FULL TITLE
ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION**
NAMES OF EDITORS

Cosmic ray feedback in hydrodynamical simulations of galaxy and galaxy cluster formation

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Abstract. It is well known that cosmic rays (CRs) contribute significantly to the pressure of the interstellar medium in our own Galaxy, suggesting that they may play an important role in regulating star formation during the formation and evolution of galaxies. We will present a novel numerical treatment of the physics of CRs and its implementation in the parallel smoothed particle hydrodynamics (SPH) code GADGET-2. In our methodology, the non-thermal CR population is treated self-consistently in order to assess its dynamical impact on the thermal gas as well as other implications on cosmological observables. In simulations of galaxy formation, we find that CRs can significantly reduce the star formation efficiencies of small galaxies. This effect becomes progressively stronger towards low mass scales. In cosmological simulations of the formation of dwarf galaxies at high redshift, we find that the total mass-to-light ratio of small halos and the faint-end of the luminosity function are affected. In high resolution simulations of galaxy clusters, we find lower contributions of CR pressure, due to the smaller CR injection efficiencies at low Mach number flow shocks inside halos, and the softer adiabatic index of CRs, which disfavours them when a composite of thermal gas and CRs is adiabatically compressed. Within cool core regions, the CR pressure reaches equipartition with the thermal pressure leading to an enhanced compressibility of the central intra-cluster medium, an effect that increases the central density and pressure of the gas. While the X-ray luminosity in low mass cool core clusters is boosted, the integrated Sunyaev-Zel'dovich effect is only slightly changed. The resolved Sunyaev-Zel'dovich maps, however, show a larger variation with an increased central flux decrement.

1. Motivation

The interstellar medium (ISM) of galaxies has an energy budget composed both of thermal and non-thermal components. The non-thermal components which are magnetic fields and cosmic rays (CRs) are known to contribute a significant part of the energy and pressure to the ISM. CRs behave quite differently compared to the thermal gas. Their equation of state is softer, they are able to propagate over macroscopic distances, and their energy loss time-scales are typically larger than the thermal ones. Furthermore, roughly half of the particle's energy losses are due to Coulomb and ionization interactions and thereby heat the thermal gas. Therefore, CR populations are an important galactic reservoir for energy from supernova explosions, and thereby help to maintain dynamical feedback of star formation for periods longer than thermal gas physics alone would permit. In contrast, it is unknown how much pressure support is provided by CRs to the thermal plasma of clusters of galaxies.

2. CR modified galaxy formation and cluster observables

Using a new numerical implementation of self-consistent CR physics in the parallel SPH code GADGET-2 (Springel 2005; Jubelgas et al. 2006; Pfrommer et al. 2006a), we perform simulations of forming galaxies of different masses, with and without CR physics. Fig. 1 presents the result of our simulation runs. The morphology and star formation rate of small mass galaxies is strongly affected by the presence of CRs, whereas massive galaxies appear to be unmodified. The suppression of star formation by CRs in small galaxies is an attractive explanation of the observed shallow slope at the faint end of the luminosity function of galaxies. This suppression, and also the oscillations in the star formation rate are a result of an inverted effective equation of state of a CR gas energized by supernovae (see Jubelgas et al. 2006, for details).

To study the impact of CRs on larger scales, we performed cosmological high-resolution simulations of a sample of galaxy clusters spanning a large range in mass and dynamical states, with and without CR physics. We account for CR acceleration at structure formation shocks and various CR loss processes (see Pfrommer et al. 2006b, for details). Within clusters, the relative CR pressure $X_{\rm CR} = P_{\rm CR}/(P_{\rm CR} + P_{\rm th})$ declines towards a low central value of $X_{\rm CR} \simeq 10^{-4}$ in non-radiative simulations due to a combination of the following effects: CR acceleration is more efficient at the peripheral strong accretion shocks compared to weak central flow shocks and adiabatic compression of a composite of CRs and thermal gas disfavours the CR pressure relative to the thermal pressure due to the softer equation of state of CRs. Interestingly, $X_{\rm CR}$ reaches high values at the centre of the parent halo and each galactic substructure in our radiative simulation due to the fast thermal cooling of gas which diminishes the thermal pressure support relative to that in CRs. This additional CR pressure support has important consequences for the thermal gas distribution at cluster centres and alters the resulting X-ray emission and the Sunyaev-Zel'dovich effect (cf. Fig. 2).

