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Hard X-Ray RXTE Observations of Clusters of Galaxies: Searching for Hard X-ray Emission due to Non-thermal processes

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Analysis of Archival RXTE X-Ray Data for Clusters of Galaxies: Searching for Non-thermal Hard X-ray Emission. Cynthia Correa (Harvard University, Cambridge, MA 02138) G.M. Madejski (Stanford Linear Accelerator Center, Menlo Park, CA 94305).

We report results of hard X-Ray observations of the clusters Coma, Abell 496, Abell 754, Abell 1060, Abell 1367, Abell 2256 and Abell 3558 using RXTE data from the NASA HEASARC public archive. Specifically we searched for clusters with hard x-ray emission that can be fitted by a power law because this would indicate that the cluster is a source of non-thermal emission. We are assuming the emission mechanism proposed by Vahé Petrosian where the inter cluster space contains clouds of relativistic electrons that by themselves create a magnetic field and emit radio synchrotron radiation. These relativistic electrons Inverse-Compton scatter Microwave Background photons up to hard x-ray energies. The clusters that were found to be sources of non-thermal hard x-rays are Coma, Abell 496, Abell 754 and Abell 1060.

Research Category: Physics (astrophysics)

TYPE ALL INFORMATION CORRECTLY AND COMPLETELY

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Introduction

One reason why clusters of galaxies are interesting topics of investigation is that they are the biggest structure formations of the universe. Clusters of galaxies are systems of galaxies containing several to thousands of member galaxies and harbor plasma gases up to 108 K. As such, they can provide evidence on the structure and evolution of the universe. As with most other astronomical objects, most of what we know about clusters has been deduced from the study of their electromagnetic spectra. Extensive observations of the lower energy emission of clusters using ground telescopes have already been made. However, because X-rays and gamma rays cannot penetrate the earth's atmosphere, the study of X-ray and gamma-ray emissions have only become possible as rocket and high-energy telescope technology have become sufficiently advanced. Because of this late start, much is still unknown about the highly energetic physical processes through which clusters give off x and gamma rays.

Presently, it is well known that most of the x-ray radiation from the inter cluster gas is thermal Bremsstrahlung and line emission. Thermal radiation is produced solely by heat and Bremsstrahlung radiation is produced when a free electron is deflected by an ion, but the free electron is not captured by the ion. Whenever a charged particle's velocity is changed, radiation is released. In addition to this, there have been found diffuse radio, EUV and hard X-ray radiation (HXR, 20-80 KeV) that are expected to be due to non-thermal processes (Petrosian 2001). Thermal emission falls off steeply past a given range of X-ray energies. The way to identify non-thermal emission from the spectral curve of the sum of all the emission is to look for emission beyond the fall off of thermal radiation, at the hard X-ray energy range.

The radio emission indicates the presence of non-thermal relativistic electrons (10-100 GeV) that are accelerated by inter cluster μG magnetic fields. The inter cluster magnetic fields are caused by the motion of charged particles in the inter cluster plasma. It has been speculated that when those same relativistic electrons are inverse Compton (IC) scattered by cosmic microwave background photons, they give off the observed EUV and HXR radiation (Hwang 1997). Previous sources of the EUV and HXR radiation that have been declared improbable are thermal and non-thermal Bremsstrahlung, respectively (Petrosian 2001). Additionally, we can confirm the non-thermal nature of the HXR radiation, because emission due to inverse-Compton scattering of relativistic electrons is expected to follow a power-law. If the excess radiation at the HXR energy range is non-thermal, then this radiation is composed of Microwave background photons that are upscattered by intercluster relativistic electrons. Since the microwave background radiation is uniform and then it will have the same power law slope as that of the synchrotron radio emission (Valinia 1998).

The goal of this observational investigation is to identify clusters that possess clouds of non-thermal relativistic electrons by searching for deviations from the thermal Bremsstrahlung forms in the spectral curves of the clusters Abell 754, Coma, Abell 2256 and Abell 1367. Abell 754 is a cluster undergoing merging for which no evidence of non-thermal HXR radiation has been found (Valinia 1998). The Coma cluster is a good candidate for this investigation, because it is a highly visible cluster whose spectra has been analyzed by other groups. Its spectral analysis has revealed radio, EUV, SXR and HXR radiation (Petrosian 2001). If our method of analysis is adequate, our observations of its emission should confirm the previous ones. Abell 2256 is also a good candidate for harboring non-thermal relativistic electrons because it is a known HXR and radio emitter. Two of the complications that we will have to deal with to isolate possible HXR emission are that there is a very strong instrumental background that will need to be subtracted accurately, and that the RXTE has an inherent instrument response uncertainty that will need to be understood. One way to verify that the background subtraction was performed correctly will be to find light curves that are nearly flat, since the flux of clusters of galaxies should show almost no variability with time.

It has also been speculated that non-thermal relativistic electrons will be inverse-Compton scattered by cosmic rays to produce gamma rays. Thus, a secondary purpose of this investigation is to identify clusters that will be interesting to observe with the Gamma-ray Large Area Space Telescope (GLAST). GLAST is expected to begin operation in 2006. Gamma-ray exploration is of great interest because it could potentially reveal unknown aspects about the formation and structure of clusters of galaxies. It has been suggested that there exists a background gamma-ray radiation that is not due to any thermal process. If in fact diffuse gamma-rays are found that cannot be attributed to the inverse Compton process or to isolated sources, it has been speculated that these gamma-rays may be relic radiation from some unknown process that occurred in the early stages of the formation of the universe or that these gamma rays may be the residual from the annihilation of dark matter made up of neutralinos. HXR observations of clusters of galaxies promise to uncover very interesting discoveries.

