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# PIERNIK MHD CODE — A MULTI–FLUID, NON–IDEAL EXTENSION OF THE RELAXING–TVD SCHEME (IV)

Michał Hanasz[1], Kacper Kowalik[1], Dominik Wóltański[1] and Rafał Pawłaszek[1]

**Abstract.** We present a new multi–fluid, grid MHD code PIERNIK, which is based on the Relaxing TVD scheme (Jin and Xin, 1995). The original scheme (see Trac & Pen (2003) and Pen *et al.* (2003)) has been extended by an addition of dynamically independent, but interacting fluids: dust and a diffusive cosmic ray gas, described within the fluid approximation, with an option to add other fluids in an easy way. The code has been equipped with shearing–box boundary conditions, and a selfgravity module, Ohmic resistivity module, as well as other facilities which are useful in astrophysical fluid–dynamical simulations. The code is parallelized by means of the MPI library. In this paper we present an extension of PIERNIK, which is designed for simulations of diffusive propagation of the Cosmic–Ray (CR) component in the magnetized ISM.

## 1 Cosmic Ray transport

The CR–MHD extension of PIERNIK code (Hanasz et al. (2009a), (2009b), (2009c)) is aimed at studies of the magnetohydrodynamical dynamo process induced by buoyancy of CRs in stratified atmospheres of galactic disks (Parker (1992), Hanasz et al. (2004)) investigated previously, in the shearing–box approximation, with the aid of ZEUS-3D code, extended with the CR transport algorithm (Hanasz & Lesch (2003)).

To describe cosmic–ray (CR) propagation in the interstellar medium (ISM) we use the diffusion–advection equation (see Schlickeiser & Lerche (1985))

$$\partial_t e + \boldsymbol{\nabla}(e\boldsymbol{v}) = -p\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{\nabla}(\hat{K}\boldsymbol{\nabla}e) + Q_{\mathrm{cr}} \tag{1.1}$$

together with the adiabatic equation of state for cosmic rays

$$p_{\mathrm{cr}} = (\gamma_{\mathrm{cr}} - 1)e_{\mathrm{cr}}, \tag{1.2}$$

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[1] Toruń Centre for Astronomy, Nicolaus Copernicus University, Toruń, Poland;
e-mail: `mhanasz@astri.uni.torun.pl`

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in addition to the standard set of MHD equations (Hanasz & Lesch (2003)). The source term $Q_{\rm cr}$ on the rhs. of Eqn. (1.1) corresponds to the production of CRs in supernova remnants. The diffusion term is written in the tensorial form to account for anisotropic diffusivity of CRs, where $\hat{K}$ is the diffusion tensor describing magnetic field–aligned CR diffusion (see Ryu et al (2003))

$$K_{ij} = K_{\perp}\delta_{ij} + (K_{\parallel} - K_{\perp})n_i n_j, \quad n_i = B_i/B, \tag{1.3}$$

We note that in the presence of CRs an additional source term: $-\nabla P_{\rm cr}$ should be included in the gas equation of motion (see e.g. Berezinski et al. (1990)), in order to incorporate the effects of CRs on gas dynamics.

In order to adopt the CR transport equation to the conservative scheme of PIERNIK code, we write Eqn. (1.1) in the conservative form

$$\partial_t e_{\rm cr} + \boldsymbol{\nabla}\cdot\boldsymbol{F}_{\rm cr,adv} + \boldsymbol{\nabla}\cdot\boldsymbol{F}_{\rm cr,diff} = -p_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} + Q_{\rm cr}, \tag{1.4}$$

where $e_{\rm cr}$ is CR energy density, $\boldsymbol{F}_{\rm cr,adv} = e_{\rm cr}\boldsymbol{v}$, is the flux of CRs advected by the gas flow, $\boldsymbol{F}_{\rm cr,diff} = -\hat{K}\boldsymbol{\nabla}e_{\rm cr}$ is CR diffusion flux and $Q_{\rm cr}$ is the CR source term.