3. Conclusions

We have argued that cosmic rays play an active role for galaxies and the large scale structure. We find that star formation is strongly CR-suppressed in small galaxies. This is a result of the modified effective equation of state of CRs in the ISM and leads to a suppression of the faint end of the galaxy luminosity function and thereby helps to reconcile observations with computational models of galaxy formation. In galaxy clusters, the X-ray luminosity is boosted predominantly in low-mass cool core clusters due to the large CR pressure contribution in the centre that leads to a higher compressibility. The integrated Sunyaev-Zel'dovich effect is only slightly changed while the central flux decrement is also increased.

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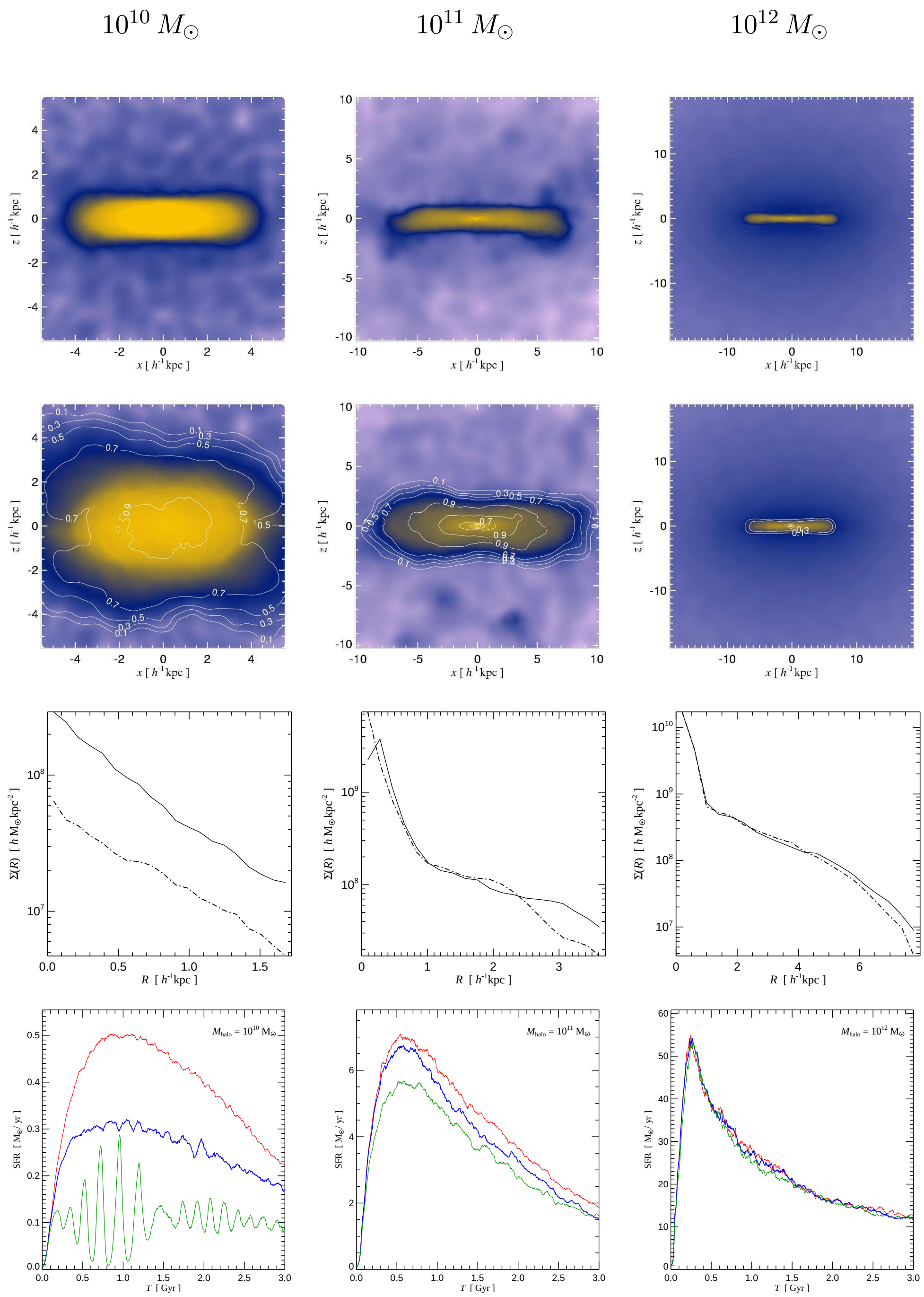

Figure 1. Simulation of isolated galaxies with different masses (different columns). The top row shows the gas distribution of galaxies without CRs. The second row shows the same with CRs included. The contour lines indicate the relative level of CR pressure support. Massive galaxies are mostly unaffected by CRs, whereas small galaxies exhibit a puffed-up gas distribution, and a strongly reduced stellar surface brightness profiles (third row). Finally, the star formation histories of galaxies for different levels of CR injection efficiencies are shown in the last row.

