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Detection of Galaxy Clusters with the XMM-Newton Large Scale Structure Survey

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For many years the power of counting clusters of galaxies as a function of their mass has been recognized as a powerful cosmological probe; however, we are only now beginning to acquire data from dedicated surveys with sufficient sky coverage and sensitivity to measure the cluster population out to distances where the dark energy came to dominate the Universe's evolution. This project uses the XMM X-ray telescope to scan a large area of sky, detecting the X-ray photons from the hot plasma that lies in the deep potential wells of massive clusters of galaxies. These clusters appear as extended (not point-like) objects, each providing just a few hundred photons in a typical observation. The detection of extended sources in such a low signal-to-noise situation is an important problem in astrophysics: we propose to solve it by using as much prior information as possible, translating our experience with well-measured clusters to define a "template" cluster that can be varied and matched to the features seen in the XMM images. Using analysis code, that can be straightforwardly adapted to this problem: the template was defined, and then the method applied to real XMM data. Presented are the findings based on the the software's ability to distinguish astronomical objects in a series of test runs and finally on real XMM data. The results of these series of experiments suggests a level of confidence for the software to be used in future eandevors to indentify clusters.

1. Introduction

Galaxy clusters are of interest because they are the largest gravitationally bound structures in the Universe, and their composition is believed to be dominated by dark matter. The number density of clusters as a function of mass and redshift is a sensitive probe of cosmology: the detection of clusters is important to the study of the evolution of large scale structure.

To date, X-ray observations have provided the highest precision measurements of galaxy clusters. The heated gas trapped within the gravitational potential well of the dark matter, emit strongly in the X-ray band. Much has been learned about the physics of galaxy clusters through pointed observations. However, to discover new clusters via their X-ray emission a "blank sky" survey is needed. For surveys where the detection of X-ray photons occurs less than 1 per second, it would be useful to be able to construct an approach to distinguish galaxy clusters from other astronomical objects.

Knowing that an object may be identified based on it's spatial extent, it is important to understand the parameters that may affect the observed spatial extent. The smearing of a point source to appear wider is due to telescope's point spread function (PSF).

In Astronomy, a point source is understood to have the spatial extent of the PSF. Any source observed to be larger is by definition extended. The physical sizes of AGN and clusters are such that, when placed at cosmological distances (100's of Mpc) the former appear point-like, and the latter extended. Typically clusters are $\sim$100's of Kpc. However some clusters are smaller than this and the X-ray emission is more concentrated than the physical extent of the cluster gas, so that there is some possibility of confusion, especially if the PSF is large.

The AGN emission comes from a comparatively very small region around the black hole at the center of the galaxy, so these always appear point-like. However, it is imprtant to keep in mind that it is possible for two AGN to be aligned and may appear as a single extended source.

The classification of an object can also be determined by spectral analysis. AGN are known to have power law spectra, whereas cluster spectra go as $\propto exp(-hv/kT)$ [2], with distinct line features produced by ions in the intracluster gas.

We used data from the XMM Newton observatory; this telescope currently provides the largest collection area and field of view, making it the instrument of choice for blank sky surveys. Data analyzed was taken with XMM-Newton's European Photon Imaging Camera (EPIC). EPIC has three cameras, two Metal Oxide Semiconductor (MOS) charge-coupled devices (CCD's) and one

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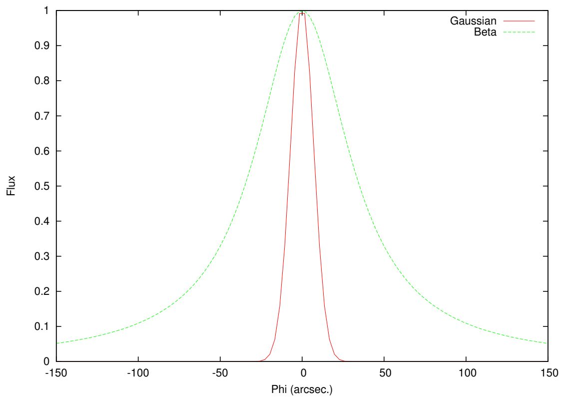

Figure 1. Here a point source is represented by a Gaussian based on the smearing affect of the Point Spread Function. The green curve is a representation of cluster model.

