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THE ROLE OF COSMIC RAY FEEDBACK IN THE EVOLUTION OF GALAXIES

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Abstract. Cosmic rays are charged particles accelerated in supernova shocks, exerting pressure on gas and heating it. As these effects can alter both the star formation and the multiphase structure of galaxies, they are likely an important feedback channel in galaxy evolution. Using Radiation-Magneto-Hydrodynamics simulations of three isolated and idealised disk galaxies of different masses, we investigate the impact of cosmic ray feedback on galaxy evolution. We find that cosmic rays have a mild effect in reducing star formation, by at most a factor two, and with decreasing efficiency in increasingly massive galaxies. At any galaxy mass however, cosmic ray pressure support increases galactic outflows, which are also much colder than when cosmic rays are excluded. We find that both the increase in outflows and their temperature are sensitive to the adopted cosmic ray diffusion coefficient, revealing the importance of the detailed modelling of cosmic ray propagation.

Keywords: galaxy evolution, cosmic rays

1 Introduction

Feedback is an essential but still not fully understood component of galaxy formation and evolution. Without any feedback, gas accreted into galaxies would cool rapidly and be converted into stars much more efficiently than what is observed. It is a long-standing challenge in theoretical astrophysics to reproduce observations, such as the galaxy mass function or the stellar mass to halo mass relation. If invoking only the energetic feedback of supernova (SN) explosions, simulated galaxies tend to contain too many stars, because the SN energy is radiated away too quickly to efficiently clear away dense gas and delay or suppress star formation. It has been shown that SN feedback by itself remains inefficient in producing fully realistic simulated galaxies, not only in terms of star formation regulation (see e.g Hopkins et al. 2011), but also in reproducing the temperature and metallicity content of gas in the interstellar medium (ISM) and circumgalactic medium (CGM) (see e.g Schaye et al. 2015), or the scaling of mass-loading factors with galaxy velocity. With time, and as numerical capabilities increase, more and more feedback sources have been investigated, such as radiation pressure, stellar winds, photoionisation heating, active galactic nuclei and cosmic rays. In particular, cosmic rays are highly regarded as being able to both play a role in regulating star formation in galaxies as well as the multiphase structure of the ISM and CGM.

Cosmic rays (CRs) are energetic charged particles, mainly consisting of protons with energy around a few GeV. Produced and accelerated in SN shock waves, they are advected with gas and diffused along magnetic field lines. Moving from dense star-forming clouds to more diffuse regions, they provide an important non thermal pressure gradient in galaxies and heat the gas through hadronic collisions and streaming losses. These effects combined have the potential to disrupt ISM clouds and hence alter the star formation rate. They can also help driving gas away from the galaxy, impacting the CGM and its observational properties. Here, we present a study of three isolated galaxies of different masses, combining supernova feedback, radiation and cosmic ray feedback together in radiation-magneto-hydrodynamics (RHMD) simulations, to know if and to what extent CRs contribute to regulate galaxy evolution.

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2 The effects of cosmic rays

We use the Ramses code (Teyssier 2002) to perform simulations of disk galaxies embedded in dark matter halos of 10^{10}, 10^{11} and 10^{12} $M_\odot$ respectively. The initial conditions for all our simulations are generated using the MakeDisk code (Springel et al. 2005). For each galaxy, we have a set of two runs, with and without cosmic ray feedback. The galaxies are evolved for 500 Myr, with a maximum cell resolution of 9 pc for the two smaller dwarf galaxies, and 18 pc for the most massive one. More details about the galaxies can be found in Rosdahl et al. (2015) and Dashyan & Dubois (2020), and we adopt a very similar setup. To give a brief overview, the simulations have been performed using the Ramses-rt version of the code (Rosdahl & Teyssier 2015) to account for the propagation of hydrogen and helium-ionising radiation and its interactions with the gas via radiative pressure and photo-ionisation. An initial toroidal magnetic field of 1 μG in strength is evolved using the Fromang et al. (2006) MHD solver. Cosmic rays are modelled as a non-collisional relativistic fluid, following the advection-diffusion approach implemented by Dubois & Commerçon (2016) and Dubois et al. (2019), with a constant diffusion coefficient $\kappa = 10^{28}$ cm^2/s. Gas is converted into stellar populations with a local star formation efficiency by the thermo-turbulent model of Federrath & Klessen (2012). The star particles, representing stellar populations, then trigger individual SN explosions between 3 and 50 Myrs after their birth, following the mechanical feedback method described in Kimm & Cen (2014) and Kimm et al. (2015). When CRs are included, 10% of the energy from each SN explosion (i.e. 10^{50} ergs) is put into non thermal cosmic ray energy.

