Modeling CR electron propagation with PIERNIK & CRESP: simulations vs. observational data of NGC891

Mateusz Ogrodnik, Michał Hanasz, Dominik Wóltański & Artur Gawryszczak

Centre for Astronomy, Nicolaus Copernicus University, Toruń, Poland

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Abstract

Galactic outflows and extended non-thermal emission due to Comic Ray (CR) electrons were observed from many edge-on galaxies in radio range of electromagnetic radiation, allowing i.a. to estimate the strength and vertical structure of galactic magnetic field. We construct a global model of NGC891, based on observational characteristics of this galaxy. We assume that on the large scales the dynamics of the magnetized ISM is driven by Cosmic Rays. We apply the coarse-grained momentum finite volume (CGMV), for solving the Fokker–Planck CR transport equation for CR electrons in "Cosmic Ray Energy SPectrum" (CRESP) module of PIERNIK MHD code to model CR propagation in this galaxy. The overall propagation of cosmic rays is described by energy Fokker-Planck equation. The numerical model exhibits magnetic field amplification by CR-driven dynamo. We perform a parameter study of the system by varying the injection spectrum slope, the magnitude and momentum dependence of the CR electron diffusion coefficients and SFR. We take into account the advection, diffusion, adiabatic changes as well as synchrotron and inverse-Compton losses. We find that the spectrum of synchrotron radiation, polarization maps and spectral index maps reproduce very well the observed structures of the real edge-on galaxy. Comparison of different models suggests harder CRe^- injection spectra, higher conversion ratios of SN $\rightarrow$ CR energies (of 10–20%) and likely 2–3 times higher diffusion coefficients.

Basic formulae

Parametrization of CR distribution function: spectrum of CR particles is described using Focker-Planck equation:

$$\frac{\partial f}{\partial t} = \underbrace{-\boldsymbol{u}\cdot\nabla f}_{\text{advection}} + \underbrace{\nabla(\kappa\nabla f)}_{\text{diffusion}} + \underbrace{\frac{1}{3}(\nabla\cdot\boldsymbol{u})p\frac{\partial f}{\partial p}}_{\text{adiabatic evolution}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 b_l f + D_p\frac{\partial f}{\partial p}\right]}_{\text{synchrotron + IC and Fermi II}} + \underbrace{j}_{\text{sources}} \quad (1)$$

Distribution function for CR e^- in momentum space p is approximated with power-law:

$$f(p) = f_{l-\frac{1}{2}}\left(\frac{p}{p_{l-\frac{1}{2}}}\right)^{-q_l}, \quad (2)$$

where $f_{i-1/2}$ – distribution function , q_l – slope indices. We parametrize diffusion coefficients for CR e^- using formula

$$\kappa(p_l)_{\parallel,\perp} \approx \kappa^{\mathrm{CRS}}_{\parallel,\perp}\left(\frac{p_l}{p_\kappa = 20000 m_e c}\right)^{\alpha_\kappa}. \quad (3)$$

where we usually assume $\kappa_\parallel \approx$ 3–9$\times 10^{28}$ cm^{2}s^{-1}, $\kappa_\perp \approx 1\%\kappa_\parallel$, and $\alpha_\kappa = 0.3$.

The Cosmic Ray Energy Spectrum Algorithm: CRESP (Ogrodnik et al. 2021) is based on Miniati's COSMOCR code (Miniati 2001). Equation (1), is added to the system of MHD equations and solved in 4D (physical + particle momentum space). CR distribution function is approximated with piece-wise power-law. The whole spectrum of CR particles can be described equivalently by two sets of discretised quantities:

$$(n_l, e_l) \Leftrightarrow (f_{l-\frac{1}{2}}, q_l), \qquad i = 1, n_{\mathrm{bin}}. \quad (4)$$

Spectrum spans in a range delimited by cutoff momenta (p_{lo}, p_{up}) variating in response to the energy loss and gain mechanisms. A small value of energy "e_{small}" is used to detect active bins of the spectrum that are processed in momentum space. The remaining bins containing CR electrons under the threshold value are subject only to advection-diffusion transport in space.

