Cosmic ray physics in calculations of cosmological structure formation

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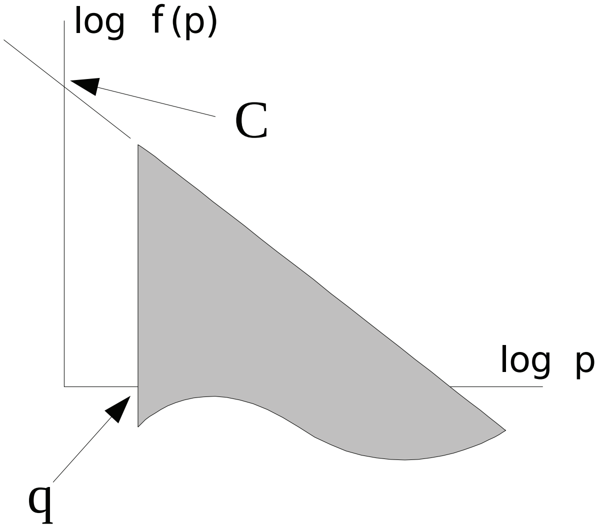
Non-equilibrium processes like shock waves and turbulence can generate and energise magnetic fields and cosmic rays (CRs) in the interstellar medium of galaxies and in the intragalactic gas. Cosmic rays in particular play a decisive role within our own Galaxy. To study the impact of CRs on galaxy formation and evolution, we develop an approximative framework for treating dynamical and radiative effects of CRs in cosmological simulations. Our guiding principle is to try to find a balance between capturing as many physical properties of CR populations as possible while at the same time requiring as little extra computational resources as possible. The processes considered include compression and rarefaction, CR injection via shocks in supernova remnants, injection in structure formation shock waves, in-situ re-acceleration of CRs, CR spatial diffusion, CR energy losses due to Coulomb interactions, ionisation losses, Bremsstrahlung losses, and, finally, hadronic interactions with the background gas. We present an implementation of the formalism in the Lagrangian simulation code GADGET-2. Using a number of test problems, we show that our scheme is numerically robust and efficient, allowing us to carry out cosmological structure formation simulations that account for cosmic ray physics. In simulations of isolated galaxies, we find that cosmic rays can significantly affect the star formation efficiencies of small galaxies, an effect that becomes progressively stronger towards low mass scales. In cosmological simulations of the formation of dwarf galaxies at high redshift, we find that both the mass-to-light ratio and the faint-end of the luminosity function are strongly affected, as required to reconcile the faint-end slope of the observed galaxy luminosity function with the halo mass function of the LCDM cosmology.

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. Magnetic fields couple the otherwise dynamically independent ingredients like the ISM plasma, and the CR gas into a single, however complex fluid.

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 ionisation 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 a galactic context, an important CR loss mechanism is escape from the galaxy by diffusion and (evt. CR driven) galactic winds. The spectral distribution of CRs is much broader than that of thermal populations (see Fig. 1), which has to be taken into account in estimating their dynamical properties.



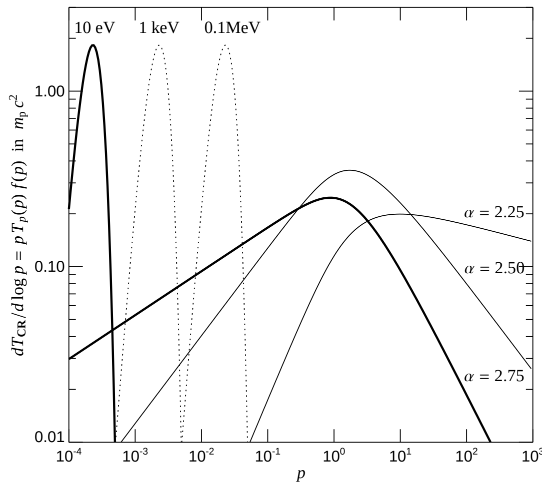


Figure 1: Left: power-law momentum spectrum and its basic variables C and q; Right: kinetic energy per logarithmic momentum interval of thermal and CR energy spectra for various temperatures and spectral indices α but with the same pressure. The dynamical important part of CR spectral distributions in momentum space easily encompasses a few orders of magnitude, whereas thermal distributions appear nearly mono-energetic on logarithmic scales. The thick lines correspond to a possible situation in the ISM.