PN CCD. As photons strike these CCD's, the location of event and the photon energy is recorded. The analyzed observation data is simply a list of photon CCD coordinates and energies.

XMM-Newton's Large Scale Structure survey covers an 8 x 8 deg^2 section of sky centered at 2h 18m 00s, -7° 00′ 00″, comprised of 24 x 24 obervations each with a field of view of 30 arcminutes.

The PSF of all X-ray telescopes is energy dependent: the chromatic aberrations in the optics are significant. To properly correct for this the data must be simulated using Monte Carlo methods; the analysis code for doing this is X-ray Monte Carlo (XMC) [1]. While used extensively in the analysis of single cluster observations, we propose to apply this "forward folding" approach to the analysis of survey data containing both AGN and clusters and use both the spectral and spatial information to distinguish the objects.

In section 2 we discuss the experiments required to ensure XMC's ability to locate objects, identify these objects based on spatial and spectral properties, and fianally, analyze data from observation. The result of these experiments are presented in section 3, while the knowledge acquired from these results and a brief conclusion is presented in section 4.

2. Methods

Ideally XMC will evaluate all the parameters of astronomical objects. How well it accomplishes this task is based on how long it is allowed to run; the more iterations allowed, the more accurate the final parameters will be. Using all available information is necessary to assign a probability of "clusterness" to an object.

2.1. Overview of XMC

It is first necessary to provide XMC with input, either previously created simulation or data from an observation. A model is then created to test against the data. The model's parameters will be set with initial trial values and a range that the parameters are allowed to explore. XMC generates a set of simulated data, which are compared with the real data, adjusts the simulated data and repeats. For each iteration it produces a value of all parameters being explored and a misfit value(χ^2). The lower the value of this misfit, the closer the mock data is to that of the real data. After an iteration the program can acquire a more accurate parameter value based on the previous misfit value. XMC returns sets of probable parameters that define models which fit the real data.

XMC outputs all parameters as lists in files. These files are used to reconstruct an image based on the fraction of photons it determines to be from AGN or clusters. The AGN photons are all plotted in green and the cluster photons are plotted in red. At a glance a user can get an idea of the nature of objects analyzed.

2.2. Experiment 1

First a simulation was defined using an AGN object, centered in the field of view. After creating the simulation, a model was created to test against. All parameters of the model were fixed save one, so that the object and the model were identical except for the location. A one dimensional coordinate was allowed to vary, to see if XMC could locate an object in a single direction (ie x or y direction).

2.3. Experiment 2

For this next experiment, it is necessary to be familiar with the three spatial models of XMC. When a model is defined within XMC, all simulated photons of that model are generated within the spatial boundaries that particular model. For a point source, the photons are confined to a six arcsecond radius. There are two extended source models, the spatial Gaussian and the Beta models. The latter is the surface brightness given by Sarazin [2],

$$I(r) \propto \frac{1}{[1+(\frac{r}{r_c})^2]^{3\beta-\frac{1}{2}}} \quad (1)$$

where r is the radius of the cluster and r_c is the core radius and is the parameter allowed to vary within XMC. The parameter β has been calculated for many pointed observations and for the simplicity of the simulation was set to .66 in accordance to these findings. Finally, the spatial Gaussian model,

$$I(r) \propto exp(\frac{-r^2}{2\sigma^2}) \quad (2)$$

where σ is the parameter allowed to vary within XMC. Considering the different models or combination of models available to test against a simulation, we will define a "blob" to be this combination of models tested.

The purpose of this second experiment is not only to determine whether or not XMC can determine the nature of the the simulation objects but also to determine which of these models or combination there of, are a better fit for the simulation. For example, the spatial Gaussian and the Beta model can both be fitted to the cluster simulation. For a point source the point source model is an option, but what if sigma in the spatial Gaussian model is allowed to go small, on the order of the PSF of the telescope. Would this be a better represenation of the smearing effect on a point source?

XMC uses these spatial models along with the spectral elemants to distinguish between AGN and clusters. This experiment consisted of two tests. In the first, an AGN object was defined, centered on the exposure map. The blob consisted of a point source model and a beta model with there location tied together so that the blob would remain together. The spatial paramters of the beta and the spectral parameters of both were allowed to vary.