The left hand side of the CR transport equation is treated in a conservative manner, while the terms on r.h.s. are added as source terms. The advection and source steps ($p_{\rm cr}\nabla\cdot\boldsymbol{v}$) for CRs are implemented within the RTVD scheme, while the CR diffusion step is realized outside the Relaxing TVD routine. The update of CR energy, corresponding to the diffusion term is performed with the aid of a directionally split, explicit algorithm (Hanasz & Lesch (2003)), which is first order in time and space. The source step corresponding to the injection of CRs in SN remnants is realized once per double timestep, outside the directional sweeps of fluid updates.

The explicit CR diffusion algorithm implemented in PIERNIK code is subject to the timestep limitation resulting from the von Neumann stability analysis. The timestep for the diffusive part of the CR diffusion–advection equation imposed in the code is

$$\Delta t = 0.5\ C_{\rm cr}\ \frac{\min(\Delta x, \Delta y, \Delta z)^2}{K_{\parallel} + K_{\perp}}, \tag{1.5}$$

where $C_{\rm cr} < 1$ is the Courant number for the CR diffusive transport algorithm, $\Delta x$, $\Delta y$ and $\Delta z$ are cell sizes. The numerical stability of the overall CRMHD algorithm, is achieved by a proper monotonic interpolation of CR gradient components computed on cell boundaries (see Hanasz & Lesch (2003)). We note, that the appropriate choice of boundary conditions for the highly diffusive CR component is to set a fixed value (zero) of CR energy density on external domain boundaries.

## 2 Test problems for CR transport

To test the magnetic field–aligned cosmic ray diffusion we present a simple 2D setup with uniform and diagonal magnetic field in the doubly–periodic computational domain. Parameters of the initial setup for the simulation are (in arbitrary units): $\rho_0 = 1$, $p_0 = 1$, $B_{\rm x} = 3$, $B_{\rm y} = 3$, $\gamma = 5/3$, $\gamma_{\rm cr} = 4/3$, $x_{\rm min} = -500$,

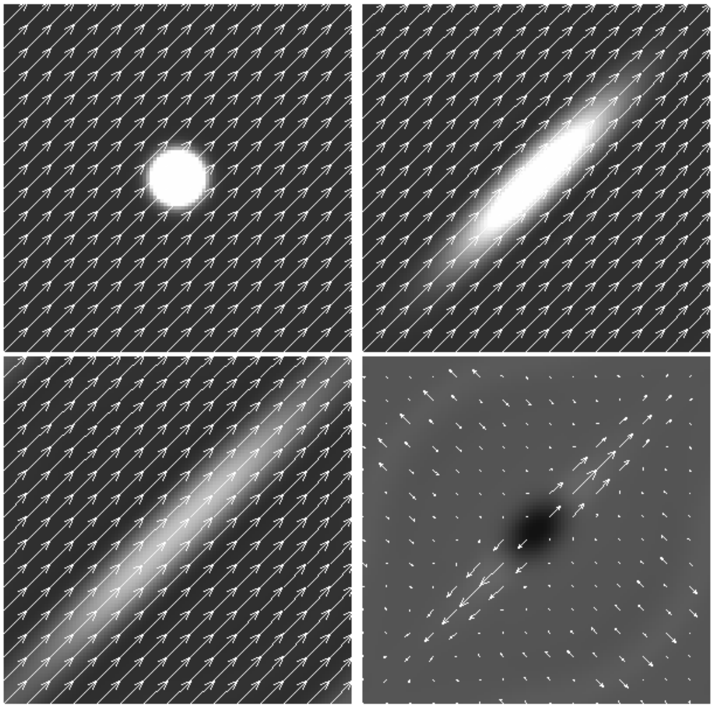

**Fig. 1.** Diffusion of cosmic rays along an inclined magnetic field: the initial spheroidal distribution of $e_{\rm cr}$ at $t = 0$ and the ellipsoidal distribution at $t = 20$ and $t = 60$. The last panel shows thermal gas density and velocity vectors at $t = 60$. The apparent flow of gas along the magnetic field direction is due to the CR pressure gradient, pushing gas along magnetic field lines. A magnetosonic wave, propagating in the direction perpendicular to magnetic field is also present.