Numerical simulations and semi-analytical models of galaxy and large-scale structure formation neglected the effects of CRs and magnetic fields so far, despite their dynamical importance. An accurate description of CRs should follow the evolution of the spectral energy distribution of CRs as a function of time and space, and keep track of their dynamical, non-linear coupling with the hydrodynamics. In order to allow the inclusion of CRs and their effects into numerical simulations and semi-analytic descriptions of galaxy formation, we present a simplified description of the CR dynamics and physics. We seek a compromise between two opposite requirements, namely: (i) to capture as many physical properties and peculiarities of CR populations as possible, and (ii) to require as little extra computational resources as possible. In our model, the emphasis is given to the dynamical impact of CRs on hydrodynamics, and not on an accurate spectral representation of the CRs. The guiding principles are energy, pressure, and particle number conservations, as well as adiabatic invariants. Non-adiabatic processes will be mapped onto modifications of these principles.

The CR description and implementation into the GADGET-2 code (Springel 2005) presented in this article was introduced in three papers: Enßlin, Pfrommer, Springel, Jubelgas (2006) introduced the basic description and the dynamical equations for the simplified CR gas. Jubelgas, Springel, Enßlin, Pfrommer (2006) present the implementation details, the code tests and first application. Pfrommer, Springel, Enßlin, Jubelgas (2006) build a smoothed-particle hydrodynamics shock wave tracer, needed for the CR injection. Here, we concentrate on the first two papers. Pfrommer et al. (2006) is presented in a parallel article.

2 Formalism for simplifying cosmic ray physics

We introduce the dimensionless proton momentum $p = P_\mathrm{p}/m_\mathrm{p}\, c$ and write the CR spectra as

$$f(p) = \frac{dN}{dp\, dV} = C\, p^{-\alpha}\, \theta(p - q)\,. \tag{1}$$

The normalisation C and the spectral cutoff q (see Fig. 1) can be easily followed through adiabatic changes if one introduces adiabatic invariant variables C_O and q_0 defined for some reference gas density ρ_0:

$$q(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{1}{3}} q_0, \quad C(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{\alpha+2}{3}} C_0\,. \tag{2}$$

The CR number density $n_{\rm CR} = \frac{C\,q^{1-\alpha}}{\alpha-1}$, pressure $P_{\rm CR} = \frac{C\,m_{\rm p}c^2}{6}\,\mathcal{B}_{\frac{1}{1+q^2}}\left(\frac{\alpha-2}{2}, \frac{3-\alpha}{2}\right)$, and other variables can easily be expressed in terms of C and q.

Non-adiabatic processes are described by their effects on spectral normalisation C and cutoff q (or C_0 and q_0) following energy and particle number conservation. We implemented the following CR processes into the GADGET-2 smooth particle hydrodynamics code: a) CR pressure on hydrodynamics, b) CR injection by supernova (sub-grid), c) CR injection in shock waves , d) CR spatial diffusion, e) Coulomb & ionisation losses, and f) hadronic interactions. Mathematical details can be found in Enßlin et al. (2006) and a description of the implementaion and its tests can be found in Jublegas et al. (2006).

3 CR modified galaxy formation

We have performed simulations of forming galaxies of different masses, with and without CR physics. Fig. 2 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 relatively unmodified. The suppression of star formation by CRs in small galaxies is an attractive explanation of the observed low faint end of the luminosity function of galaxies. This suppression, and also the oscilations in the star formation rate are a result of an inverted effective equation of state of a CR gas energised by supernovae (see Jubelgas et al. (2006) for details).

4 Conclusions

We have argued that cosmic rays are an active agent of galaxies and the large scale structure. In order to permit studies of cosmic rays we developed and presented new self-consistent CR simulations in cosmological setting using the GADGET-2 code. These include adiabatic and non-adiabatic cosmic ray processes. We find that star formation is strongly CR-suppressed in small galaxies. This is a result of the inverted effective equation of state of CRs in the ISM (less energy at higher pressure) and leads to a suppression of the faint end of the galaxy luminosity function and thereby help to reconcile observations with computational models of galaxy formation. A number of future studies enclosing CR in cosmological structure formation are underway.