In the second test, the simulation was identical; the blob consisted of two Gaussian spatial models one with the spectral paramters of an AGN and one with cluster spectral parameters. Again the location of the models were tied together as well as the σ parameter. XMC would then explore the spatial and spectral parameters of the simulation and return the fraction of photons that were "AGN-like" and "cluster-like".

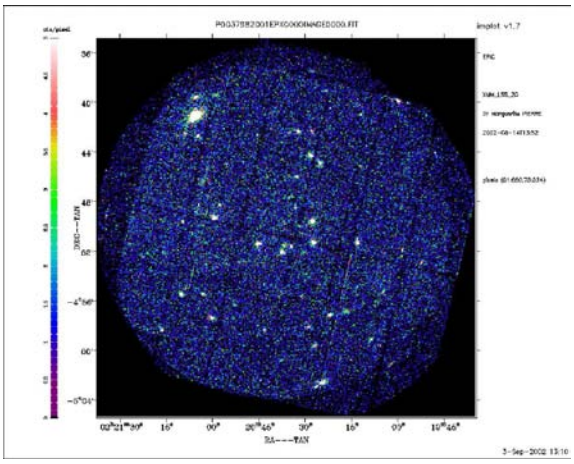

Figure 2. A single field from the Large Scale Structure survery, LSS-20

2.4. Experiment 3

A final simulation was created using a mixture of six AGN and cluster objects placed in various locations on the map. Again two tests were run. The comparison blobs were the same the ones used previously with a mixture of AGN and clusters. Six blobs were used to match the six simulation objects. The point of this experiment was to ascertain XMC's ability to not only track the location but the spatial and spectral parameters of each object.

2.5. XMM Data

Data from the Large Scale Structure survey, was downloaded, and reduced to a list of photon location and energy, was read into XMC. The same blobs were used on the data from the telescope as with the previous experiment. Two spatial Gaussian models tied together with x-ray background built in was used and then a point source and a Beta model also with x-ray background bult in.

It is interesting to note some features of the EPIC cameras. We can see (Fig. 2) the PSF affect the objects in the exposure map. The central objects all have a width of about 6 arcseconds. In

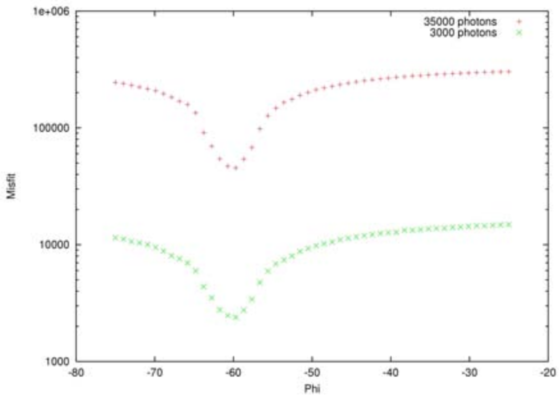

Figure 3. Plot of Misfit χ^2 vs Phi. XMC located the AGN simulation with 3000 photons and again with 35000 phtons.

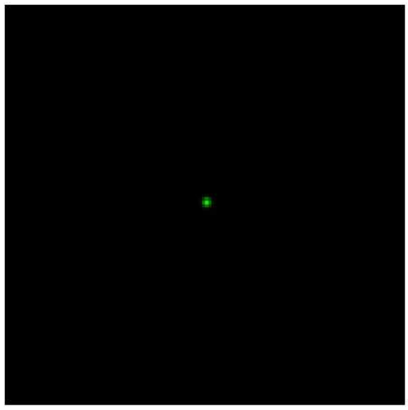

Figure 4. The simulation was set as an AGN. The model was allowed to vary between AGN and cluster parameters. XMC determined that the simulation photons consisted that of only AGN to one part in 1000.

the upper left corner there is an object which is much larger than any other object. This could be the PSF greatly smearing the object near the edge of the camera or this could be an extended source. The gaps between the CCD's is also noticeable in the exposure map.

3. Results

3.1. Experiment 1

The parameter we wanted to explore was allowed to vary, in this case the Phi coordinate. The simulation object's location parameter, Phi, was set at a value of -60. XMC then tried to match the object location of the model to the object location of the simulation along the Phi coordinate; the results are shown in Fig. 3. As shown in the plot the lowest misfit value corresponds with the correct parameter value. When applying this same technique to the Psi coordinate, an error was discovered and corrected in the XMC code when the program failed to locate the object.