Materials and Methods

A. Instruments

The data analyzed were light curves and energy spectra of X-ray flux from clusters of galaxies collected by the currently operational satellite, Rossi X-ray Timing Explorer (RXTE) that is available from the NASA High Energy Science Archive Research Center's public archive. It is composed of two instruments, the Proportional Counter Array (PCA) that covers the 2-60 KeV energy range and the High Energy X-ray Timing Experiment (HEXTE) that detects X-Rays of up to 200 KeV. The instrument used here is the PCA which has five collimated xenon gas proportional counter detectors and a collecting area of 6500 cm^2. X-rays enter the chambers ionizing the gas inside, freeing electrons that drift towards charged wires in the chambers. As the initial electrons drift towards the wires they ionize more atoms on their way, amplifying the signal in proportion to the magnitude of the initial signal. During most of the observations PCU 3 and 4 are not used here because they malfunctioned soon after the satellite was launched. For observations after May, 2000 PCU 1 is turned off after it suffered a Xenon gas leak. Thus, most observations only include data for PCU's 0,1,2 and for most observations performed after May 2000 only PCU's 0,2 are used.

The detector's reliability is dependent on this amplification of the signal, thus the data for lower fluxes are less reliable than the data for strong signals. Below 3 KeV the calibration of the detector is not sufficiently reliable. Since beyond energies of 30 KeV source counts drop more rapidly than the instrumental background, the data for energies beyond 30 KeV are not reliable. For these reasons, the range for all of the observations is 3-30 KeV.

B. Methods

RXTE data in FITS format was downloaded along with a set of filter files that are provided by the XTE Science Data Center. The filter files contain time-histories of various parameters that are helpful in screening the data. The data was reduced using the Rex script. It predicts what the sky background signal was for a set of specific observations. This background signal consists of the sky background as well as the instrument background. Rex then produces model background files that are subtracted from the raw data to isolate only the flux emitted by the object. Once the object's flux has been isolated, Rex generates a light curve and spectra curve for each individual observation and for the merged observations. Light curves (which are time histories of flux) will be examined to establish the quality of the background subtraction: clusters of galaxies do not vary in brightness so the created light curve should be almost flat. It is not possible to isolate the object flux to a decent degree of confidence simply by inverting the background signal because the RXTE PCA's energy resolution is poor. Instead, the model spectrum has to be convolved fitting the object spectrum with a combination of preprogrammed models of the emission specific to certain astrophysical x-ray sources via XSPEC. The closeness of a fit can be expressed by a value referred to as reduced X^2 (RCS). Chi-squared is the difference-squared between the observed and expected counts, divided by the expected value. When any data set obeying Gaussian statistics is fitted to a correct model with the best-fit parameters should yield a chi-square of about 1, so spectral models that result in a RCS near 1 will be considered possible descriptions of the emission mechanism of the cluster. An RCS below might indicate that statistical uncertainty might have been overestimated such as when error bars are greater than they are supposed to be.

Two models used in this investigation used to simulate this emission are mekal and raymond. These two models include emission lines appropriate for the atomic transitions of elements in the plasma. One difference between the two models is that Mekal has updated element abundances and thus should fit better than Raymond. Most of the X-ray emission from clusters of galaxies is thermal Bremsstrahlung radiation that is well described by Bremsstrahlung spectrum and line emission. Since a cluster can contain up to thousands of galaxies and can usually be well fit to models that assume isothermal gas distribution, their emission is well approximated as a cloud of hot (kT= 3-15 KeV) diffuse gas. To account for any photoelectric absorption due to gas in the line of sight we used the Wisconsin absorption model. Finally any flux that is detected beyond he falloff of thermal emission can be fitted the power law model because non-thermal energy follows a power law. Such flux, if found, is likely to be due to very energetic, non-thermal radiating particles.

C. Sources

The clusters herein analyzed are Coma cluster, Abell 496, Abell 754, Abell 1060, Abell 1367, Abell 2256, Abell 3558. Abell 754 is a cluster undergoing merging for which no evidence of non-thermal HXR radiation has been found (Valinia 1998). The Coma cluster is a good candidate for this investigation, because it is a highly visible cluster whose spectra has been analyzed by other groups. Its spectral analysis has revealed radio, EUV, SXR and HXR radiation (Petrosian 2001). If our method of analysis is adequate, our observations of its emission should confirm the previous ones. Abell 2256 is also a good candidate for harboring non-thermal relativistic electrons because it is a known HXR and radio emitter. A table of characteristics of these clusters can be found in the results section. The background files used by Rex are pca_bkgd_cmfaintl7_e[epoch number]v20020201.mdl.

Results

The best-fit models for each cluster are summarized on table 2. An interesting observation that is true for all of the clusters is that the Raymond-Smith emission model gave slightly better fits than Mekal. One possible explanation why Mekal did not fit better than Raymond even though it should have is that the calibration of the instrument might not be very accurate. The Coma data is made up of two observations: P10368 and P50197. For the P10368 observation, the best fit was given by the Wisconsin absorption (wabs) +Raymond models (ray), with a reduced chi-squared (RCS) of 2.46. In this case, the Wisconsin absorption caused a very significant improvement of the RCS. This suggests that there is significant photoelectric absorption of the signal. The power law (pow) model however worsened the RCS. It is important to note that the Coma is sufficiently bright that systematic errors along the lower end of the X-ray spectrum caused RCS to be as high as 12. Allowing for a systematic error of 2% reduced the RCS to as little as 1.54. The inclusion of a systematic error of 2% is proper because it significantly reduces the residuals at the lower X-Ray energies while having a negligible effect on the residuals at the higher energies that are important to this observation. This cluster is the only one bright enough to need a systematic error. The best fit for the P50197 observation was given by wabs ray pow (RCS of 1.54).

Abell 496

The best-fit model was wabs ray pow with a RCS of 2.18. The addition of the power law model improved the RCS from 2.59 to 2.18.