2.1 Star formation rate

Fig. 1 shows the stellar mass produced in our three galaxies as a function of time, with and without cosmic ray feedback. Each galaxy includes an initial distribution of stellar particles, which contribute to the baryonic mass, but never explode as supernova, and hence do not provide any feedback. We exclude these initial stellar particles from Fig. 1 to show only the stellar mass formed since the start of the run. By exerting their pressure on gas, CRs tend to smooth the gas distribution in the ISM, and reduce the number of star-forming clumps. By the end of the 500 Myr runtime, they suppress the total amount of stars formed by a factor two for the dwarf galaxies. For a galaxy as massive as our Milky-Way (i.e. with a halo mass of 10^{12} $M_\odot$), they are not efficient enough at the ISM scale to affect the star formation at any time. This can be explained by the stronger gravitational potential of the massive galaxy, which reduces the CR feedback efficiency to make any significant disruptions in the ISM.

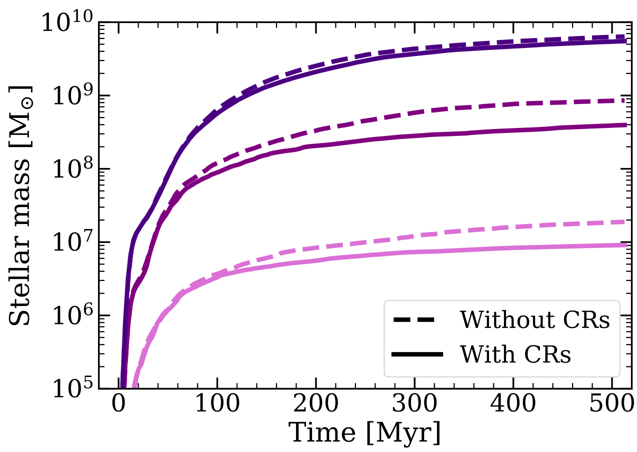

Fig. 1. Cumulative formation of stars in the three galaxies. The three sets of two curves correspond to each galaxy being simulated with (solid) and without (dashed) CRs, by order of increasing galaxy mass from light to dark purple. Cosmic ray feedback efficiency in suppressing the star formation decreases with galaxy mass.

2.2 Outflows

Cosmic rays also have the ability to impact galactic outflows and the properties of the CGM. In Fig. 2, we show the time evolution of the flux of outflowing gas crossing parallel planes located 10 kpc from the disks. For each galaxy, we show the total amount of outflows in black before and decompose it into its cold ($\mathrm{T} < 10^4$ K), warm ($10^4 \leq \mathrm{T} < 10^5$ K) and hot ($\mathrm{T} > 10^5$ K) components in blue, green, red respectively. Solid lines represent the cases with CR feedback included, while the dashed lines show the counterpart runs without CRs. At any galaxy mass, including CRs clearly enhances the amount of outflows, by at least a factor 2, compared to runs where the outflows are generated only by SN feedback. This is the direct consequence of the extra pressure support cosmic rays provide, helping to drive more gas away from the galactic disks. Additionally, their energy is dissipated much less efficiently than the thermal energy of gas, so that they can in practice hold it on longer timescales. Moreover, the energy lost by CRs is injected directly into the gas, which increases the thermal pressure more than it decreases the cosmic ray one, since the gas has a harder equation of state. Combined with the fact that cosmic ray pressure decreases less quickly upon adiabatic expansion than the thermal pressure does, all of this explains why CRs can energise winds and maintain outflows more efficiently than with (largely thermalised) SN feedback only.

Another consequence of CRs is a change in the temperature of the outflowing gas. Without CR feedback, the outflows are dominated by hot gas, especially for the two most massive disks. With CRs included, the outflows become dominated by the warm phase, and even gas with temperature below 10^4 K appears in the outflows.

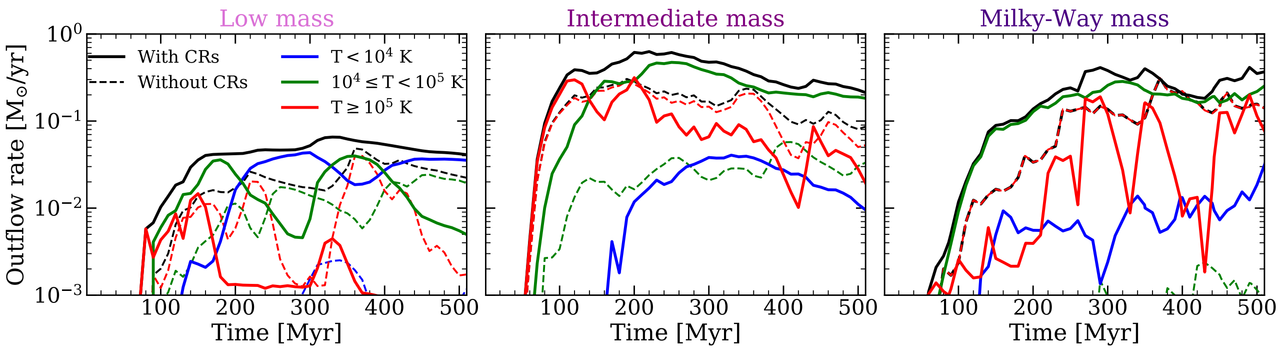

Fig. 2. Mass outflow rate of gas as a function of time, measured 10 kpc from the disks, with increasing galaxy mass from left to right. Each panel shows two sets of 4 curves for one galaxy, one set for a run with cosmic ray feedback (solid lines) and another set without (dashed lines). Black curves show the total rate of outflowing gas, while blue, green, red lines show how it separates into the cold, warm and hot phases. At any galaxy mass, adding CRs leads to stronger and colder outflows.