It is interesting to note the slope of the curve in this plot. As XMC's estimation of the parameter value approaches that of the simulation, the slope sharpens drastically, while the slope levels out the further away one gets from the true value. From this we can better understand the burn in time required for XMC. For the first few hundred iterations the program simply "guesses" parameter values in the specified allowed range and records a misfit value until it has enough data points to recognize sloping curves, making it possible to hone in on the parameter value. However, to some extent XMC is always guessing; the χ^2 simply helps XMC judge when and how much to adjust a paramter.

3.2. Experiment 2

The next test run, as mentioned before, was to evaluate XMC's ability to distinguish between AGN and cluster objects. This was the first time using the technique to reconstruct an image in multiple colors based on the fraction of photons XMC determined to be from AGN or clusters.

As can be seen in Fig. 4, XMC has correctly inferred that the simulation object was an AGN. The spatial extent corresponds with XMM's PSF, about 6 arcseconds. The blobs of this run consisted of a point source model and Beta model. The number of photons XMC determined to be of AGN origin is approximately 1000 times greater than cluster photons. This information can be used to give a rough estimate on the probability of being an AGN. The results of the blobs with two spatial Gaussians tied together were similar. However, the ratio of AGN to cluster flux is not

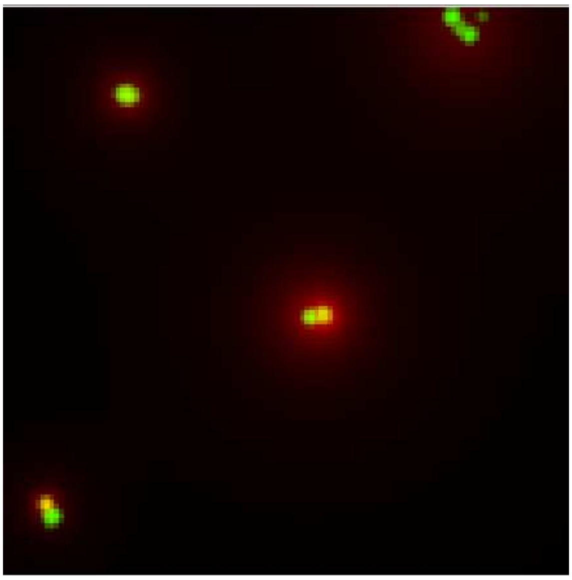

Figure 5. 3 cluster & 3 AGN objects. In the center and top left corner are cluster simulations, in the top right two AGN and bottom left a cluster. XMC located every object but the two clusters still have significant AGN flux. There still is some uncertainty of the nature of some objects.

as extreme.

3.3. Experiment 3

The final simulation consists of six objects, three AGN and three clusters. Knowing that XMC can locate and distinguish simulation objects, it necessary to evaluate how well XMC can distinguish objects in close proximity of one another. In the upper right corner of this simulation two AGN were placed near one another which were both located within the radius of a cluster object. In the center was cluster, bottom left an AGN and top left another cluster.

The result show (Fig. 5) XMC's ability to identify the two AGN and cluster in the upper right corner. However, there seems to be some ambiguity about the other objects. The two remaining cluster objects appear to have just as much AGN flux as cluster flux.

3.4. XMM LSS 20

For simulations, the number of objects is known and creating the number of model objects to be the same is simple enough. However when analyzing real data, the number of objects will not be known, so it is necessary to take a somewhat different approach.

Experience with pointed observations suggests that a combination of Gaussian components is a good way of characterising a complex image. In practical terms, one defines a model within XMC consisting of some large number, typically 100, of Gaussian "blobs" with given spectral properties. Following previous experiments, we define each blob to be two concentric Gaussians of equal size, that differ in their spectral properties. The function of the flux assigned to each spectral component is an indication of the "clusterness" of that blob. Bright objects in the data can then be built up from collections of blobs, whose clusterness function should change during the XMC analysis to reflect the spectral type of the object.

Data from the Large Scale Structure survey was read into XMC. Since this was not a simulation, the X-ray background had to be taken in to account. A model for the background was created and the same AGN, cluster model was used as in the test runs. However, 100 model objects were used. With the extra models stacking on top of one another, only the number of objects in the data will be detected. However, in this run, only the data from the PN CCD's was used.