Abell 754

The best fit both Abell 754 observations (P20355 and P30272) was given by the wabs + ray model with a RCS of .84. The wabs brought an improvement of .1 while the addition of a power law worsened the RCS by .05. Since the power law worsens the RCS by such a small amount, we cannot bar the possibility that Abell 754 is the source of non-thermal hard x-rays.

Abell 1060

Abell 1060 was best fit by the ray pow combination, giving a RCS of 1.46. The pow addition improves the RCS from 1.98 to 1.46. The wabs addition, however, does not improve the RCS.

Abell 1367

The Raymond spectrum model gave the lowest RCS of 1.83 for Abell 1367. The wabs and the pow additions worsened the RCS by .04 and .07 respectively. Since the values are closer to 2 than to 1, not even the best fit can be considered a very reliable diagnostic.

Abell 2256

The data for this cluster consists of observations P20355 and P60154. The best fit models for the two observations should coincide, yet P20355 is best fit by the wabs Raymond model (RCS of 1.07) while P60154 is best fit by the ray pow combination of models (RCS of .466). Also since even the worst fit gave a RCS as good as .6, the diagnostic for the P60154 observation is quite uncertain.

Abell 3558

The Raymond model gave the best fit (RCS of .628) for Abell 3558. However, this is another case in which even the worst fit was as good as .651. Since several of the models result in good RCS values, all of these models need to be considered plausible fits. It is important to note that the Raymond pow model gave a RCS of .65 that would suggest that Abell 3558 might be the source of non-thermal hard x-ray emission. However, the fitted power law index is 3.579 with an error of 743.8. We interpret this as that the power law model does not make up a significant fraction of the cluster emission because, although the addition of the power law model improves the fit, the model is not very sensitive to a change in the slope of the power law. Thus, Abell 3558 is not expected to be a source of non-thermal hard X-Ray emission.

Cluster	Redshift used	Epoch	PCU configuration	Flux for 2-10 KeV (ergs*cm^-2*s^-1)
Coma	.023	P10368: 3a P50197: 5	0,1,2 0, 2	1.0671E-09
Abell 496	.033	P40191: 3b	0,1,2,3	7.0262E-11
Abell 754	.054	P20355: 3a P30272: 3a	0,1,2 0,1,2	1.1149E-10
Abell 1060	.011	P40189: 4	0,1,2	4.2739E-11
Abell 1367	.022	P20355: 3a	0,1,2	5.0282E-11
Abell 2256	.058	P20355: 3a P60154: 5	0,1,2,3 0,2	7.2298E-11
Abell 3558	.048	P30271: 3b	0,1,2	8.4334E-11

Table 1. Red shift value, background Epoch and PCU configuration used for XSPEC spectrum analysis.

Cluster	Best-fit model	Reduced Chi Squared
Coma	P10368: Wisconsin Abs. + Raymond-Smith P50197: Wisconsin Abs. + Raymond-Smith + Power Law	2.46 1.54
Abell 496	Raymond-Smith + Power Law	2.18
Abell 754	P20355: Wisconsin Abs. + Raymond-Smith P30272: Wisconsin Abs. + Raymond-Smith	.85 2.18
Abell 1060	Raymond-Smith + Power Law	1.46
Abell 1367	Raymond-Smith	1.83
Abell 2256	P20355: Wisconsin Abs. + Raymond-Smith P60154: Raymond-Smith + Power Law	1.07 .47
Abell 3558	Raymond-Smith	.63

Table 2. XSPEC model combination that resulted in the best fit based on the value of the RCS.

XSPEC Results Summary

Looking at 3-30 KeV energy range.
Models tried:

- Mekal
- Raymond

Subsequently adding:

- Wabs
- Pow

Coma Cluster

P10368

```
------------------------------------------------------------------------
 Model:  mekal [1]
 Model Fit Model Component Parameter  Unit     Value
 par  par comp
  1   1   1   mekal     kT      keV       8.089    +/-  0.1261E-01
  2   2   1   mekal     nH      cm-3      1.000    +/-  -1.000
  3   3   1   mekal     Abundance         0.2515    +/-  0.2007E-02
  4   4   1   mekal     Red shift        2.3100E-02 frozen
  5   5   1   mekal     Switch           1.000     frozen
  6   6   1   mekal     norm            0.3377    +/-  0.3353E-03
 ------------------------------------------------------------------------
 ------------------------------------------------------------------------
 Chi-Squared =     725.6372    using    59 PHA bins.
 Reduced chi-squared =     13.19340    for    55 degrees of freedom
 Null hypothesis probability =  0.00
```

```
---------------------------------------------------------------------------
Model: wabs[1]( mekal[2] )
Model Fit Model Component  Parameter  Unit     Value
par   par comp
 1   1   1  wabs      nH       10^22    0.3933    +/-  0.2127E-01
 2   2   2  mekal     kT       keV      7.835     +/-  0.1799E-01
 3   3   2  mekal     nH       cm-3     1.000     +/-  -1.000
 4   4   2  mekal     Abundance          0.2233   +/-  0.2380E-02
 5   5   2  mekal     Red shift        2.3100E-02 frozen
 6   6   2  mekal     Switch            1.000     frozen
 7   7   2  mekal     norm              0.3520    +/-  0.8483E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =     380.8995    using   59 PHA bins.
Reduced chi-squared =     7.053694    for    54 degrees of freedom
Null hypothesis probability =  0.00

---------------------------------------------------------------------------
Model: wabs[1]( mekal[2] + power law[3] )
Model Fit Model Component  Parameter  Unit     Value
par   par comp
 1   1   1  wabs      nH       10^22    0.3843    +/-  0.1099
 2   2   2  mekal     kT       keV      7.841     +/-  0.2788E-01
 3   3   2  mekal     nH       cm-3     1.000     +/-  -1.000
 4   4   2  mekal     Abundance          0.2240   +/-  0.3157E-02
 5   5   2  mekal     Red shift        2.3100E-02 frozen
 6   6   2  mekal     Switch            1.000     frozen
 7   7   2  mekal     norm              0.3516    +/-  0.1793E-02
 8   8   3  power law  PhoIndex           6.921   +/-  -1.000
 9   9   3  power law  norm          1.8994E-08 +/-  0.8085
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =     381.0953    using   59 PHA bins.
Reduced chi-squared =     7.328755    for    52 degrees of freedom
Null hypothesis probability =  0.00

---------------------------------------------------------------------------
Model: wabs[1]( raymond[2] )
Model Fit Model Component  Parameter  Unit     Value
par   par comp
 1   1   1  wabs      nH       10^22    0.3787    +/-  0.2118E-01
 2   2   2  raymond   kT       keV      7.908     +/-  0.1824E-01
 3   3   2  raymond   Abundance          0.2047   +/-  0.2188E-02
 4   4   2  raymond   Red shift        2.3100E-02 frozen
 5   5   2  raymond   norm              0.3539    +/-  0.8462E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =     351.0324    using   59 PHA bins.
Reduced chi-squared =     6.382408    for    55 degrees of freedom
Null hypothesis probability = 9.809E-45

---------------------------------------------------------------------------
Model: wabs[1]( raymond[2] + power law[3] )
Model Fit Model Component  Parameter  Unit     Value
par   par comp
 1   1   1  wabs      nH       10^22    0.3776    +/-  0.2289
 2   2   2  raymond   kT       keV      7.911     +/-  0.2746E-01
 3   3   2  raymond   Abundance          0.2050   +/-  0.3428E-02
 4   4   2  raymond   Red shift        2.3100E-02 frozen
 5   5   2  raymond   norm              0.3538    +/-  0.1638E-02
 6   6   3  power law  PhoIndex           8.340   +/-  215.5
 7   7   3  power law  norm          5.0638E-05 +/-  0.1254
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =     351.0838    using   59 PHA bins.
Reduced chi-squared =     6.624222    for    53 degrees of freedom
Null hypothesis probability = 1.401E-45
```

