Automation of Reduction and Analysis of Chandra X-Ray Satellite Data for Studies of Clusters of Galaxies

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Abstract. In this work we developed a system to automate the processes of data reduction and analysis of galaxy clusters observed by Chandra X-ray satellite. This automation enables generation of temperature and gas density profiles from raw data of multiple observations, making data reduction and analysis easier and faster. The automation script uses a standard reducing data process from Chandra, extracts spectrum from data, and simultaneously fits the spectra of multiple observations while performing the deprojection process. We show some outputs of the reduction and analysis to demonstrate how the automation works.

1. Introduction

As the largest structures in the universe to have reached an approximate dynamical equilibrium, clusters are important for our understanding of the structure and evolution of the universe as a whole. Clusters serve both as astrophysical laboratories, in which many astrophysical phenomena take place, and as important cosmological probes.

It was not until 1970s that astronomers found that galaxy clusters are luminous in X-ray. The typical luminosity or energy output is $L_X \sim 10^{43} - 10^{45}$ erg/s. The X-ray emission originates from hot diffuse Intracluster Medium (ICM) of tens to hundred million Kelvin ($1 - 10$ keV) and is primarily a combination of thermal bremsstrahlung and optically thin line emissions (the main line is Ly$\alpha$ from 25 times ionized Fe at $\sim 7$ keV). X-ray observations provide information on the amount, distribution, temperature and chemical composition of the ICM. By observing a cluster in X-ray and assuming that it is in hydrostatic equilibrium, the total mass of the cluster can be estimated from its temperature and density profiles.

Chandra X-ray satellite, with a good spatial resolution ($\sim 0.5$ arcsec), plays important roles in observations of galaxy clusters. Its ACIS (Advanced CCD Imaging Spectrometer) detector is capable of providing spatial and spectrum information, making Chandra excellent for observing and analyzing galaxy clusters. Density and temperature profiles of the ICM are two properties among others that one usually wants to determine. It takes a series of complicated data processing and analysis to obtain density and temperature profiles of the ICM. Chandra
scripts are available for most of these purposes, still some processes should be done "by hands" and therefore are quite tedious and time consuming, especially if we have to work with many clusters, which is common in cosmological studies. We developed therefore a script to automate the processes of data reduction and analysis. Basically, the automation enables us to generate temperature and density profiles from raw image data. Most modern X-ray detectors including ACIS of Chandra are imaging spectrometers, so that each observation results in a photon list from which images, spectra and light curves can be extracted. In general the numbers of photons detected in X-ray observations are small. To improve statistics it is often demanded that we combine data of several observations of the clusters. Our automation system allows simultaneous reduction and analysis of multiple observations.

2. The automation script
The automation script we developed is written in python. Our script make use of CIAO (Chandra Interactive Analysis of Observations) version 4.9 (http://cxc.harvard.edu/ciao/), an open source software released for analysis of observational data of the Chandra X-ray satellite, with Chandra Calibration Database (CALDB) 4.7.3. This software runs on 64-bit Linux operating systems.

Our script has the abilities to:

- perform data reductions from raw data to produce clean images that are free from bad pixels, point sources, flares, and background
- combine images of several OBS-IDs of the same object (the users are responsible to check which OBS-IDs are belong to the same object)
- define various annuli with certain net counts, total counts, SNRs, or use the default values
- extract spectrum for each OBS-ID
- perform curve fittings and deprojections with multiple OBS-ID spectrum, and estimate errors
- generate temperature and gas density profiles and errors in the form of .txt file.

The automated processes are briefly described in the following subsections.

2.1. Automation of data reduction
Data reduction consists of three steps: data reprocessing, removal of point sources, and X-ray background subtraction. We automate data reduction by combining the otherwise separate processes in Chandra data reduction into automatic consecutive steps.

2.1.1. Data reprocessing
L1 images (raw data that has been corrected from instrumental errors) are reprocessed using the latest calibration data, bad pixels and bad columns are removed. This process utilizes Chandra tool chandra_repro available in CIAO. The result of this process is L2 images that are free from bad pixels and bad columns.

2.1.2. Removal of point sources
Since the objects to be analyzed are galaxy clusters, i.e. spatially extended objects, point sources are considered as noise and must be removed from the observational data. Prior to removal of point sources L2 images are corrected with exposure maps, i.e. maps of effective area of ACIS CCD as a function of energy and position. Users may choose which tools in Chandra (wavdetect, celldetect, or vtpdetect) to be used to remove point sources.
2.1.3. Subtraction of X-ray background sources

In principle there are 3 types of X-ray backgrounds we have to deal with, i.e. instrumental background such as thermal noise, high energy particles that hit CCDs or interact with materials on the satellite and produce either continuous or line spectra, and cosmic X-ray background (CXB) that is dominant in the energy \( E < 2 \) keV.