Synchrotron radiation mapping: simulation results are post-processed in order to construct Stokes parameters using stored information about magnetic field, number and energy density data of CR particles. Spectrum is recovered (relation 4) and used to compute number density $N_{\mathrm{CRe-}}(\gamma)$ corresponding to observed frequency ν and local $\mathbf{B}$. Each cell contributes to synchrotron emissivity:

$$J(\nu)d\nu \propto B^{\frac{1}{2}}\,\nu_{\mathrm{crit}}^{\frac{1}{2}}\,N_{\mathrm{CRe-}}(\gamma)\,d\nu. \quad (5)$$

Setup

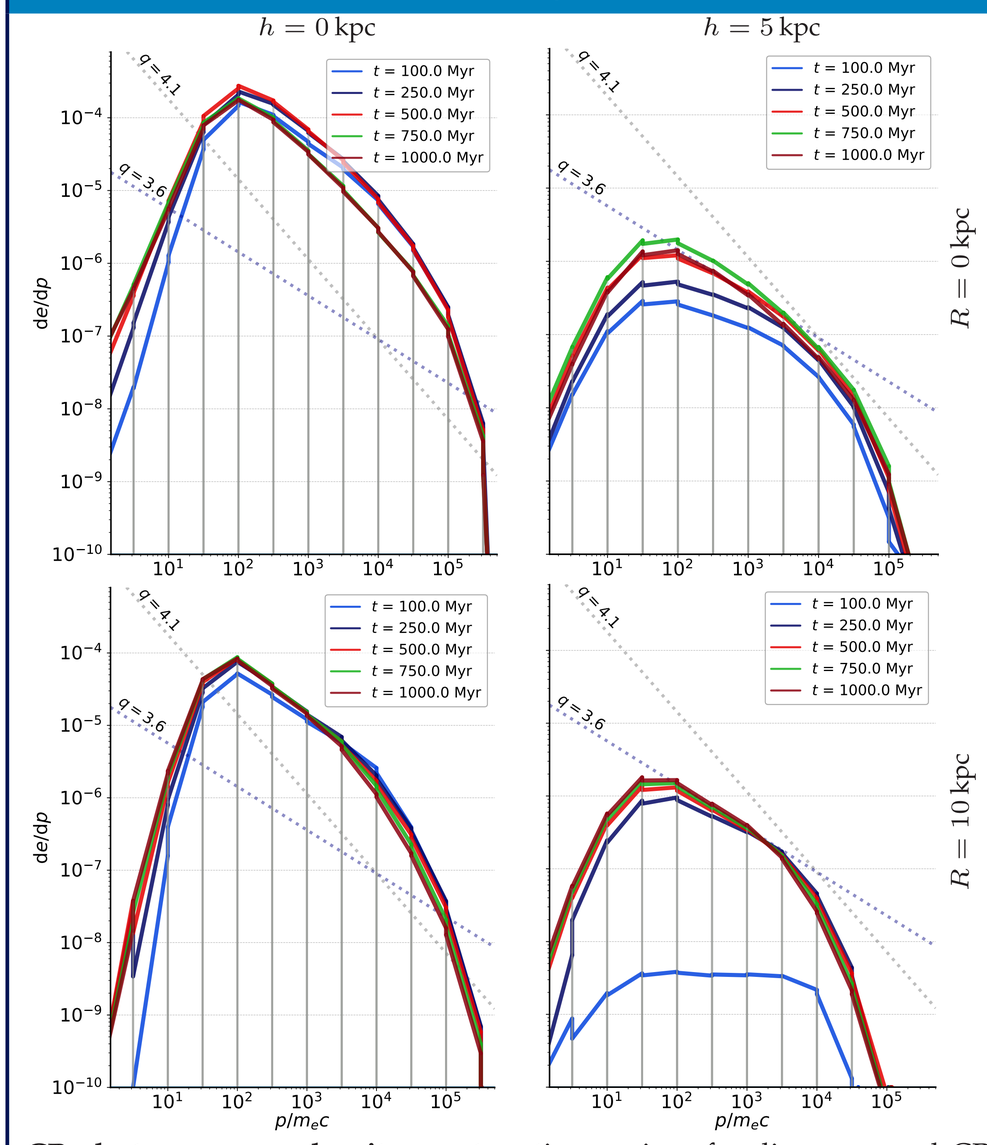
Each test is run on static Eulerian AMR grid with base resolution $96\times96\times64$ on with physical size $115.2\times115.2\times76.8\,\mathrm{kpc}^3$. Smallest effective cell size is $(150\mathrm{pc})^3$. We apply Schmidt-Kennicutt SFR $\propto \Sigma_{\mathrm{gas}}(r)^a$ and CR acceleration efficiency of 10%. Synchrotron, adiabatic and Inverse-Compton processes are considered for CRe^-. Here we present 4 cases:

- AK10I: $q = 4.1$, $\kappa_\parallel \approx 3\times10^{28}$ cm^{2}s^{-1}, $a = 1.45$
- AL10hI: $q = 3.6$, $\kappa_\parallel \approx 3\times10^{28}$ cm^{2}s^{-1}, $a = 1$
- AK10hI: $q = 3.6$, $\kappa_\parallel \approx 3\times10^{28}$ cm^{2}s^{-1}, $a = 1.45$
- BL10hI: $q = 3.6$, $\kappa_\parallel \approx 9\times10^{28}$ cm^{2}s^{-1}, $a = 1$

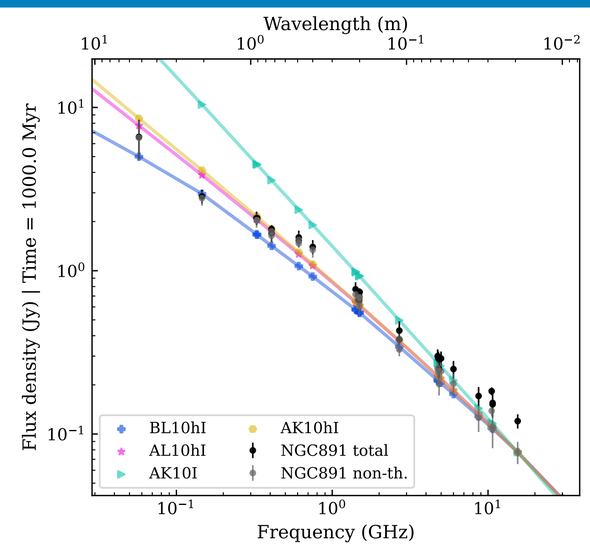
References

Miniati, F. 2001 *Computer Physics Communications 141, 17-38*
Girichidis, P., Naab, T., Walch, S., Hanasz, M. 2016, *ApJ 816, L19*
Hanasz, M., Lesch, H., Naab, T., et al. 2013, *ApJ 777, L38*
Hanasz, M., Otmianowska-Mazur, K., Kowal, G., and Lesch, H. 2009a *A&A 498, 335*
Wóltański, D., Hanasz, M. Kowalik, K. *Astrophysics and Space Science Proceedings 34, 2013*
Mulcahy D. D., Horneffer A., Beck R. et al.2018 *A&A 615 A98*
Ogrodnik, M., A., Hanasz M., Wóltański, D., 2021 *ApJS 253 180*
Wóltański, D., "Cosmic-Ray-driven dynamo in spiral galaxies", 2014
Hanasz, M., Wóltański, D., and Kowalik, K. 2009b *ApJ 706, L155*
Ogrodnik, M. A., Hanasz, M., Wóltański, D., and Gawryszczak, A. 2022 *MNRAS (in prep.)*

CR electron and total emission spectra



CR electron energy density spectra: time series of radius-averaged CR electron spectra from test BL10hI, in which adiabatic, synchrotron and Inverse-Compton mechanism were considered, drawn for 100, 250, 500, 750 Myr and 1 Gyr (blue, darkblue, red, green and crimson, respectively).