Using systematic .02

```
---------------------------------------------------------------------------
Model:  wabs[1]( raymond[2] )
Model Fit Model Component  Parameter  Unit     Value
par  par comp
 1    1    1  wabs       nH       10^22    0.3793    +/-  0.2121E-01
 2    2    2  raymond   kT        keV       7.908    +/-  0.1825E-01
 3    3    2  raymond   Abundance           0.2047    +/-  0.2187E-02
 4    4    2  raymond   Red shift          2.3100E-02 frozen
 5    5    2  raymond   norm               0.3539    +/-  0.8464E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =      135.5409    using    59 PHA bins.
Reduced chi-squared =      2.464380    for    55 degrees of freedom
Null hypothesis probability = 9.552E-09
```

P50197

```
---------------------------------------------------------------------------
Model:  mekal[1]
Model Fit Model Component  Parameter  Unit     Value
par  par comp
 1    1    1  mekal     kT        keV       8.471    +/-  0.1756E-01
 2    2    1  mekal     nH        cm-3      1.000    +/-  -1.000
 3    3    1  mekal     Abundance           0.2269    +/-  0.5970E-02
 4    4    1  mekal     Red shift          2.3100E-02 frozen
 5    5    1  mekal     Switch             1.000    +/-  0.9245
 6    6    1  mekal     norm               0.3201    +/-  0.4209E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =      611.8843    using    53 PHA bins.
Reduced chi-squared =      12.74759    for    48 degrees of freedom
Null hypothesis probability =  0.00
```

```
---------------------------------------------------------------------------
Model:  raymond[1]
Model Fit Model Component  Parameter  Unit     Value
par  par comp
 1    1    1  raymond   kT        keV       8.541    +/-  0.1262E-01
 2    2    1  raymond   Abundance           0.2066    +/-  0.1660E-02
 3    3    1  raymond   Red shift          2.3100E-02 frozen
 4    4    1  raymond   norm               0.3224    +/-  0.3012E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =      614.5869    using    53 PHA bins.
Reduced chi-squared =      12.29174    for    50 degrees of freedom
Null hypothesis probability =  0.00
```

```
---------------------------------------------------------------------------
Model:  wabs[1]( raymond[2] )
Model Fit Model Component  Parameter  Unit     Value
par  par comp
 1    1    1  wabs       nH       10^22    0.000    +/-  -1.000
 2    2    2  raymond   kT        keV       8.541    +/-  0.1262E-01
 3    3    2  raymond   Abundance           0.2066    +/-  0.1659E-02
 4    4    2  raymond   Red shift          2.3100E-02 frozen
 5    5    2  raymond   norm               0.3224    +/-  0.3011E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =      614.5920    using    53 PHA bins.
Reduced chi-squared =      12.54270    for    49 degrees of freedom
Null hypothesis probability =  0.00
```

```
------------------------------------------------------------------------
 Model:  wabs[1]( raymond[2] + power law[3] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs       nH       10^22     0.000      +/-  -1.000
  2    2    2   raymond   kT        keV       8.775      +/-  0.4573E-01
  3    3    2   raymond   Abundance           0.2289     +/-  0.4111E-02
  4    4    2   raymond   Red shift           2.3100E-02 frozen
  5    5    2   raymond   norm                0.3122     +/-  0.2267E-02
  6    6    3   power law  PhoIndex           5.375      +/-  0.8237
  7    7    3   power law  norm               0.3082     +/-  0.2649
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      351.9691     using    53 PHA bins.
Reduced chi-squared =      7.488705     for    47 degrees of freedom
Null hypothesis probability =  0.00
```