The step of X-ray background subtraction consists of the following substeps:

- **flares removal.** Flares are induced by charged particles that hit CCDs. The disturbing events can be recognized in the light curves. Chandra script `lc_clean` is used in the light curves analysis.

- **normalize count rate of high energy particle background with blank-sky background.** Blank-sky backgrounds are images of empty sky without any source of emissions from galaxies (point sources) or galaxy clusters (spatially extended sources). Blank-sky backgrounds contain photons originated from high energy particles and CXB. High energy particles count rates are stable enough on a short time scale. But on a longer time scale the count rates of high energy particles change, causing differences between the counts of high energy particles in the observation data and in the blank sky backgrounds. Therefore, normalization between the two should be done. Our automation script does this only for high energy particles, which are dominant in the \( E > 2 \) keV regime. Below this energy, CXB is dominant. Vikhlinin et al. [1] however argued that correction in the low energy regime would not alter temperature profiles significantly.

- **subtracting background from observational image.** In this process the observational image and the blank-sky background image are corrected with the exposure maps. Thereafter, background is subtracted from the observation image to produce image that originates from galaxy cluster only.

2.2. Automation in defining annuli

In studies where temperature and density profiles of the ICM gas are required such as in cluster mass determination, we need first to define annuli and then extract the spectrum for each annulus. In the simplest case we divide the image into several concentric circulars, whose center is determined by the locus with highest number of photon counts. This basically advisable for relaxed clusters, whose structure are approximately spherically symmetric. Checking for relaxedness is not facilitated in our script, the users are advised to settle this beforehand.

Cooling flows are well known to occur in the centers of galaxy clusters, causing the hydrostatic equilibrium not to be met. Therefore, the common trick is to not include the core regions of the clusters in the determination of the temperature and gas density profiles. The values of the core radii should be supplied by the users.

There are no specific guidelines on how to define good annuli. Cavagnolo [2] for example defined annuli in such a way that each annulus has the same number of counts, so that the size of the annulus increases with the increasing radius from the center. Schellenberger [3] in his study of galaxy clusters in the HIFLUGGS (HIghest X-ray FLUx Galaxy Cluster Sample) set each annulus to have \( \text{SNR} \geq 60 \). The process of defining annuli manually is very tedious and time consuming. We therefore automate this. In our script users may choose to define the annuli based on certain total counts, nett counts or SNRs. The default in our script is a constant total net count for 7 annuli in the radius of 5.0\'. For each cluster, the clean images of all OBS-IDs are combined and afterward annuli are set based on the combined images.

2.3. Automation of spectral fitting dan deprojection

Spectra are extracted from the annuli area that have been set. Spectral extraction is performed both for observational data and blank sky background. The resulting spectra must be corrected
with ARF (Auxiliary Response File) that contains data of the effective area and quantum efficiency of ACIS as a function of energy and position and RMF (Redistribution Matrix File), which is the data of the probability of photons being captured in different energy ranges. The blank-sky background spectrum is subtracted from the spectrum of observational data to produce a spectrum of the galaxy cluster. Our script does not create ARF and RMF from the background, because the background spectrum will only be subtracted from the observation data (no fittings will be done for the background spectrum) and because it takes a long time to extract ARF and RMF for the background spectrum.

All spectra are fitted with Astrophysical Plasma Emission Code (APEC) model for the hot plasma emission (http://cxc.harvard.edu/ciao/dictionary/apec.html) convoluted with photoelectric absorption with Wisconsin cross-section (WABS) model for the Galactic absorption. Our script employs Chandra script called Sherpa to perform this task. Users need to set the values of metalicity, hydrogen column density and redshift of the cluster.

From the spectral and density fitting aforementioned we obtained 2-dimensional profiles of projected images. Therefore, assuming that galaxy clusters are spherically symmetric with constant emissivity, a deprojection technique is performed to recover the three-dimensional source properties such as temperature and density profiles. Our script employs deprojection modul developed by Tom Aldcroft, which is an extension package of CIAO Sherpa.

3. Example of results
As an example we show here how the reduction and analysis works for cluster RXJ1532.9-3021. Shown in Figure 1 and Figure 2 are respectively the L1 dirty image and L2 clean image of this cluster after data reduction. The electron density and temperature profiles obtained from deprojection procedure are displayed in Figure 3 dan 4. One can do further analysis for example to fit the density profile with a single $\beta$ model and the temperature profile with an exponential model.

![Figure 1. L1 dirty image of RXJ1532.9-3021.](image1.png)

![Figure 2. L2 clean image of RXJ1532.9-3021 after data reduction.](image2.png)
Figure 3. Electron density profile of RXJ1532.9-3021 fitted with a single $\beta$ model.

Figure 4. Temperature profile of RXJ1532.9-3021 fitted with an exponential model

4. Conclusions
We have developed an automation system based on phyton that enables generation of temperature and gas density profiles from raw data of multiple observations of Chandra galaxy clusters. The automation ease and quicken data reduction and analysis of galaxy clusters, which is desirable for cosmological studies.

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