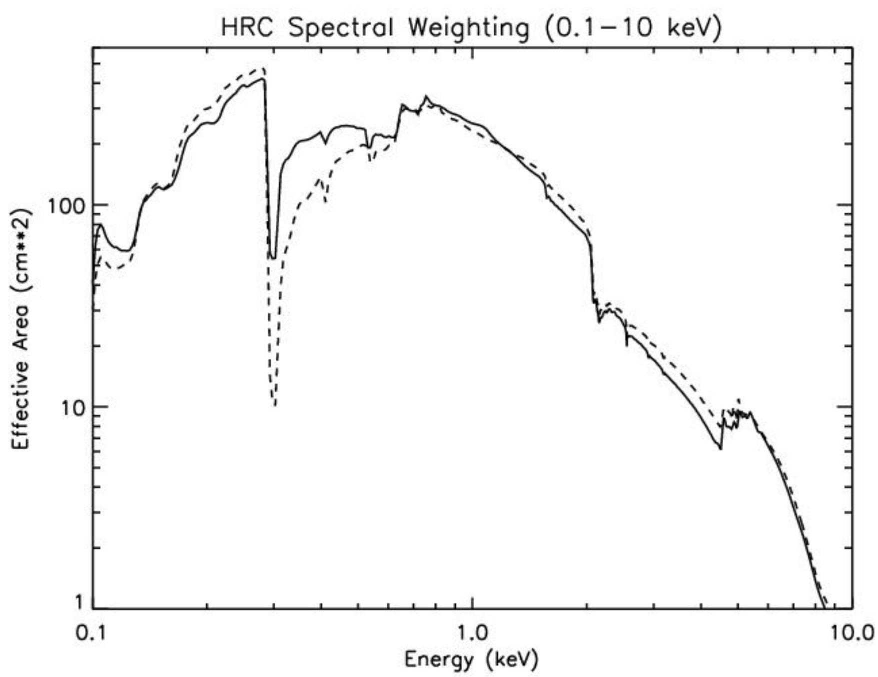

Fig. 11: This is a plot of the product of the effective area of the telescope with quantum efficiency of the detector times a spectral weighting function (see text). The solid line is the HRC-S detector and the dashed line is the HRC-I detector.

II. Effective Band Energy

For calculating exposure/instrument maps, psf, etc. for the CSC bands one needs to have an effective single energy to represent the band. Below is given the method of calculating the effective energy of each band. A number of cases are considered and the final values are given.

A. Method of Calculation

We calculate that effective energy for each band using the following relation:

$$E_{eff} = \frac{E_b}{E_n}$$

where the weighted energy E_b and the normalization E_n are given by:

$$E_b = \sum E_i A_i Q_i C_i S_i \Delta E_i$$

and

$$E_n = \sum A_i Q_i C_i S_i \Delta E_i$$

Where:

E_i : Energy of interval i of the band being considered.

A_i : Effective Area of the telescope (HRMA) of interval i of the band being considered.

Q_i : Detector quantum efficiency for interval i of the band being considered.

C_i : Reduction in transmission due to the build up of contamination on ACIS for interval i of the band being considered.

S_i : Spectral weighting function of the form $(E_i / E_0)^{-\alpha}$ where E_0 is the normalization energy (taken to be 1 keV) and α is the spectral index.

ΔE_i : The width of energy interval i of the band being considered.

In both E_b and E_n the sum is performed over the sampling of the energy band in question.

B. Results for ACIS and HRC Bands

The effective energies for each ACIS band were calculated for the following cases:

1. E_a : The energy determined by only weighting by effective area of the telescope. Done for both ACIS and HRC.

2. E_I : The energy determined by weighting by the effective area of the telescope and quantum efficiency of the I3 chip (ACIS) or HRC-I.

3. E_{Ic} : The energy determined by weighting by the effective area of the telescope, the quantum efficiency of the I3 chip, and the maximum value of the transmission reduction due to contamination. (ACIS only)

4. E_{Is} : The energy determined by weighting by the effective area of the telescope, the quantum efficiency of the I3 chip or HRC-I, and a spectral weighting ($\alpha = 1$).

5. E_{Ics} : The energy determined by weighting by the effective area of the telescope, the quantum efficiency of the I3 chip, the maximum value of the transmission reduction due to contamination, and a spectral weighting ($\alpha = 1$). (ACIS only)

6. E_S : The energy determined by weighting by the effective area of the telescope and quantum efficiency of the S3 chip or HRC-S.

7. E_{Sc} : The energy determined by weighting by the effective area of the telescope, the quantum efficiency of the S3 chip, and the maximum value of the transmission reduction due to contamination. (ACIS only)

8. E_{Ss} : The energy determined by weighting by the effective area of the telescope, the quantum efficiency of the S3 chip or HRC-S, and a spectral weighting ($\alpha = 1$).

9. E_{Scs} : The energy determined by weighting by the effective area of the telescope, the quantum efficiency of the S3 chip, the maximum value of the transmission reduction due to contamination, and a spectral weighting ($\alpha = 1$). (ACIS only)

Cases	***0.5-7.0 keV***	***0.2-0.5 keV***	***0.5-1.2 keV***	***1.2-2.0 keV***	***2.0-7.0 keV***	***HRC***
E_a	3.04 keV	0.35 keV	0.85 keV	1.59 keV	4.22 keV	3.14 keV
E_I	3.38 keV	0.44 keV	0.95 keV	1.58 keV	4.27 keV	2.77 keV
E_{Ic}	3.49 keV	0.45 keV	0.98 keV	1.59 keV	4.28 keV	
E_{Is}	2.36 keV	0.44 keV	0.91 keV	1.55 keV	3.86 keV	1.44 keV
E_{Ics}	2.54 keV	0.45 keV	0.95 keV	1.56 keV	3.86 keV	

Cases	***0.5-7.0 keV***	***0.2-0.5 keV***	***0.5-1.2 keV***	***1.2-2.0 keV***	***2.0-7.0 keV***	***HRC***
E_{S}	3.04 keV	0.38 keV	0.88 keV	1.59 keV	4.11 keV	2.77 keV
E_{Sc}	3.21 keV	0.36 keV	0.92 keV	1.60 keV	4.12 keV	
E_{Ss}	1.99 keV	0.36 keV	0.84 keV	1.55 keV	3.69 keV	1.44 keV
E_{Scs}	2.22 keV	0.33 keV	0.88 keV	1.56 keV	3.70 keV	

The above cases which most likely represent what will be found in the CSC catalog are those found with spectral weighting (with and without contamination). One also has to weight somewhat between how many sources will be found in an front illuminated vs. a back illuminated chip. With that in mind we chose the following as effective energies for the chosen bandpasses.

Bands	***0.5-7.0 keV***	***0.2-0.5 keV***	***0.5-1.2 keV***	***1.2-2.0 keV***	***2.0-7.0 keV***	***HRC***
Energy	2.3 keV	0.4 keV	0.92 keV	1.56 keV	3.8 keV	1.5 keV

These will be used in creating quantities that need a single energy in order to calculate (instrument/exposure maps, psfs, etc.).