Using systematic .02

```
------------------------------------------------------------------------
 Model:  wabs[1]( raymond[2] + power law[3] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs       nH       10^22     7.5890E-12 +/-  0.5304
  2    2    2   raymond   kT        keV       8.740      +/-  0.3625E-01
  3    3    2   raymond   Abundance           0.2258     +/-  0.3462E-02
  4    4    2   raymond   Red shift           2.3100E-02 frozen
  5    5    2   raymond   norm                0.3138     +/-  0.1905E-02
  6    6    3   power law  PhoIndex           6.423      +/-  1.511
  7    7    3   power law  norm               0.8323     +/-  1.179
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      72.55401     using    53 PHA bins.
Reduced chi-squared =      1.543702     for    47 degrees of freedom
Null hypothesis probability = 9.773E-03
```

ABELL 496

```
------------------------------------------------------------------------
 Model:  mekal[1]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   mekal     kT        keV       4.131      +/-  0.1922E-01
  2    2    1   mekal     nH        cm-3      52.43      +/-  630.2
  3    3    1   mekal     Abundance           0.3642     +/-  0.6686E-02
  4    4    1   mekal     Red shift           3.2600E-02 frozen
  5    5    1   mekal     Switch              1.2974E-20 +/-  0.9755
  6    6    1   mekal     norm                9.6351E-02 +/-  0.4615E-03
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      179.5431     using    58 PHA bins.
Reduced chi-squared =      3.387606     for    53 degrees of freedom
Null hypothesis probability = 1.159E-15

------------------------------------------------------------------------
 Model:  wabs[1]( mekal[2] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs       nH       10^22     0.000      +/-  -1.000
  2    2    2   mekal     kT        keV       4.113      +/-  0.1597E-01
  3    3    2   mekal     nH        cm-3      1.000      +/-  -1.000
  4    4    2   mekal     Abundance           0.3719     +/-  0.4774E-02
  5    5    2   mekal     Red shift           3.2600E-02 frozen
  6    6    2   mekal     Switch              1.000      frozen
  7    7    2   mekal     norm                9.6891E-02 +/-  0.3443E-03
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      203.3200     using    58 PHA bins.
Reduced chi-squared =      3.836226     for    53 degrees of freedom
Null hypothesis probability = 1.818E-19
```

```
---------------------------------------------------------------------------
Model:  wabs[1]( mekal[2] + power law[3] )
Model Fit Model Component  Parameter  Unit     Value
par  par comp
 1   1   1  wabs       nH       10^22    0.000     +/-  -1.000
 2   2   2  mekal      kT       keV      4.293     +/-  0.5029E-01
 3   3   2  mekal      nH       cm-3     1.000     +/-  -1.000
 4   4   2  mekal      Abundance          0.4086    +/-  0.3296E-01
 5   5   2  mekal      Red shift         3.2600E-02 frozen
 6   6   2  mekal      Switch            1.000      frozen
 7   7   2  mekal      norm              8.7210E-02 +/-  0.7076E-02
 8   8   3  power law  PhoIndex            4.223    +/-  1.794
 9   9   3  power law  norm               3.9370E-02 +/-  0.5679E-01
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =     154.4148     using    58 PHA bins.
Reduced chi-squared =     3.027741     for     51 degrees of freedom
Null hypothesis probability = 2.452E-12
```

```
---------------------------------------------------------------------------
Model:  wabs[1]( raymond[2] )
Model Fit Model Component  Parameter  Unit     Value
par  par comp
 1   1   1  wabs       nH       10^22    0.000     +/-  -1.000
 2   2   2  raymond    kT       keV       4.136     +/-  0.1599E-01
 3   3   2  raymond    Abundance            0.3449    +/-  0.4396E-02
 4   4   2  raymond    Red shift          3.2600E-02 frozen
 5   5   2  raymond    norm              9.8383E-02 +/-  0.3576E-03
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =     139.9676     using    58 PHA bins.
Reduced chi-squared =     2.591992     for     54 degrees of freedom
Null hypothesis probability = 1.469E-09
XSPEC>pl da res
```

```
---------------------------------------------------------------------------
Model:  wabs[1]( raymond[2] + power law[3] )
Model Fit Model Component  Parameter  Unit     Value
par  par comp
 1   1   1  wabs       nH       10^22    0.000     +/-  -1.000
 2   2   2  raymond    kT       keV       4.267     +/-  0.5709E-01
 3   3   2  raymond    Abundance            0.3672    +/-  0.2919E-01
 4   4   2  raymond    Red shift          3.2600E-02 frozen
 5   5   2  raymond    norm              9.1317E-02 +/-  0.7355E-02
 6   6   3  power law  PhoIndex             4.326    +/-  2.622
 7   7   3  power law  norm               3.1722E-02 +/-  0.6783E-01
---------------------------------------------------------------------------
---------------------------------------------------------------------------
Chi-Squared =     113.7244     using    58 PHA bins.
Reduced chi-squared =     2.187008     for     52 degrees of freedom
Null hypothesis probability = 1.686E-06
```

