Deprojection analysis of X-MAS images of a simulated cool-core cluster

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Abstract

We apply a standard deprojection analysis to simulated X-ray observations by X-MAS[1] of a model cool-core cluster of galaxies similar to A2390[2], in order to assess the robustness and reliability of results of analogous observations by Chandra. We simulate the cluster evolution using FLASH[3], starting from a condition of hydrostatic equilibrium and in the presence of bubbles of hot plasma, and allowing the gas to cool radiatively. We consider different evolutionary times as well as distances and exposure times, comparing the physical quantities in the simulations to the results of deprojection analysis applied to the simulated observations. In general, we found a remarkably good fit , which improves with the number of counts. On the other hand, quantities obtained without deprojection show systematic biases even under the best observational conditions.

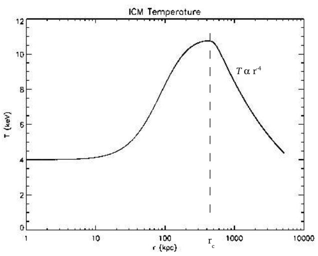
The X-MAS package

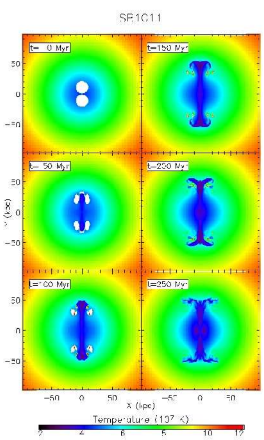
The X-MAS (X-ray Map Simulator) package is a tool designed to simulate X-ray observations obtained by hydro/N-body simulations. Starting from a set of fluid elements of given (V_i, ρ_i, T_i, $\mathbf{v}_i$), we assign to each one a spectral emissivity $\varepsilon_i^{\nu}(\rho_i, T_i, Z)$ in (ct/s/cm^3/keV) using a given spectral model(e.g. APEC, MeKaL). Metallicity is set to $Z = 0.5\ Z_{\odot}$ using the GRSA XSPEC abundance table[4].We then compute the volume luminosity $L_i = \varepsilon_i^{\nu}\ V_i$ and photon flux $F_i = (1+z)^2\ L_i^{\nu(1+z)}/(4\pi D_L^2)$. The volumes are then projected onto the plane of the sky, and the flux of incoming photons is uniformly distributed on the sky according to the volume size. All the spatial and spectral information is stored in a 3-D array: $N^2_{pixel} \times N_{energy\text{-}bins}$. ($N_{pixel} = 512$; Energy band = (0.3,9.5) keV, $\Delta E = 0.02$ keV) The WABS model accounts for Galactic absorption.

We define a correspondence between the spatial part of the box of the source flux (N^2_{pixels}) and the ACIS-S3 CCD (1024^2 pixels). The response of the optical system and of the ACIS-S3 CCD is described by 1024 ARFs and RMFs defined on 32x32 pixel regions (FEF regions). In each FEF region, XSPEC(fakeit none) generates a spectrum of detected photons after assuming on input the related ARF and RMF, and as input model the photon flux corresponding to that region. Photon spatial coordinates are randomly extracted inside the FEF region: this is our lowest resolution. To increase spatial resolution, a Quad-Tree algorithm recursively divides regions in subregions if the expected number of photons exceeds a threshold value ($N_{th} > 50$).

The cluster model

The cluster parameters have been chosen to resemble X-ray observations of A2390. We assume a NFW [5] density profile for the overall mass with scale radius r_c = 520 kpc, and a total mass $M_{vir} = 1.7 \times 10^{15}\ M_{\odot}$ within a virial radius r_{vir} = 2.5 Mpc. The figure (right) shows the assumed initial temperature profile suggested by the results of De Grandi & Molendi (2002) [6]. The gas density profile is then derived by hydrostatic equilibrium.





A pair of bubbles is set in the cluster atmosphere, mimicking the late evolutionary phases of the outflows of a central AGN. The bubbles are initially filled by relativistic (γ=4/3) plasma, which has the same pressure as the surrounding ICM, while its temperature and density are 100 times higher and lower respectively.The bubbles are spherical, with radius R_b=10 kpc and are set at d_b=11 kpc from the cluster center. Their internal energy amounts to $E_{int} = 5.9 \times 10^{59}$ erg.

