Simulations of Galaxy Clusters observed by Chandra

Alessandro Gardini

Dipartimento di Astronomia, Università di Padova, vicolo
dell’Osservatorio 2, 35122 Padova - ITALY

Abstract. A software package able to simulate imaging observations of
galaxy clusters by the Chandra X-ray telescope is here presented. We
start from high resolution N-body hydrodynamical simulations of galaxy
clusters and assign to each gas particle a spectrum of emissivity, after as-
suming the MeKaL model. We then construct spatial images of the source
differential flux which are used to create lists of incoming X-ray photons,
preserving information on photon direction and energy. The photon lists
are passed on to the Chandra simulator (MARX) to produce the final
observation events. Background events are added to complete the simu-
lation. Data analysis is currently in progress and simulated observations
by other telescopes will become available in the Future.

1. Introduction

We present a software package that, starting from high resolution hydro-dynam-
ical simulations of galaxy clusters, reproduces observations of the ICM by the
Chandra X-ray telescope. Syntetic data can then be processed and analysed
using the same tools and procedures as real observations. This enables us to
directly compare the results of the simulations with the observational data and
furthermore to compare the intrinsic properties of clusters, as given by simu-
lations, with the same quantities obtained at the end of the process of data
reduction and analysis. In this way, we are able to check the reconstructed
properties of clusters as well as to get indication on the quantity of information
retained or lost in the observations. On the other hand it has to be remem-
bered that the reliability of the comparison between a simulated quantity and
the real counterpart depends on how well the relevant physics inside simulations
is modelled.

2. Cluster Simulations

The package can be easily adapted to run on every kind on hydro-simulations.
For our input we used a set of cluster simulations realized by G.Tormen via
the resimulation technique of regions of interest inside a cosmological simulation
(see e.g. Tormen, Bouchet, & White 1996).

This starting simulation reproduces a ΛCDM model of Universe, with pa-
rameters $\Omega_0 = 0.3, \Omega_\Lambda = 0.7, H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and baryon fraction $\sim 0.1$. 
Figure 1. Left: map of projected flux \((\text{photon s}^{-1} \text{ cm}^{-2})\) per pixel of a cluster at redshift \(z \simeq 0.778\). Right: simulated observation of the same object by the Chandra ACIS-S3 detector given an exposure time of 19500 s. The image is turned upside-down and the main clump is set at the Chandra ACIS-S aimpoint.

It describes a box of size equal to 479 \(Mpc h^{-1}\) with \(512^3\) particles of Dark Matter\(^1\).

Clusters are identified in its final output using a spherical overdensity algorithm and resimulated singularly from the beginning using the GADGET Tree-SPH code. Each resimulation makes use of \(\sim 10^6 + 10^6\) particles of Dark Matter and gas to model the cluster and the surrounding region, while the external tidal field is reproduced by a smaller number of more massive particles. The mass of the Dark Matter particles ranges between 2 and \(5 \cdot 10^9 M_\odot h^{-1}\) depending on the cluster, and the gas particle mass scales accordingly. The softening related to the cubic spline kernel is \(\sim 5 \text{kpc} h^{-1}\). At the end of the simulation the cluster is described by 2 to \(3 \cdot 10^5\) particles for each species inside the virial radius. A set of twelve clusters has been simulated and for each one 50 outputs were retained between \(z = 10\) and \(z = 0\).

3. Method : (1) general

In order to describe how the package works, it can be useful to distinguish between a first general part of the method and a second one related to Chandra. For a cluster at a given redshift \(z\), the first part accounts for the construction

\(^1\) [http://www.mpa-garching.mpg.de/Virgo/VLS.html](http://www.mpa-garching.mpg.de/Virgo/VLS.html)
of a map of the incoming flux (or of some other related quantity) that preserves the energy information.

We start by considering the position $\vec{x}_i$, mass $m_i$, density $\rho_i$ and temperature $T_i$ for each gas particle $i$. We then assign to the particle a volume $V_i = m_i/\rho_i$ that is assumed cubic and centered on $\vec{x}_i$.