Abell 754
P20355

```
------------------------------------------------------------------------
 Model: mekal[1]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   mekal      kT        keV      9.203     +/-  0.7438E-01
  2    2    1   mekal      nH        cm-3     1.000     +/-  -1.000
  3    3    1   mekal      Abundance          0.2543    +/-  0.1054E-01
  4    4    1   mekal      Red shift          5.4000E-02 frozen
  5    5    1   mekal      Switch             1.000     frozen
  6    6    1   mekal      norm               9.9170E-02 +/-  0.5296E-03
 ------------------------------------------------------------------------
 ------------------------------------------------------------------------
Chi-Squared =    55.96313    using   58 PHA bins.
Reduced chi-squared =    1.036354    for    54 degrees of freedom
Null hypothesis probability = 0.401

------------------------------------------------------------------------
 Model: raymond[1]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   raymond    kT        keV      9.282     +/-  0.7514E-01
  2    2    1   raymond    Abundance          0.2302    +/-  0.9634E-02
  3    3    1   raymond    Red shift          5.4000E-02 frozen
  4    4    1   raymond    norm               9.9921E-02 +/-  0.5291E-03
 ------------------------------------------------------------------------
 ------------------------------------------------------------------------
Chi-Squared =    53.20153    using   58 PHA bins.
Reduced chi-squared =    0.9673006    for    55 degrees of freedom
Null hypothesis probability = 0.544

 ------------------------------------------------------------------------
 Model: wabs[1]( raymond[2] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs       nH        10^22    0.3960    +/-  0.1444
  2    2    2   raymond    kT        keV      9.006     +/-  0.1218
  3    3    2   raymond    Abundance          0.2050    +/-  0.1264E-01
  4    4    2   raymond    Red shift          5.4000E-02 frozen
  5    5    2   raymond    norm               0.1039    +/-  0.1569E-02
 ------------------------------------------------------------------------
 ------------------------------------------------------------------------
Chi-Squared =    45.73119    using   58 PHA bins.
Reduced chi-squared =    0.8468739    for    54 degrees of freedom
Null hypothesis probability = 0.781

------------------------------------------------------------------------
 Model: wabs[1]( raymond[2] + power law[3] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs       nH        10^22    0.3655    +/-  0.4978
  2    2    2   raymond    kT        keV      9.024     +/-  0.1971
  3    3    2   raymond    Abundance          0.2066    +/-  0.1827E-01
  4    4    2   raymond    Red shift          5.4000E-02 frozen
  5    5    2   raymond    norm               0.1037    +/-  0.3148E-02
  6    6    3   power law  PhoIndex           9.357     +/-  -1.000
  7    7    3   power law  norm               1.8760E-26 +/-  18.05
 ------------------------------------------------------------------------
 ------------------------------------------------------------------------
Chi-Squared =    45.77863    using   58 PHA bins.
Reduced chi-squared =    0.8803582    for    52 degrees of freedom
Null hypothesis probability = 0.716
```

P30271

```
--------------------------------------------------------------------------
 Model:  mekal[1]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   mekal      kT       keV      9.107     +/-  0.4394E-01
  2    2    1   mekal      nH       cm-3     1.000     +/-  -1.000
  3    3    1   mekal      Abundance          0.2538    +/-  0.6192E-02
  4    4    1   mekal      Red shift         5.4000E-02 frozen
  5    5    1   mekal      Switch            1.000      frozen
  6    6    1   mekal      norm              9.4621E-02 +/-  0.2990E-03
 --------------------------------------------------------------------------
 --------------------------------------------------------------------------
Chi-Squared =     150.1367     using    58 PHA bins.
Reduced chi-squared =     2.780309     for    54 degrees of freedom
Null hypothesis probability = 5.429E-11

--------------------------------------------------------------------------
 Model:  raymond[1]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   raymond    kT       keV      9.184     +/-  0.4437E-01
  2    2    1   raymond    Abundance          0.2301    +/-  0.5659E-02
  3    3    1   raymond    Red shift         5.4000E-02 frozen
  4    4    1   raymond    norm              9.5340E-02 +/-  0.2986E-03
 --------------------------------------------------------------------------
 --------------------------------------------------------------------------
Chi-Squared =     140.7258     using    58 PHA bins.
Reduced chi-squared =     2.558651     for    55 degrees of freedom
Null hypothesis probability = 1.891E-09
Model:  wabs[1]( raymond[2] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs       nH       10^22    0.4093    +/-  0.8539E-01
  2    2    2   raymond    kT       keV      8.899     +/-  0.7167E-01
  3    3    2   raymond    Abundance          0.2041    +/-  0.7437E-02
  4    4    2   raymond    Red shift         5.4000E-02 frozen
  5    5    2   raymond    norm              9.9311E-02 +/-  0.8889E-03
 --------------------------------------------------------------------------
 --------------------------------------------------------------------------
Chi-Squared =     117.8367     using    58 PHA bins.
Reduced chi-squared =     2.182162     for    54 degrees of freedom
Null hypothesis probability = 1.192E-06

--------------------------------------------------------------------------
 Model:  wabs[1]( raymond[2] + power law[3] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs       nH       10^22    0.3712    +/-  0.7268
  2    2    2   raymond    kT       keV      8.932     +/-  0.9989E-01
  3    3    2   raymond    Abundance          0.2068    +/-  0.8775E-02
  4    4    2   raymond    Red shift         5.4000E-02 frozen
  5    5    2   raymond    norm              9.8887E-02 +/-  0.1192E-02
  6    6    3   power law  PhoIndex           3.747     +/-  695.5
  7    7    3   power law  norm              9.7335E-07 +/-  0.1223
 --------------------------------------------------------------------------
 --------------------------------------------------------------------------
Chi-Squared =     118.0743     using    58 PHA bins.
Reduced chi-squared =     2.270660     for    52 degrees of freedom
Null hypothesis probability = 4.772E-07
```

Abell 1060

```
------------------------------------------------------------------------
Model:  mekal[1]
Model Fit Model Component  Parameter  Unit     Value
par   par comp
  1    1    1  mekal     kT       keV      3.241     +/-  0.2311E-01
  2    2    1  mekal     nH       cm-3     1.000     +/-  -1.000
  3    3    1  mekal     Abundance          0.3149    +/-  0.8971E-02
  4    4    1  mekal     Red shift         1.1000E-02 frozen
  5    5    1  mekal     Switch            1.000     frozen
  6    6    1  mekal     norm              7.0873E-02 +/-  0.5214E-03
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      99.60511     using   53 PHA bins.
Reduced chi-squared =       2.032757     for    49 degrees of freedom
Null hypothesis probability = 2.633E-05

------------------------------------------------------------------------
Model:  raymond[1]
Model Fit Model Component  Parameter  Unit     Value
par   par comp
  1    1    1  raymond   kT       keV      3.269     +/-  0.2299E-01
  2    2    1  raymond   Abundance          0.2941    +/-  0.8372E-02
  3    3    1  raymond   Red shift         1.1000E-02 frozen
  4    4    1  raymond   norm              7.1840E-02 +/-  0.5322E-03
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      98.81174     using   53 PHA bins.
Reduced chi-squared =       1.976235     for    50 degrees of freedom
Null hypothesis probability = 4.744E-05

------------------------------------------------------------------------
Model:  raymond[1] + power law[2]
Model Fit Model Component  Parameter  Unit     Value
par   par comp
  1    1    1  raymond   kT       keV      3.059     +/-  0.1199
  2    2    1  raymond   Abundance          0.3825    +/-  0.2779E-01
  3    3    1  raymond   Red shift         1.1000E-02 frozen
  4    4    1  raymond   norm              6.2985E-02 +/-  0.6274E-02
  5    5    2  power law  PhoIndex          2.617     +/-  0.4046
  6    6    2  power law  norm              6.6351E-03 +/-  0.7020E-02
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      70.00959     using   53 PHA bins.
Reduced chi-squared =       1.458533     for    48 degrees of freedom
Null hypothesis probability = 2.073E-02
```