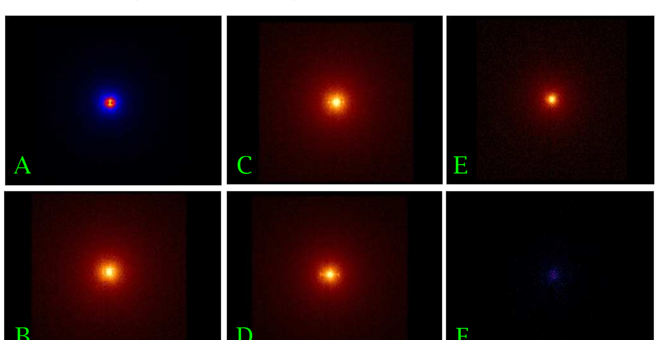
The evolution of the bubbles is shown in the maps of temperature of the cluster (left). During its rise, the bubble entrains a column of cold material which first gives it a mushroom shape, and later bisects it; the bubble then assumes the shape of a vortex ring. In the end, the cold material falls back toward the cluster center and affects the developing cooling flow. During the simulation, the coldest ICM is part of the uplifted material or accumulated in a torus surrounding the center of the cluster.

X-ray images of the cluster by X-MAS

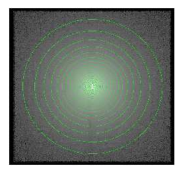
Image	t_{evol}(Myr)	redshift	t_{exp}(ks)	N_{count}	scaling
A/Clus0	0	0.1	500	6.9E6	linear
B	50	0.1	500	6.9E6	squared
C	100	0.1	500	7.0E6	squared
D	200	0.1	500	7.1E6	squared
E	0	0.23	500	1.8E6	squared
F	0	0.23	5	1.7E4	linear

We constructed images at various evolutionary times and redshift, and for different exposures. In all images, we assumed the APEC spectral model for the ICM emission and a column density of $n_H = 5 \times 10^{21}$ cm^{-2} for the Galactic absorption. The Doppler effect due to gas motion is accounted for.

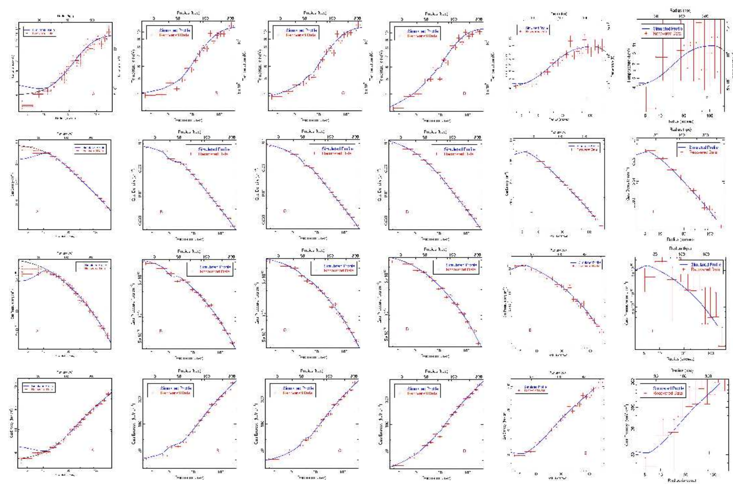
The table above summarizes the parameters of the X-MAS images: their label, the evolutionary time of the simulation, the cluster redshift, the exposure time, the number of counts, and the scaling used in the figures below. The Clus0 image refers to the same image as A, but without bubbles.



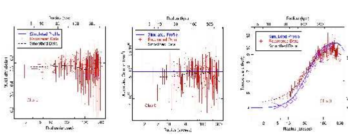
The deprojected profiles



The X-MAS events files were subjected to a standard deprojection analysis, as described in Sanderson et al. (2005) [7]. Source and background spectra were extracted from the same set of 19 concentric annular regions in the cases A-E. Each spectrum was fitted in XSPEC with an APEC hot plasma model, linked together using the PROJCT model to handle the deprojection. Each annulus maps onto a corresponding spherical shell; the projected contributions from shells lying further out are allowed for, and the temperature and normalization for each of the 19 spectral models were simultaneously optimized to obtain the best fit. Metallicity and Galactic absorption components for each annulus were fixed at the best-fit values obtained by fitting each spectrum separately (i.e. without deprojecting).



Comparison between the profiles obtained by the standard deprojection analysis of X-MAS images and the data of simulations (above). The blue and black curves refer to profiles of clusters with and without bubbles respectively; temperatures are obtained by weighting by emissivity. Dots on dashed lines represent the results of the deprojection analysis after excluding the counts in the regions containing the bubbles. The drop in the measured temperature in the central bins of the case A is still under investigation and is probably an artifact of the adopted technique. The fits of the data are otherwise remarkably good, except in the case F, in which the number of counts is much lower. Even in that case, however, the density profile is well reconstructed.



Comparison between the profiles obtained by the analysis without deprojection of the Clus0 image and the data of simulations (left). The observation has the same parameters as the case A, but bubbles are not included. The analysis systematically overestimates metallicity and underestimates the Galactic absorption despite the large number of counts available.

The temperature profile results also smoothed respect to the simulation data, while it is well reconstructed by the deprojection technique (purple squares) instead.

The work is in progress. The next steps will include a quantitative analysis of the goodness of the profiles as well as the comparison of derived integrated quantities (like the overall mass of the cluster) to the simulation data.

References

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