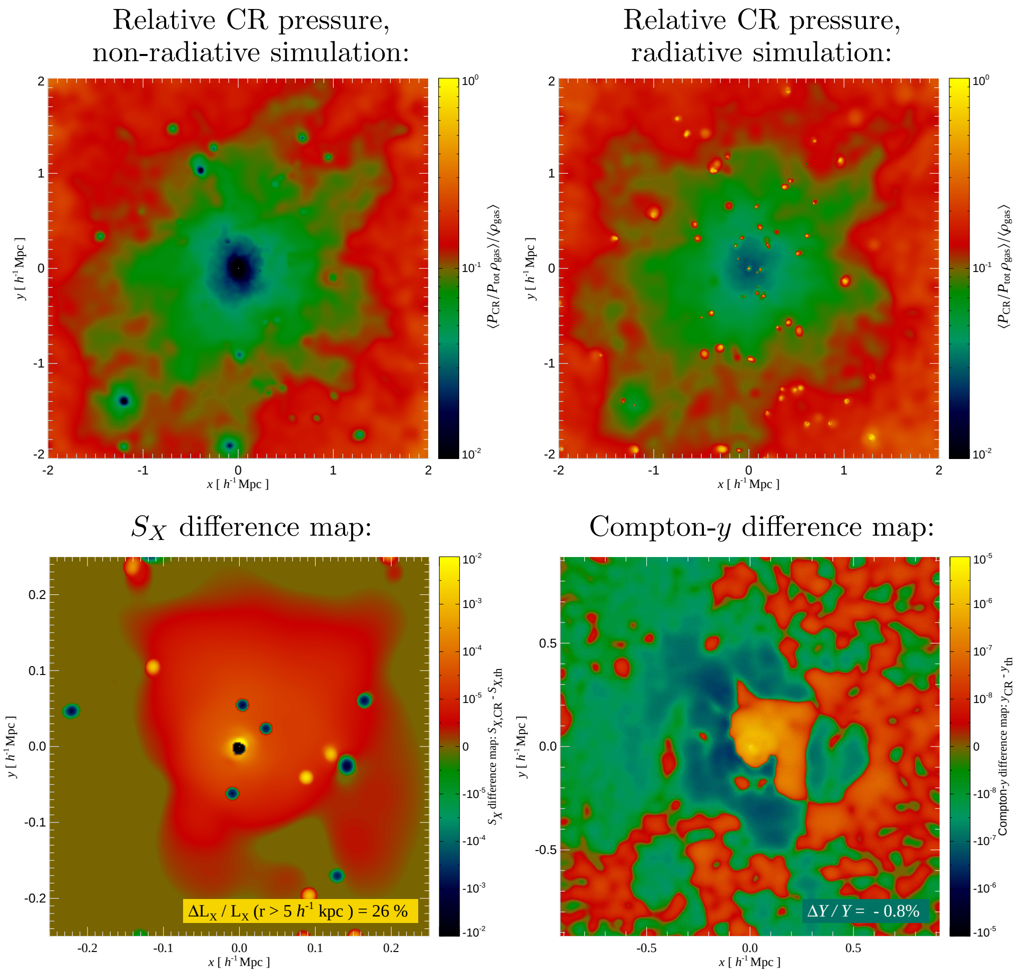

Figure 2. The top panels show a visualization of the pressure contained in CRs relative to the total pressure $X_{\rm CR} = P_{\rm CR}/(P_{\rm CR} + P_{\rm th})$ in a zoomed simulation of an individual galaxy cluster with mass $M = 10^{14} h^{-1} M_\odot$. The map on the *left-hand side* shows a non-radiative simulation with CRs accelerated at structure formation shock waves while the map on the *right-hand side* is from a simulation with dissipative gas physics including cooling, star formation, supernova feedback, and structure formation CRs. The lower panels show the CR-induced difference of the X-ray surface brightness S_X (*left-hand side*) and the Compton-y parameter (*right-hand side*) in a radiative simulation with structure formation CRs compared to the corresponding reference simulation without CRs. The relative difference of the integrated X-ray surface brightness/Compton-y parameter is given in the inlay. Within cool core regions, the CR pressure reaches equipartition with the thermal pressure, an effect that increases the compressibility of the central intracluster medium and thus the central density and pressure of the gas. This boosts the X-ray luminosity of the cluster and the central Sunyaev-Zel'dovich decrement while the integrated Sunyaev-Zel'dovich effect remains largely unaffected.