Abell 1367

```
------------------------------------------------------------------------
Model:  mekal[1]
Model Fit Model Component  Parameter  Unit     Value
par   par comp
  1    1    1  mekal     kT       keV      4.008     +/-  0.4231E-01
  2    2    1  mekal     nH       cm-3     1.000     +/-  -1.000
  3    3    1  mekal     Abundance          0.1937    +/-  0.1102E-01
  4    4    1  mekal     Red shift         2.1500E-02 frozen
  5    5    1  mekal     Switch            1.000     frozen
  6    6    1  mekal     norm              7.4177E-02 +/-  0.7009E-03
------------------------------------------------------------------------
------------------------------------------------------------------------
Chi-Squared =      101.1111     using   58 PHA bins.
Reduced chi-squared =       1.872427     for    54 degrees of freedom
Null hypothesis probability = 1.081E-04
```

Model: raymond[1]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	raymond	kT	keV	4.027 +/- 0.4243E-01
2	2	1	raymond	Abundance		0.1811 +/- 0.1025E-01
3	3	1	raymond	Red shift		2.1500E-02 frozen
4	4	1	raymond	norm		7.5117E-02 +/- 0.7286E-03

Chi-Squared = 100.7806 using 58 PHA bins.
Reduced chi-squared = 1.832375 for 55 degrees of freedom
Null hypothesis probability = 1.643E-04

Model: raymond[1] + power law[2]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	raymond	kT	keV	4.041 +/- 0.1242
2	2	1	raymond	Abundance		0.1825 +/- 0.3945E-01
3	3	1	raymond	Red shift		2.1500E-02 frozen
4	4	1	raymond	norm		7.4493E-02 +/- 0.1428E-01
5	5	2	power law	PhoIndex		4.358 +/- 62.21
6	6	2	power law	norm		2.8155E-03 +/- 0.2308

Chi-Squared = 100.7395 using 58 PHA bins.
Reduced chi-squared = 1.900745 for 53 degrees of freedom
Null hypothesis probability = 8.416E-05

Model: wabs[1](raymond[2] + power law[3])

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	wabs	nH	10^22	0.1394 +/- 3.760
2	2	2	raymond	kT	keV	4.051 +/- 0.3245
3	3	2	raymond	Abundance		0.1859 +/- 0.4315E-01
4	4	2	raymond	Red shift		2.1500E-02 frozen
5	5	2	raymond	norm		7.3336E-02 +/- 0.1325E-01
6	6	3	power law	PhoIndex		3.856 +/- 20.54
7	7	3	power law	norm		7.7482E-03 +/- 0.2928

Chi-Squared = 100.7762 using 58 PHA bins.
Reduced chi-squared = 1.938004 for 52 degrees of freedom
Null hypothesis probability = 5.854E-05

Abell 2256
P20355

Model: mekal[1]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	mekal	kT	keV	7.323 +/- 0.7026E-01
2	2	1	mekal	nH	cm-3	1.000 +/- -1.000
3	3	1	mekal	Abundance		0.2590 +/- 0.1080E-01
4	4	1	mekal	Red shift		5.8000E-02 frozen
5	5	1	mekal	Switch		1.000 frozen
6	6	1	mekal	norm		7.3882E-02 +/- 0.5229E-03

Chi-Squared = 60.87632 using 58 PHA bins.
Reduced chi-squared = 1.127339 for 54 degrees of freedom
Null hypothesis probability = 0.242

```
--------------------------------------------------------------------------
 Model:  raymond[1]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   raymond   kT        keV       7.375     +/-  0.7118E-01
  2    2    1   raymond   Abundance           0.2363    +/-  0.9900E-02
  3    3    1   raymond   Red shift           5.8000E-02 frozen
  4    4    1   raymond   norm                7.4351E-02 +/-  0.5274E-03
 ---------------------------------------------------------------------------
 ---------------------------------------------------------------------------
 Chi-Squared =      60.42782     using    58 PHA bins.
 Reduced chi-squared =      1.098688     for     55 degrees of freedom
 Null hypothesis probability = 0.286
```

```
--------------------------------------------------------------------------
 Model:  wabs[1]( raymond[2] )
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   wabs      nH        10^22     0.2877    +/-  0.1855
  2    2    2   raymond   kT        keV       7.225     +/-  0.1170
  3    3    2   raymond   Abundance           0.2222    +/-  0.1310E-01
  4    4    2   raymond   Red shift           5.8000E-02 frozen
  5    5    2   raymond   norm                7.6700E-02 +/-  0.1619E-02
 ---------------------------------------------------------------------------
 ---------------------------------------------------------------------------
 Chi-Squared =      57.97827     using    58 PHA bins.
 Reduced chi-squared =      1.073672     for     54 degrees of freedom
 Null hypothesis probability = 0.331
```

```
 ---------------------------------------------------------------------------
 Model:  raymond[1] + power law[2]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   raymond   kT        keV       7.386     +/-  0.1784
  2    2    1   raymond   Abundance           0.2368    +/-  0.2874E-01
  3    3    1   raymond   Red shift           5.8000E-02 frozen
  4    4    1   raymond   norm                7.4262E-02 +/-  0.6129E-02
  5    5    2   power law PhoIndex            3.415     +/-  1636.
  6    6    2   power law norm                1.0944E-06 +/-  0.1265E-01
 ---------------------------------------------------------------------------
 ---------------------------------------------------------------------------
 Chi-Squared =      60.46077     using    58 PHA bins.
 Reduced chi-squared =      1.140769     for     53 degrees of freedom
 Null hypothesis probability = 0.224
```