3 Sensitivity of the results to the diffusion coefficient

Our understanding of CR transport is limited by a number of uncertainties, making the study of their role in shaping galaxies model-dependant. This is especially true for the diffusion coefficient κ, which regulates the transport of the cosmic ray energy away from their production sites. Hence the value of κ can alter how CRs affect galaxy evolution. Theoretically or observationally, the diffusion coefficient is not well constrained. Some empirical constraints exist, from gamma-ray emission or spallation products measured in the Milky-Way. While κ is usually determined to be around a few 10^{28} cm^2/s, values at least ten times larger or smaller are still well within the realm of possibility.

In Fig. 3, we show the evolution of the mass outflow rate, measured at 10 kpc, when varying the diffusion coefficient from 10^{27} to 3×10^{29} cm^2/s in our most massive galaxy. Globally, the higher the diffusion coefficient, the larger the outflow rate, even if this increase becomes less and less significant for the highest values. For the lowest value adopted, $\kappa = 10^{27}$ cm^2/s, the amount of outflowing gas is actually lower than in the counterpart run without cosmic ray feedback. This is the consequence of CRs remaining trapped in the disk, with the pressure they exert sufficient to start pushing gas from the midplane, but not enough to completely overcome the gravitational potential of the disk. As the diffusion coefficient increases, larger cosmic ray pressure and

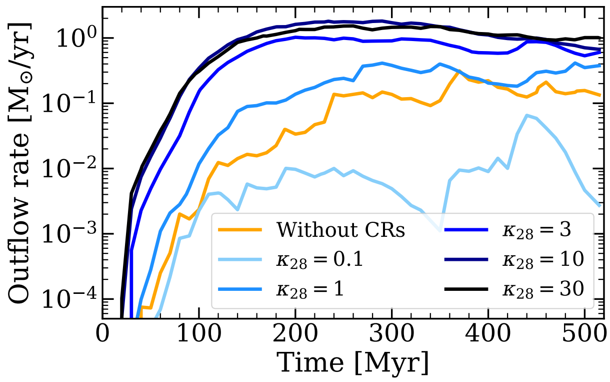

Fig. 3. Mass outflow rates for the Milky-Way mass galaxy. The orange curve corresponds to the run without cosmic ray feedback. From light blue to black, we increase the diffusion coefficient (expressed in units of 10^{28} cm^2/s). Globally, increasing its value increases the outflow rate. If it is very low, there is actually less gas outflowing than in the counterpart run without CRs. In the most extreme case of the largest diffusion coefficient, the outflow rate stops increasing.

velocities make it is easier to remove more and more material out of the galaxy up to larger distances. In the most extreme case of $\kappa = 3 \cdot 10^{29}$ cm^2/s, CRs escape the galaxy so quickly that they do not apply their pressure gradually. Consequently, we do not measure a net increase of outflows anymore.

4 Conclusions

We perform simulations of three idealised galaxies in dark matter halos with masses from 10^{10} to 10^{12} $M_\odot$, with radiation, a magnetic field, mechanical feedback from supernovae and with or without cosmic rays. Our results show that cosmic ray feedback has as an effect similar to SNe in reducing star formation, and that this effect decreases with galaxy mass. Additionally, the pressure support provided by CRs helps driving gas away from all our galaxies. They dramatically change the temperature of these outflows, which are dominated by gas between 10^4 and 10^5 K, while much hotter with SN feedback only and without cosmic rays. Pushing this gas more gently than supernovae, they also allow for outflows colder than 10^4 K to be found at large distances from the disks. However, changing the diffusion coefficient can alter quite significantly the amount of outflowing gas. In our Milky-Way mass galaxy, a diffusion coefficient $\kappa = 10^{27}$ cm^2/s is too low to render CRs dynamically relevant in driving more gas away from the disk than the counterpart run without CRs. Generally, increasing the diffusion coefficient increases the total outflow rate, but in the most extreme case where $\kappa = 3 \times 10^{29}$ cm^2/s, CRs escape so quickly that the flux of outflowing gas slowly starts to drop. A better understanding of CR propagation remains essential to determine their role in shaping galaxies and their CGM environment, bringing us a step closer to understanding galaxy evolution.

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