Propagation of CR secondary species and gamma ray emissions in MHD simulations of galaxies

Antoine Baldacchino, Michał Hanasz, Mateusz Ogrodnik & Dominik Wółtański

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Institute of Astronomy, Nicolaus Copernicus University, Toruń, Poland

Abstract

We develop a new algorithm for the production and propagation of cosmic ray (CR) secondary elements within the framework of Cosmic Ray Energy SPectrum (CRESP) module of Piernik MHD code (Ogrodnik et al ApJS 253, 18, 2021). CRESP is based on the piece-wise power-law (coarse-grained) method for selfconsistent and numerically efficient cosmic ray (CR) propagation in the magnetized ISM of galaxies. We present implementation of the method and preliminary results demonstrating production and propagation of secondary CR species in MHD simulations of the interstellar medium stratified by vertical gravity.

Motivation

So far, two approaches have been developed to numerically implement CR propagation in galaxies : GALPROP [6], where the structure of the interstellar medium (ISM) deduced from observational data is stationary, and the selfconsistent approach which combines the propagation of CRs with the system of MHD equations that include the dynamical coupling of CRs with thermal gas and magnetic fields (see the review by [2]. Some recent progresses combined both approaches [1, 5, 3], with spectrally resolved CR propagation in the MHD context. The CRESP algorithm [5] added recently to PIERNIK MHD code implemented the algorithm for the momentum-dependent transport of spectrally resolved CR electrons on Eulerian grids. Our goal is to extend the CRESP algorithm with the capability to model propagation of multiple spectrally resolved CR species, including production and propagation of secondary CR elements.

Within the present project we extend the data structure of PIERNIK code with the capability to propagate an arbitrary number of spectrally resolved CR species, including primaries and secondaries. We assume that primary CR species are accelerated in astrophysical MHD shocks via explicit source terms, while the secondary CR particles result from hadronic collisions of CR primaries against the kernels of the interstellar gas.

CR species spectrum

We assume that CR species are represented by a piece-wise power-law distribution function and are described by the Focker-Planck equation [4, see poster by Mateusz Ogrodnik et al.]. We take into account advection, energy-dependent ($D \propto p^{0.5}$), magnetic field-aligned diffusion as well as pressure gradient effects in dynamical evolution of CR species in the wind driven by CR protons.

For secondary species, we numerically implement the source function for both energy and number density using piece-wise power-law approach for density distribution function in phase space :

$$f_l(p) = f_{\mathrm{L}} \left(\frac{p}{p_{\mathrm{L}}} \right)^{-q_l} \qquad (1)$$

