

THE CLEF-SSH SIMULATION PROJECT

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Abstract. The CLEF-SSH simulation project is an international collaboration, involving the IAS, LATT and the University of Sussex, to produce large hydrodynamic simulations of large-scale structure that implement realistic models of radiative gas cooling and energy feedback. The objective is to use these simulations to study the physics of galaxy clusters and to construct maps of large angular size of the Sunyaev–Zel’dovich (SZ) effect, for the preparation of future experiments. Here we present results from a first run, the CLEF hydrodynamics simulation, which features $2(428)^3$ particles of gas and dark matter inside a comoving box with $200 h^{-1}$ Mpc on a side.

1 The CLEF-SSH simulation project

Future cluster surveys probing different wavebands, such as in the X-ray and the microwave spectral regions (see e.g. Romer et al. (2001), Carlstrom et al. (2003)), will provide invaluable information on the study of galaxy clusters and the formation of cosmological structure (e.g. Viana et al. (2003), Carlstrom, Holder and Reese (2002)). Hydrodynamic N -body simulations are undoubtedly one of the best tools for the preparation and scientific interpretation of these surveys. They permit a deeper understanding of galaxy cluster physics and much-improved quality of simulated maps for dedicated instrument studies.

The CLEF-SSH (CLuster Evolution & Formation using Supercomputer Simulations with Hydrodynamics) project is a collaboration between the Institut d’Astrophysique Spatiale (IAS, France), the Laboratoire d’Astrophysique Toulouse Tarbes (LATT, France), and the University of Sussex (Astronomy Centre, UK), to perform large simulations of large-scale structure (LSS), using state-of-the-art hydrodynamic techniques and realistic models of cosmological gas physics. Our aim is to use these simulations to perform studies of galaxy clusters with improved statistics and to construct large SZ maps for dedicated instrument studies.

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The project was awarded with 100,000 CPU hours at CINES, the French national parallel computing centre in Montpellier, during 2004. Sixty-six per cent of this time was consumed to produce a first run (the CLEF simulation) with $2(428)^3$ particles of gas and dark matter inside a comoving volume of $(200 h^{-1} \text{Mpc})^3$. The simulation was generated using a parallel version of the code Gadget II (Springel, Yoshida & White 2001) and includes radiative gas cooling and an energy feedback model described in Kay (2004). It assumes a flat Λ CDM cosmology with cosmological parameters matching present observations: matter density $\Omega_m = 0.3$, baryon density $\Omega_B = 0.0486$, hubble parameter $h = 0.7$, and $\sigma_8 = 0.9$. The mass of each gas and dark matter particles are $m_{\text{gas}} = 1.4 \times 10^9 h^{-1} M_\odot$ and $m_{\text{dark}} = 7.1 \times 10^9 h^{-1} M_\odot$, respectively. With these characteristics (see Kay et al (2004) for further simulation details), CLEF is one of the largest existing simulations with radiative cooling and energy feedback. This allowed us to generate extensive cluster catalogues over a wide range of mass and redshift. Our cluster catalogue at redshift $z = 0$ contains more than a thousand objects with mass $M \gtrsim 5 \times 10^{13} h^{-1} M_\odot$, each resolved with at least 7000 particles. The design of CLEF permits us to address several important issues of the formation and evolution of cosmological structure. In the next sections we present preliminary results regarding cluster scaling relations and simulated maps of the SZ effect from CLEF.

2 Cluster scaling relations

In Kay et al. (2004) we present X-ray cluster scaling relations from the CLEF simulation at $z = 0$. These show an overall good agreement with observations. Here we concentrate on the correlation between the cluster integrated SZ flux, $Y = \int y d\Omega$ (y is the comptonization parameter) and X-ray luminosity, L_X . This relation permits an estimation of the SZ fluxes of known X-ray clusters (for example in future Planck observations) without the need to resort to scalings that involve mass determinations.

In Fig. 1 we plot the *intrinsic* SZ flux, $Y^{\text{int}} = Y d_A^2$ (d_A is the angular diameter distance), versus bolometric X-ray luminosity of clusters from the CLEF run at $z = 0$ (filled circles). Quantities are evaluated within spherical regions where the mean overdensity is 200 times the critical density. We use $Y_{200}^{\text{int}} = \frac{\sigma_T k_B}{m_e c^2} \frac{0.88}{m_p} \sum m_i T_i$ and $L_{X,200} = \sum m_i \rho_i \Lambda(T_i, Z) / (\mu m_p)^2$, where m_i and T_i , are the mass and temperature of the particle i , summations run over hot ($T_i > 10^5 \text{K}$) gas particles, and $\Lambda(T_i, Z)$ is the bolometric cooling function, see e.g. da Silva et al. (2004). The dashed line is a power-law best fit to the cluster distribution,

$$Y_{200}^{\text{int}} = (6.2 \pm 0.1) \times 10^{-6} (L_{X,200}/L_{44})^{0.92 \pm 0.01} (h^{-1} \text{Mpc})^2, \quad (2.1)$$

where $L_{44} = 10^{44} h^{-2} \text{erg s}^{-1}$. The slope of this relation deviates significantly from the slope predicted by the self-similar model, which assumes a purely gravitational scenario of cluster formation. To illustrate this deviation, we also plot the self-similar scaling, $Y^{\text{int}} \propto L_X^{1.25}$, normalised to the brightest cluster (dotted line).