References

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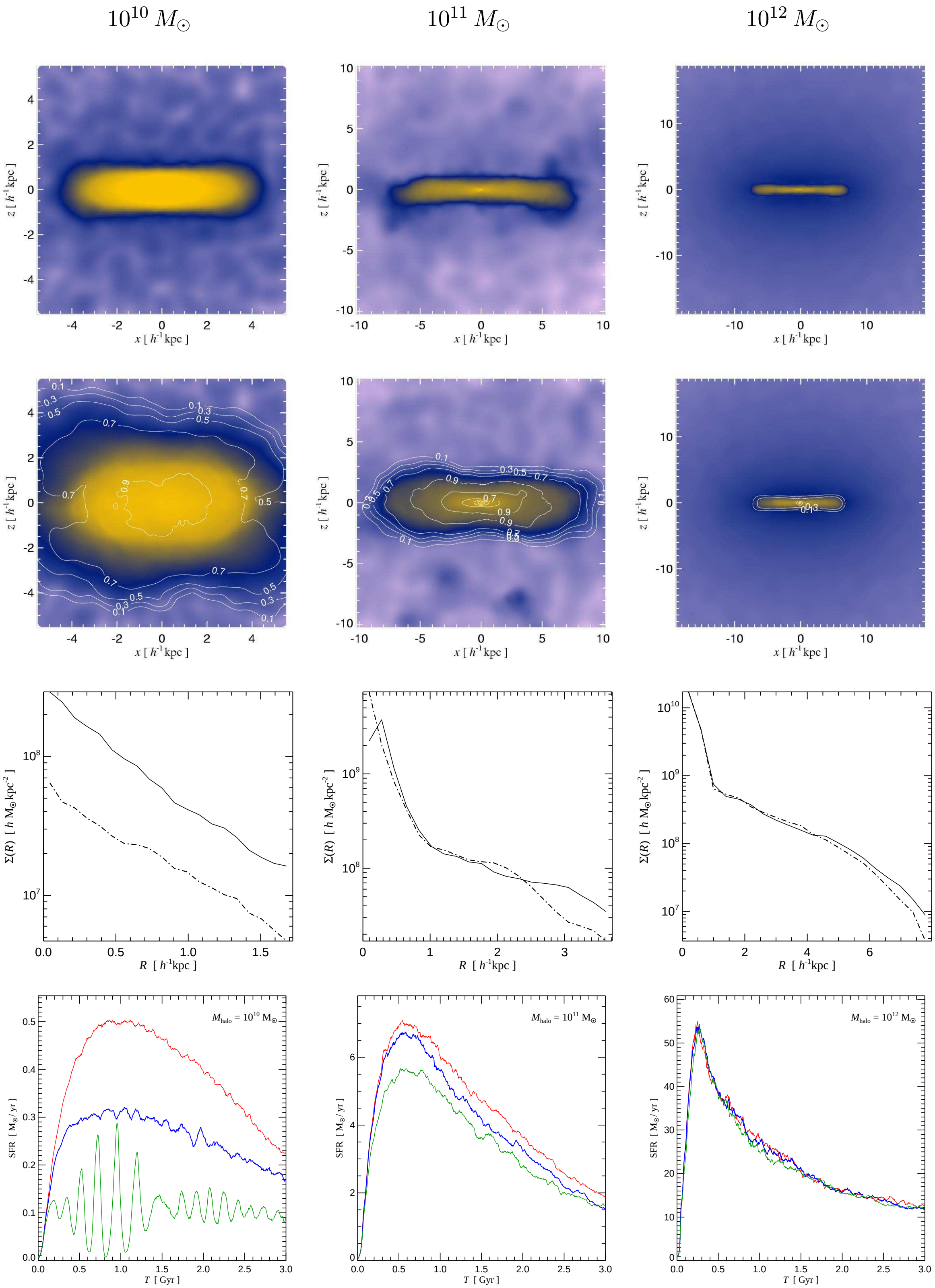

Figure 2: Simulation of isolated galaxies with different masses (different columns). The top row shows the gas distribution of galaxies without CRs. The second row shows the same with CRs included. The contour lines indicate the relative level of CR pressure support. Massive galaxies are mostly unaffected 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.