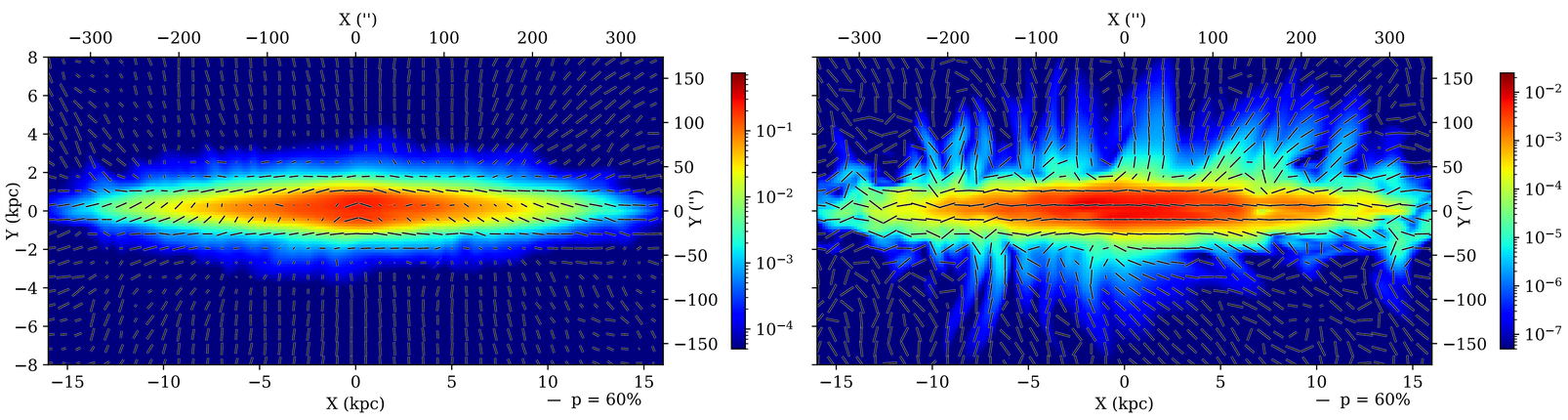


Total synchrotron emission spectra: NGC891 flux densities (Mulcahy et al. 2018) compared with results from synthetic observational data at 1Gyr. Synthetic spectrum amplitudes are normalized to match observational data at 15 GHz.

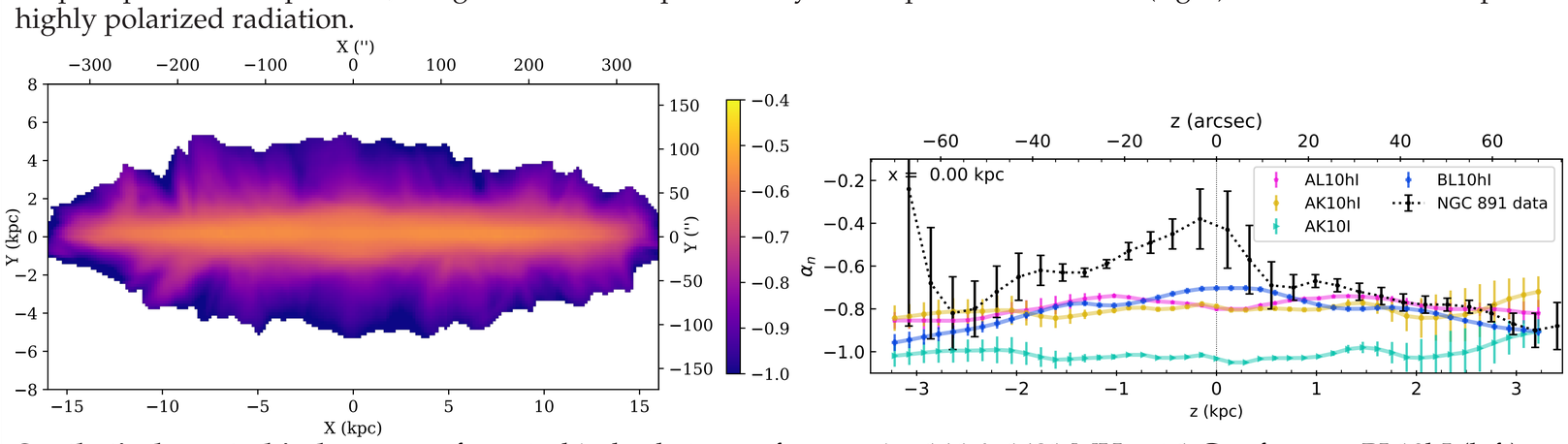
We draw following conclusions:

- Harder injection spectrum $q \sim 3.6$, higher diffusion coefficients $\kappa_\parallel \sim 9\times10^{28}$cm^{2}s^{-1}, and lower momentum dependence $\alpha_\kappa = 0.3$ show better agreement with observational data.
- SFR scaling does not show significant impact on flux density and spectral index.
- CR electron spectra vary depending on position in galactic disk; softening in the center in the disk plane and harder above the disk.

Synthetical observational data: maps & profiles



Synthetical total intensity: radio emission at 5cm for epoch 1Gyr, integrated over the whole line of sight (left) – visible 'X-shaped' polarization patterns, integrated in one 1kpc-thick layer at 5kpc from the center (right) – visible Parker loops with highly polarized radiation.



Synthetical spectral index: map of spectral index between frequencies 146 & 1421 MHz at 1 Gyr for case BL10hI (left) and averaged profile of spectral index in the map center for a set of tests (right).
Among the presented cases, test BL10hI, with harder injection spectrum and higher diffusion coefficients, shows the best agreement with observational data, even at a very advanced stage.

Acknowledgements

This work is supported by Polish Ministry of Sciences and Higher Education and National Science Centre under the OPUS-ST grant no. UMO-2015/19/B/ST9/02959. Computations were carried out in Academic Informatics Centre „TASK" in Gdańsk and TCfA's Hydra cluster.