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Influence of adaptive mesh refinement and the hydro solver on shear-induced mass stripping in a minor-merger scenario

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ABSTRACT

We compare two different codes for simulations of cosmological structure formation to investigate the sensitivity of hydrodynamical instabilities to numerics, in particular, the hydro solver and the application of adaptive mesh refinement (AMR). As a simple test problem, we consider an initially spherical gas cloud in a wind, which is an idealized model for the merger of a subcluster or galaxy with a big cluster. Based on an entropy criterion, we calculate the mass stripping from the subcluster as a function of time. Moreover, the turbulent velocity field is analyzed with a multi-scale filtering technique. We find remarkable differences between the commonly used PPM solver with directional splitting in the ENZO code and an unsplit variant of PPM in the NYX code, which demonstrates that different codes can converge to systematically different solutions even when using uniform grids. For the test case of an unbound cloud, AMR simulations reproduce uniform-grid results for the mass stripping quite well, although the flow realizations can differ substantially. If the cloud is bound by a static gravitational potential, however, we find strong sensitivity to spurious fluctuations which are induced at the cutoff radius of the potential and amplified by the bow shock. This gives rise to substantial deviations between uniform-grid and AMR runs performed with ENZO, while the mass stripping in NYX simulations of the subcluster is nearly independent of numerical resolution and AMR. Although many factors related to numerics are involved, our study indicates that unsplit solvers with advanced flux limiters help to reduce grid effects and to keep numerical noise under control, which is important for hydrodynamical instabilities and turbulent flows.

1. Introduction and astrophysical motivation

In the widely accepted paradigm of hierarchical formation of cosmic structure, large virialized objects like clusters of galaxies grow by accretion of smaller subclusters. In this process, which proceeds up to the current epoch, the merging of halos and subhalos is believed to be an important source of turbulence in the intra-cluster medium (hereafter ICM; e.g., Paul et al., 2011; Vazza et al., 2011) together with other mechanisms like the baroclinic injection of vorticity at curved shocks (Kang et al., 2007; Iapichino and Brüggen, 2012), outflows of active galactic nuclei (Heinz et al., 2006; Sijacki and Springel, 2006; Brüggen et al., 2009) and the motion of single galaxies through the ICM (Kim, 2007; Ruszkowski and Oh, 2011). The importance of cluster mergers goes beyond being mere stirring agents in the ICM. For example, they are strongly correlated with the occurrence of central cluster diffuse radio emission (radio halos; Cassano et al., 2010) via some still debated mechanism of cosmic ray acceleration (Brunetti and Jones, 2014). Moreover, major mergers launch shock waves in the ICM, which are observed as brightness and temperature edges in X-ray images (Markevitch, 2010). There is also the prospect of measuring turbulence with the up-coming Astro-H mission (Biffi et al., 2013; Shang and Oh, 2013).

The role of mergers as injectors of bulk flow and turbulence in the ICM has been recognized in hydrodynamical simulations of the build-up of galaxy clusters (e.g., Ricker, 1998; Norman

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and Bryan, 1999; Iapichino and Niemeyer, 2008; Vazza et al., 2011, 2012; Miniati, 2014). Complementary to cosmological simulations starting from realistic initial conditions, idealized cluster simulations are useful to study mergers in a simplified setup and with a better control on the problem parameters (Roettiger et al., 1996; Ricker and Sarazin, 2001; McCarthy et al., 2007). A special subclass of cluster mergers is constituted by minor mergers, where one the merging objects has a much smaller mass than the other. Although these processes do not have the same impact on the energy budget of the ICM as major mergers, they are interesting in their own right. For example, they are associated with observed structures like merger cold fronts (Markevitch and Vikhlinin, 2007; Russell et al., 2014). During minor mergers, the interface between the host ICM and the subcluster is subject to the Kelvin–Helmholtz instability, which results in gas stripping and injection of turbulence in the downstream region (Subramanian et al., 2006; Russell et al., 2014; Eckert et al., 2014). This process has been noticed in full cosmological simulations (Iapichino and Niemeyer, 2008; Maier et al., 2009) and has been studied in greater detail by means of idealized setups, following the infall of a low-mass subcluster or an elliptical galaxy into the static ICM of a big cluster as it is seen from an observer moving with the subcluster (Heinz et al., 2003; Takizawa, 2005; Xiang et al., 2007; Asai et al., 2007; Dursi and Pfrommer, 2008; Roediger et al., 2014a,b).

The study of Iapichino et al. (2008) belongs to the latter class of simulations. A particularly interesting aspect of this study is the transition from laminar flow to turbulence in the boundary layer of the subcluster, which is difficult to tackle for compressible hydro solvers with numerical viscosity. In this article, we further elaborate on this computational problem by comparing simulations carried out with the cosmological fluid dynamics codes Enzo and Nyx, which implement a split and an unsplit variant of the widely applied piecewise parabolic method (PPM, Colella and Woodward, 1984). In order to gain a clearer insight into the simulations performed with the setup from Iapichino et al. (2008), we also address the simpler case of an unbound cloud in a wind as in Agertz et al. (2007). In this case, the cloud is initially defined as a spherical region of higher gas density in pressure equilibrium with the ambient medium. The code comparison by Agertz et al. (2007) was a seminal work that demonstrated striking differences between smoothed particle hydrodynamics (SPH) and grid-based codes.