In a survey such as as this, it was expected that 70% of the objects would be AGN. As is shown in Fig. 5, all the objects have some green. Some objects seem to have a considerable amount of cluster photons as well.

4. Discussion and Conclusion

The test runs provided some level of confidence in XMC's ability to locate and distinguish astronomical objects. The accuracy of XMC for simple simulation was encouraging. When complicating a test run by introducing a larger number of blobs, the program became slower, because of the greater number of parameters to evaluate.

In experiment 2, there seemed to be some ambiguity of the nature of the object when using the spatial Gaussian blobs. However, some ambiguity is to be expected when allowing the spatial parameters of the Gaussians to vary. By tying

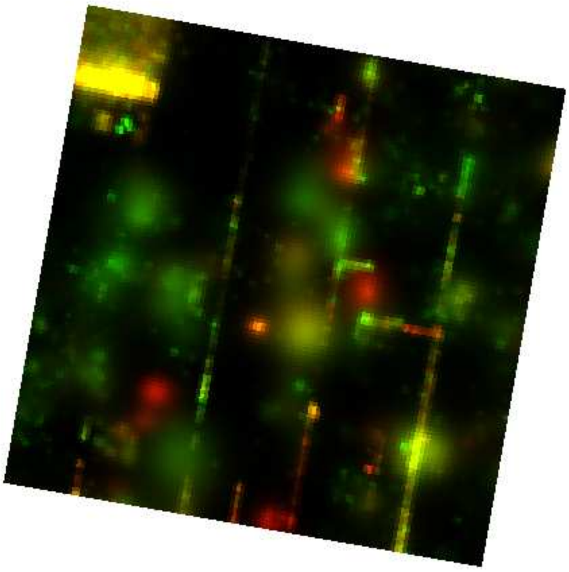

Figure 6. The results of the LSS data set with green blobs representing AGN and red representing clusters.

the σ parameter of each Gaussian, the model with AGN spectrum would be allowed to grow to the size of a cluster, whereas the model with cluster spectrum would also be allowed to shrink to the size of the telescopes PSF. The extra degree of freedom allowed provides us with useful information of the ability of the program to determine astronomical objects.

The six blobs in experiment 3 matched the location of the simulation. However the nature of the objects was not determined accurately (Fig. 5). This is due the low number of iterations XMC was allowed to make. It is believed that if the program was allowed to run longer, it would eventually infer the correct spectral and spatial parameters of the simulation objects.

An incredible amount of information was acquired from the results of the XMM data. It can be seen that in areas between the CCD's, XMC assumes there is AGN photon flux, although no data is actually recorded by the telescope in these regions. When the data from the MOS detector along with the PN is used the gaps between the CCD's will be resolved.

The results of the LSS data suggests that using mutliple blobs to reconstruct a single object is a viable procedure for distinguishing objects. The color representation of AGN and cluster objects has allowed a rough estimation of probability to be assigned to the LSS data. Averaging the last few hundred iterations of XMC to create a colored plot demonstrates the effectiveness of programs ability to locate and determine objects' nature. Taking a look at the top left object, which seems to be smeared, we see both AGN and cluster flux. Also the elongation of the reconstructed object is much greater than that of the object in the data. This could possibly be the greater PSF of the telescope at the edges, smearing the object. However, one would expect the reconstructed image to be similar to that of the exposure map. Considering that this object is the brightest in the field of view, it is possible that XMC positioned a majority of the 100 blobs on this one object. The average of which smeared the recontructed image.

5. Acknowledgments

I would like to thank my mentor Phil Marshall for not only exposing me to the world of research, but taking the time to help me develop skills that will be highly valuable in future endeavors. Thanks Phil Marshall, John Peterson and Karl Anderson for sharing their research and for their guidance toward a better understanding of the Astrophysics.

Graduate school and narrower field of study is just over the horizon for me. I appreciate the opportunity to test the waters, to get a feel for what I may want to study in graduate school. So, my thanks to the Department of Energy and the Science Undergraduate Laboratory Internship program for making this possible. Thanks to everyone at the Stanford Linear Accelerator Center for sharing their wealth of knowledge and for hosting this program.

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