P60154

```
 ---------------------------------------------------------------------------
 Model:  mekal[1]
 Model Fit Model Component  Parameter  Unit     Value
 par   par comp
  1    1    1   mekal     kT        keV       7.600     +/-  0.1015
  2    2    1   mekal     nH        cm-3      1.000     +/-  -1.000
  3    3    1   mekal     Abundance           0.2513    +/-  0.1333E-01
  4    4    1   mekal     Red shift           5.8000E-02 frozen
  5    5    1   mekal     Switch              1.000      frozen
  6    6    1   mekal     norm                7.0779E-02 +/-  0.5316E-03
 ---------------------------------------------------------------------------
 ---------------------------------------------------------------------------
 Chi-Squared =      29.99125     using    53 PHA bins.
 Reduced chi-squared =     0.6120663     for     49 degrees of freedom
 Null hypothesis probability = 0.985
```

Model: raymond[1]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	raymond	kT	keV	7.662 +/- 0.1024
2	2	1	raymond	Abundance		0.2300 +/- 0.1224E-01
3	3	1	raymond	Red shift		5.8000E-02 frozen
4	4	1	raymond	norm		7.1273E-02 +/- 0.5302E-03

Chi-Squared = 30.05647 using 53 PHA bins.
Reduced chi-squared = 0.6011294 for 50 degrees of freedom
Null hypothesis probability = 0.989

Model: raymond[1] + power law[2]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	raymond	kT	keV	7.933 +/- 0.3138
2	2	1	raymond	Abundance		0.2577 +/- 0.3185E-01
3	3	1	raymond	Red shift		5.8000E-02 frozen
4	4	1	raymond	norm		6.8560E-02 +/- 0.3455E-02
5	5	2	power law	PhoIndex		6.228 +/- 5.788
6	6	2	power law	norm		0.2133 +/- 1.234

Chi-Squared = 22.54014 using 53 PHA bins.
Reduced chi-squared = 0.4695863 for 48 degrees of freedom
Null hypothesis probability = 0.999

Abell 3558

Model: mekal[1]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	mekal	kT	keV	5.106 +/- 0.4697
2	2	1	mekal	nH	cm-3	1.000 +/- -1.000
3	3	1	mekal	Abundance		0.1571 +/- 0.9389E-01
4	4	1	mekal	Red shift		4.8000E-02 frozen
5	5	1	mekal	Switch		1.000 frozen
6	6	1	mekal	norm		0.1102 +/- 0.8435E-02

Chi-Squared = 34.55154 using 58 PHA bins.
Reduced chi-squared = 0.6398433 for 54 degrees of freedom
Null hypothesis probability = 0.982

Model: raymond[1]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	raymond	kT	keV	5.134 +/- 0.4746
2	2	1	raymond	Abundance		0.1458 +/- 0.8649E-01
3	3	1	raymond	Red shift		4.8000E-02 frozen
4	4	1	raymond	norm		0.1111 +/- 0.8634E-02

Chi-Squared = 34.51263 using 58 PHA bins.
Reduced chi-squared = 0.6275024 for 55 degrees of freedom
Null hypothesis probability = 0.986

Model: raymond[1] + power law[2]

Model par	Fit par	Model comp	Component	Parameter	Unit	Value
1	1	1	raymond	kT	keV	5.170 +/- 3.342
2	2	1	raymond	Abundance		0.1445 +/- 0.1463
3	3	1	raymond	Red shift		4.8000E-02 frozen
4	4	1	raymond	norm		0.1107 +/- 0.6651E-01
5	5	2	power law	PhoIndex		3.579 +/- 743.8
6	6	2	power law	norm		3.8446E-05 +/- 0.1656

Chi-Squared = 34.52465 using 58 PHA bins.
Reduced chi-squared = 0.6514085 for 53 degrees of freedom
Null hypothesis probability = 0.977

Discussion and Conclusion

For most of the clusters, it was assumed that the spectral spectral fit that gave the smallest RCS best describes the nature of the X-Ray emission from the cluster. Using this logic, the clusters that are expected to be sources of non-thermal hard x-ray emission are Coma, Abell 496, Abell 754 and Abell 1060. There were cases such as with Abell 3558 where the addition of a power law resulted in a RCS near 1 but that were not considered to have a hard x-ray tail because the fitted value of the power law index had an enormous error of up to 700. An error of that magnitude is obviously an artifact of the fitting program and reveals that there is no power law component in the spectrum of the object. The P10368 Coma observation is controversial because it does not agree with either the P50197 Coma observation or with observations published by Fusco-Fermiano in 1998 that detected non-thermal emission from Coma using BeppoSAX data. A possible explanation for this inconsistency is that the response matrices used are the most recent but not the finished versions. When the new instrument calibration matrices become available we will be able to verify or correct our spectral analysis results. Previously published Abell 754 observations support our conclusion that this cluster is not a source of non-thermal emission. We suspect that some of the clusters might need to be analyzed beyond the 30 KeV energy range to find their hard x-ray tails. HEXTE data should be useful because HEXTE covers the higher end of x-ray spectrum. We plan on analyzing HEXTE data in hopes of confirming the results gathered from PCA data.

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