Another question concerns an assumption that is often taken for granted in computational astrophysics, namely the equivalence between a run performed with a uniform grid and the corresponding simulation using adaptive mesh refinement (AMR) at the same effective spatial resolution. Recently, Miniati (2014) has questioned that dynamic refinement reproduces turbulent fluid properties, particularly if the refinement method is based on keeping the mass in a cell roughly constant. Thus, we want to investigate in a systematic way under which conditions statistical agreement between computations with AMR and uniform grids at the same effective resolutions can be achieved. By computing statistics related to the stripping of mass from the subcluster and by investigating the flow structure, a significant impact of refinement strategies in AMR simulations has been shown by Iapichino et al. (2008). In particular, AMR based on local gradients of density or temperature is not able to follow the formation of the turbulent subcluster wake, whereas this is possible with criteria based on the variability of structural invariants of the flow. This means that thresholds for refinement are calculated from statistical moments of scalars such as the squared vorticity (cf. Schmidt et al., 2009 and Schmidt, 2014).

To infer the impact of the different hydro solvers implemented in Enzo and in Nyx and to compare uniform-grid versus AMR runs, we compute the mass stripped from the subcluster as a function of time. For the definition of the cloud mass, we propose a criterion that is based on an entropy threshold. We find systematic differences, which are further analyzed by means of the multi-scale filtering approach of Vazza et al. (2012). After explaining our methodology in Section 2 in more detail, the results for the simple cloud without gravity and the subcluster are presented in Sections 3 and 4, respectively. Our conclusions are presented in the last section.

2. Numerical methods and simulations

We consider both gravitationally bound and unbound variants of the cloud in a wind, as defined by Iapichino et al. (2008). As initial condition, we set a spherically symmetric isothermal cloud in pressure equilibrium with a homogeneous background medium with temperature $k_{\mathrm{B}}T_{\mathrm{b}} = 8.0$ keV and density $\rho_{\mathrm{b}} = 7.9 \times 10^{-28}\ \mathrm{g\,cm^{-3}}$. In the simple case of an unbound cloud, we assume a sphere of radius 250 kpc with constant density $\rho_{\mathrm{c}} = 6.3 \times 10^{-27}\ \mathrm{g\,cm^{-3}}$. The condition of pressure equilibrium implies a temperature $k_{\mathrm{B}}T_{\mathrm{c}} = 1.0$ keV inside the cloud. To produce a wind in x-direction, an inflowing boundary condition with a uniform velocity $v_{\mathrm{b}} = 1.6 \times 10^3\ \mathrm{km\,s^{-1}}$ is imposed at the left face of the domain. The boundary conditions at the other faces of the domain are outflowing. Since the cloud is not anchored by a gravitational well, it drifts in the downstream direction. For this reason, we use an elongated box of size $16 \times 4 \times 4$ Mpc. Apart from the chosen scales, this setup is similar to the blob test of Agertz et al. (2007).

Iapichino et al. (2008), on the other hand, assume that the cloud is bound by an external gravitational potential, which corresponds to a static dark-matter halo with a King profile:

$$\rho_{\mathrm{dm}}(r) = \rho_{\mathrm{dm,c}}\left[1 + \left(\frac{r}{r_{\mathrm{core}}}\right)^2\right]^{-3/2}. \tag{1}$$

The initial density profile of the cloud is obtained by integrating the equation of hydrostatic equilibrium for the central density $\rho_{\mathrm{c}} = 0.1\rho_{\mathrm{dm,c}} = 6.3 \times 10^{-27}\ \mathrm{g\,cm^{-3}}$, constant temperature $k_{\mathrm{B}}T_{\mathrm{b}} = 3.65$ keV, and the core radius $r_{\mathrm{core}} = 250$ kpc. We use the same setup here, except for a cutoff at the radius $r_{\mathrm{max}} = 6r_{\mathrm{core}}$. The Cartesian coordinates of the cloud center ($r = 0$) are $(0.4, 0.5, 0.5) \times 4$ Mpc in a cubic domain of 4 Mpc linear size. For $r > r_{\mathrm{max}}$, the gravitational acceleration is set to zero and the state is given by the state of the background medium. The cutoff is necessary because of the applied boundary conditions, which are the same as in the case without gravity. In principle, the wind could be assumed to be in a turbulent state. However, the properties of turbulence in the ICM are quite uncertain and there is no suitable method that would allow us to self-consistently add turbulence to the background medium. Artificially added perturbations at the inflow boundary would largely decay before the could reach the cloud. Consequently, we consider only turbulence that is produced by hydrodynamical instabilities in this study. This has furthermore the advantage that perturbations of numerical origin can be investigated in a clear manner. For brevity, we subsequently refer to the cloud with static gravitational potential as "subcluster".

To compute the gas-dynamical evolution for an adiabatic equation of state with $\gamma = 5/3$, we apply the cosmological AMR codes Enzo (ascl:1010.072, O'Shea et al., 2005; Bryan et al., 2014)[1] and Nyx (Almgren et al., 2013). As described in the method paper by Bryan et al. (2014), Enzo uses directionally split PPM (Colella and Woodward, 1984). A variety of Riemann solvers are available in the current code version. We are using the default two-shock approximation (see Toro, 1997), with the Harten–Lax–van

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[1] While we used version 2.3 for the unbound cloud problem, the subcluster simulations were computed with the older version 2.1. We repeated selected runs with version 2.3, but did not find substantial differences that would affect the conclusions drawn in this article.