$x_{\rm max} = 500$, $y_{\rm min} = -500$ and $y_{\rm max} = 500$. At $t = 0$ a portion of CRs, forming a 2D Gaussian profile, with half-width equal to 50 units and $e_{\rm cr} = 8$ at maximum around the domain center. The diffusion coefficients are $K_{\parallel} = 1000$ and $K_{\perp} = 0$.

The results of the test run demonstrate that the CR diffusion proceeds along magnetic field lines, as expected (see first three panels of Fig. 1). A detailed quantitative analysis ensures that in case of passive CR propagation (without the back-reaction of CR pressure on the thermal gas) numerical results fit accurately to the analytical solution. In the present case of active CR propagation, CR pressure gradients affect thermal gas (see the fourth panel of Fig. 1). The excess of cosmic ray pressure near the center of computational domain accelerates gas, along the oblique magnetic field, forming an ellipsoidal cavity in the gas distribution.

The present implementation of CR transport within the very efficient and flexible Relaxing TVD scheme (Pen et al. (2003)), combined with the MPI parallelization of PIERNIK, makes it possible to study the dynamic of CRs, and CR-driven dynamo in global simulations of galactic disks. First results of global galactic dynamo simulations (Hanasz et al. (2009d), (2009e)) demonstrate that magnetic fields can be efficiently amplified to equipartition values, on the timescale of galactic rotation, starting from weak magnetic fields of stellar origin.

In a more general case the cosmic ray (CR) component can be considered as an additional set of fluids extending the vector **u** of conservative variables. A subsequent extension of the CR transport module in PIERNIK code, aiming at energy dependent treatment of CR–electrons, and incorporation of synchrotron losses is currently under development.

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## References

Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., and Ptuskin, V. S.: 1990, *Astrophysics of cosmic rays*, Amsterdam: North-Holland, ed. by Ginzburg, V.L.

Hanasz, M., Kowal, G., Otmianowska-Mazur, K., and Lesch, H.: 2004, *Astrophys. J., Lett.* **605**, L33

Hanasz, M., Kowalik, K., Wóltański, D., and Pawłaszek, R.: 2009a, in K. Goździewski (eds.), *Extrasolar planets in multi–body systems: theory and observations*, (submitted), arXiv:0812.2161

Hanasz, M., Kowalik, K., Wóltański, D., Pawłaszek, R., and Kornet, K.: 2009b, in K. Goździewski (eds.), *Extrasolar planets in multi–body systems: theory and observations*, (submitted), arXiv:0812.2799

Hanasz, M., Kowalik, K., Wóltański, D., and Pawłaszek, R.: 2009c, in M. de Avillez (eds.), *The Role of Disk–Halo Interaction in Galaxy Evolution: Outflow vs Infall?*, (submitted), arXiv:0812.4839

Hanasz, M. and Lesch, H.: 2003, *Astron. Astrophys.* **412**, 331

Hanasz, M., Otmianowska-Mazur, K., Lesch, H., Kowal, G., Soida, M., Wóltański, D., Kowalik, K., Pawłaszek, R., and Kulesza-Żydzik, B.: 2009d, in K.G. Strassmeier, et al. (eds) *Cosmic Magnetic Fields: From Planets, to Stars and Galaxies*, Proceedings IAU Symposium No. 259, (submitted), arXiv:0901.0111

Hanasz, M., Wóltański, D., Kowalik, K., and Pawłaszek, R.: 2009e, in K.G. Strassmeier, et al. (eds) *Cosmic Magnetic Fields: From Planets, to Stars and Galaxies*, Proceedings IAU Symposium No. 259, (submitted), arXiv:0901.0116

Jin, S. and Xin, Z.: 1995, *Comm. Pure Appl. Math.* **48**, 235

Parker, E. N.: 1992, *Astrophys. J.* **401**, 137

Pen, U.-L., Arras, P., and Wong, S.: 2003, *Astrophys. J., Suppl. Ser.* **149**, 447

Ryu, D., Kim, J., Hong, S. S., and Jones, T. W.: 2003, *Astrophys. J.* **589**, 338

Schlickeiser, R. and Lerche, I.: 1985, *Astron. Astrophys.* **151**, 151

Trac, H. and Pen, U.-L.: 2003, *Publ. Astron. Soc. Pac.* **115**, 303