The open squares in Fig. 1 represent clusters from the *preheating* run in da Silva et al. (2004). This simulation implemented a simple heating mechanism

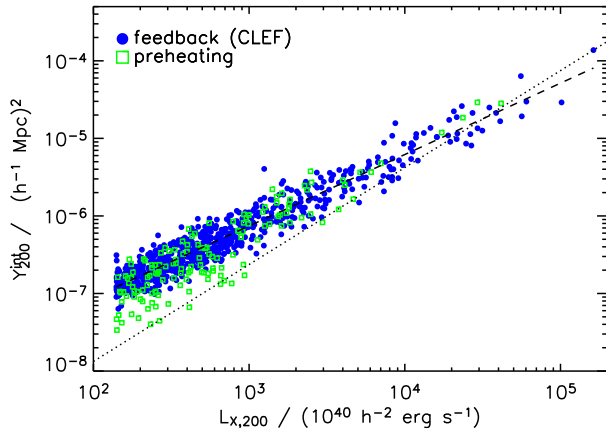


Fig. 1. Cluster integrated SZ flux versus bolometric X-ray luminosity of clusters at $z=0$ in CLEF (dots) and the preheating simulation in da Silva et al. (2004) (open squares). The dashed line is a power-law best fit to the CLEF cluster distribution. The dotted line illustrates the self-similar scaling normalised to the most luminous cluster.

where the gas was impulsively heated by 1.5 keV per particle at $z = 4$. Despite the good overlap for luminous clusters, the preheating cluster distribution shows a somewhat larger dispersion than in CLEF and lower SZ fluxes for less luminous objects. This is because our feedback model has a relatively larger effect in smaller systems. The deviation from self-similarity is therefore larger in the CLEF case than in the preheating simulation of da Silva et al. (2004), where $Y_{200}^{\text{int}} \propto L_{x,200}^{0.98}$.

3 Simulation maps

One important aspect of the CLEF run is that it was designed with abutting outputs to permit the construction of simulated maps. Direct application of the map-making method of da Silva et al. (2000) to this run allows us to obtain maps of the SZ effect with 5 deg^2 of size, with the signal integrated up to $z = 4.6$. This is already a major achievement when compared with previous works (where map sizes are typically one square degree in size), which demonstrates one of the major advantages of having a much (typically eight times) larger simulation volume in CLEF. Maps constructed from CLEF include more massive structures and large-scale power than in previous works. Moreover the effect of non-gravitational heating was also lacking, or only crudely estimated, in most of these simulations.

In Fig. 2 we present the first thermal (left panel) and kinetic (right panel) SZ maps from the CLEF simulation with 5 deg^2 of size and (raw) resolution of 5 arc-seconds. The mapped quantities are the y -comptonization parameter, for the thermal effect, and the temperature fluctuation $\Delta T_{\text{ksz}}/T$, for the kinetic effect. These were computed in the usual way — see da Silva et al. (2001). The mean y -distortion, averaged over lines of sight, gives an important measure of the global state of the gas in the Universe. In the CLEF run we find $y_{\text{mean}} = 3.6 \times 10^{-6}$,

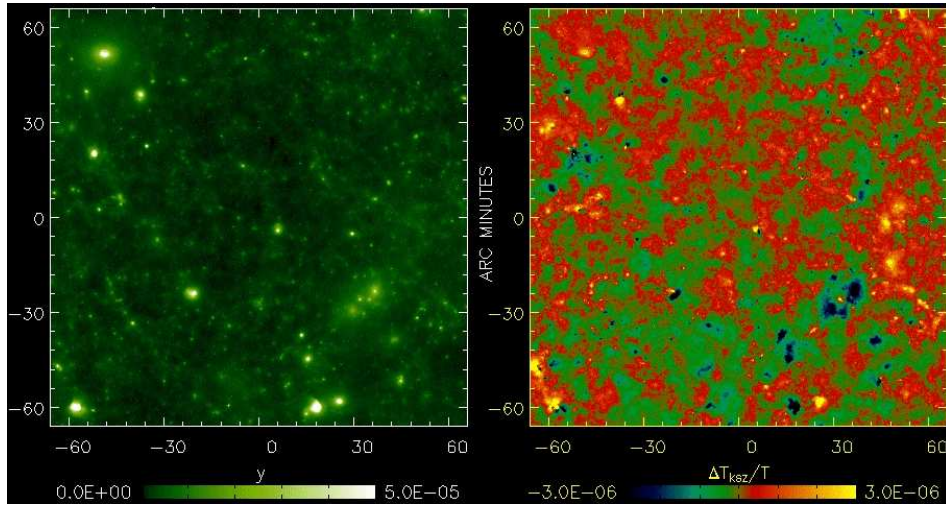


Fig. 2. Five square degree maps of the thermal y -comptonization parameter (left panel) and kinetic temperature fluctuations (right panel) of the SZ effect from the CLEF hydrodynamics simulation. Maps show the same sky realisation with a resolution of $5''$.

obtained by averaging over 60 square degrees of area (12 sky realisations, each with 5 deg^2). This comfortably satisfies *COBE-FIRAS* constraints on y_{mean} (Fixsen et al. 1996).

Our primary objectives with the CLEF hydrodynamics run are to create realistic simulations of galaxy clusters and large maps of the SZ effect for dedicated instrument studies. Templates of simulated cluster maps can also be created from CLEF to improve present all-sky simulations of the SZ effect. All these aspects are important for a better understanding of galaxy cluster observations and the preparation of future CMB/SZ missions such as Planck, AMiBA and SPT.

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