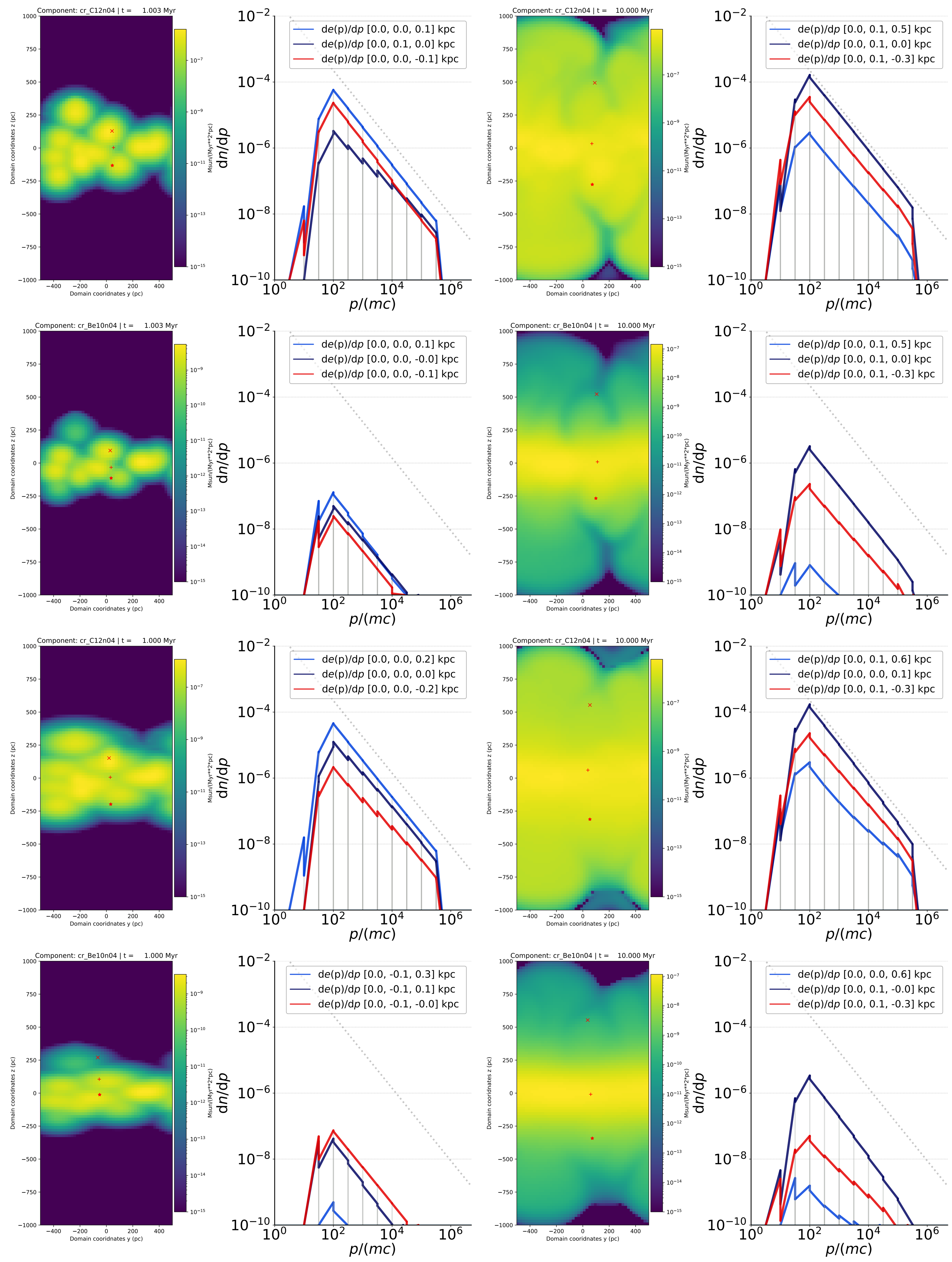
Both number and energy density n_j and e_j depends on f and the sources give :

$$\tilde{q}_N^k = \sum_i n_i \sum_j \beta \left(\frac{A_{\mathrm{j}}}{A_{\mathrm{k}}} \right) \sigma_j n_j \qquad (2)$$

$$\tilde{S}_N^k = \sum_i n_i \sum_j \beta \left(\frac{A_{\mathrm{j}}}{A_{\mathrm{k}}} \right) \sigma_j e_j \qquad (3)$$

2D simulations are performed with presence of primaries and secondaries. Primaries are initialized with relatives abundances to protons, and continuously injected in the ISM with supernovae.

Evolution of primary and secondary cosmic rays



We compute the evolution of primary C12 and secondary Be10 CR species in 2D simulations including ISM stratified by gravity, with diffusion coefficients of order 3.10^{27} and 3.10^{28} $\mathrm{cm^2 s^{-1}}$. The spectra of primaries and secondaries have different slopes and amplitudes depending on the height above the disk mid plane. This indicates that the ratio of secondaries to primaries depends on the position. We plan to investigate this dependence in the framework of global galactic disks.

Future goal : gamma ray modelisation

The next step is to implement, in a similar way, gamma ray production from proton - proton collision in the ISM. We aim to calculate and implement a piece wise power law method for the gamma ray spectrum from the reaction $p + p \to p + p + \pi^0, \pi^0 \to 2\gamma$. As for CR secondaries, we have a source function :

$$q_\gamma(\vec{r}, E_\gamma) = 2 \int_{E_\gamma + \frac{m_{\pi^0}^2 c^4}{4E_\gamma}}^{+\infty} \mathrm{d}E_{\pi^0} (E_{\pi^0}^2 - m_{\pi^0}^2 c^4)^{-1/2} q_{\pi^0}(\vec{r}, E_{\pi^0}) \qquad (4)$$

Some preliminary work has already been done for gamma rays from monoenergetic protons. The next step is the extension to spectral protons, and then to integrate them to the PIERNIK code.

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