We then assign to each particle the related spectral emissivity $\epsilon^\nu_i = \epsilon^\nu_i(\rho_i, T_i)$ computed by XSPEC using the MeKaL spectral model. The metallicity enters as a parameter; here we present results obtained assuming $Z = 0.3 Z_\odot$, but any other value is possible. The luminosity of each particle becomes then $L^\nu_i = \epsilon^\nu_i \cdot V_i$ and is assumed uniformly distributed on $V_i$.

In general, we consider emissivity and derived quantities (luminosity, flux, surface brightness) in terms of incoming photons instead of energy because this quantity is more easily related to observations.

Given an observational direction, we get a bidimensional map of the cluster spectral luminosity projecting each $L^\nu_i$ on a pixellized perpendicular image and summing on particles. The information is then stored in a 3D array, where two dimensions are spatial and the third one contains the energy channels. The transformation from the cluster luminosity at redshift $z$ to the flux per pixel at $z = 0$ is then direct: in term of incoming photons, it holds

$$F^\nu = \frac{(1 + z)^2 L^\nu(1+z)}{4\pi D_L^2},$$

being $D_L$ the luminosity distance. Note that the frequency $\nu$ in the flux is related to $\nu(1 + z)$ in the cluster luminosity.

Typically, the number of pixels ranges from $256^2$ to $1024^2$, depending on the field of view, while the energy ranges from 0.1 to $10 keV$ in bins of $20 eV$, even if $100 eV$ should be sufficient according to the energy resolution of Chandra (Chandra Proposers’ Observatory Guide\textsuperscript{[2]}).

4. Method : (2) Chandra

It has to be remembered that a simulator of Chandra already exists: it is called MARX\textsuperscript{[3]} and performs the ray-tracing of incoming photons of a given source inside the telescope up to the possible final detection. It returns a list of binary data files describing the detection events that can be assembled to reproduce a CXC Level 1 FITS data file.

However, only some kind of sources of simple form and uniform spectral flux are implemented in MARX, while users are allowed to construct their specific source writing some C routines and linking it dynamically to the code. So did we, as described in the following.

For a given cluster, we generate a list of incoming photons by random extraction from the cumulative distribution of the spectral flux array described above. Each photon hence owns a position in a pixel and an energy in the energy

\textsuperscript{[2]}http://asc.harvard.edu/udocs/docs/docs.html
\textsuperscript{[3]}http://space.mit.edu/ASC/MARX
band, with the given resolution. Other random extractions define the position of photon inside the pixel and its energy in the bin. The number of photons extracted is set to $10^6$.

We then enable MARX to accept as input this photon list and the total flux of the cluster (in $\text{photons s}^{-1} \text{cm}^{-2}$): photons are randomly extracted from the list according to the total flux and the exposure time, and usually processed up to the possible detection.

No background is introduced by MARX. We add background events randomly extracting them from Chandra ACIS observations of empty fields available in the home page of M.Markevitch$^4$. An example of a complete simulated observation is shown in the Fig. 1.

5. Data analysis and future developments

As written above, the detection events generated by MARX have the same characteristics of the CXC Level 1 observational data file and can be analysed using the same procedures and CIAO tools. This analysis is currently in progress and will concern the reconstructed properties of clusters, the cluster morphology (maps and profiles) and its relation to the dynamical state of the object. Detectability of clusters at high redshift is another possible application.

We plan to extend this package to the XMM-Newton telescope, using the related simulator SCISIM, in the next future.

6. Acknowledgments

The author wish to thank L.Moscardini, G.Tormen and S.DeGrandi, that collaborate to this project.

References

Tormen, G., Bouchet, F.R., & White, S.D.M., 1997, MNRAS, 286, 865

$^4$http://hea-www.harvard.edu/~maxim
This figure "fig1.gif" is available in "gif" format from:

http://arxiv.org/ps/astro-ph/0110233v1