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Relativistic cosmic-ray backreaction instability along the background magnetic field

Cosmic-ray current across the background magnetic field

INTRODUCTION

- Supernova remnant shocks – a source of cosmic rays
- Mechanism - 1st order Fermi acceleration

Effects of cosmic rays

- Interaction with an existing turbulence
- Ionization of interstellar matter
- Heating of plasma
- Pressure on plasma
- Generation of magnetic fields through instabilities

Generation of magnetic fields
The Bell instability, MNRAS 2004, 353, 550

- Cosmic-ray current-driven (CRCD)instability.
- Usually, one says that this instability is due to drifting cosmic rays.
- However, the active role of cosmic rays is also in the generation of the return plasma current.
- The contribution of cosmic-ray current to the dispersion relation in the case $k_{z}v_{z} \gg \omega_{ci}$ is negligible.
- Some of these points are contained in the paper by Zweibel, E. G. 2003, ApJ, 587, 625.
- The Bell instability is due to return plasma current.

The Bell instability

$$\mathbf{k} \parallel \mathbf{B}_0 \parallel \mathbf{v}_{cr0}$$

$$\delta_{\text{Bell}} = \frac{1}{2}\omega_{ci}\frac{n_{cr0}}{n_{i0}}\frac{v_{cr0}}{c_{Ai}}$$

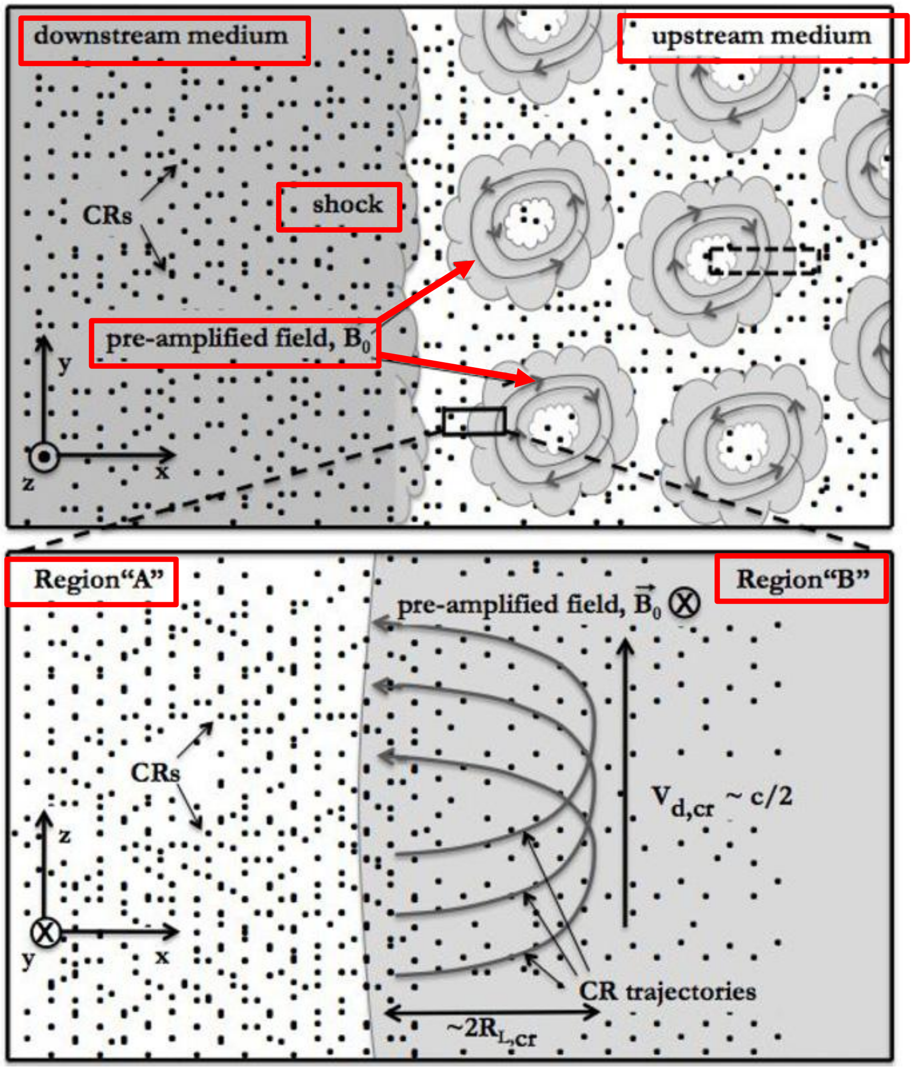
$$k_{\text{Bell}} = \frac{1}{2}\omega_{ci}\frac{n_{cr0}}{n_{i0}}\frac{v_{cr0}}{c_{Ai}^2}$$

Numerical calculations: $$\frac{B_{0fin}}{B_{0init}} \sim 10.$$

"The evidence from X-ray observations of SNRs has allowed the estimation of the strength of the field, suggesting downstream amplitudes∼100 times larger than that typically expected in the interstellar medium of the Galaxy" (from Riquelme and Spitkovsky 2010)

Riquelme and Spitkovsky
(ApJ 2010, 717, 1054)

$$\mathbf{k} \parallel \mathbf{B}_0 \perp \mathbf{v}_{cr0}$$



- **Upper panel:**
- Downstream and upstream regions of a shock.
- Doughnut-like shapes of pre-amplified field.
- Black dots: "Magnetized" CRs with small Larmor radii.
- **Lower panel:**
- Small, solid-line rectangle shown in the upper panel.
- Region "A": low initial magnetic field, Region "B": the pre-amplified magnetic field *B_0.*
- CRs from region "A" penetrate into region "B" by a distance ~2R_L,cr
- The coherent deflection produces a net mean velocity along *z of* magnitude ~c/2.

Riquelme and Spitkovsky
(ApJ 2010, 717, 1054)

- The perpendicular current-driven instability (PCDI) of Riquelme and Spitkovsky has the similar growth rate as that of Bell‘s instability.

$$\delta_{RS} \sim \delta_B$$

- The PCDI, in combination with the CRCD instability, suggests that CRs are responsible for the significant fraction of magnetic amplification inferred from SNR shock observations.
- However, the back-reaction of cosmic rays not included in analytical considerations.

Main points in the paper by Nekrasov and Schadmehri, ApJ 2012, 756, 77

- Multi-fluid approach
- Electron-ion-cosmic-ray astrophysical objects
- Cosmic-ray drift velocity is perpendicular to the background magnetic field
- One-dimensional perturbations along the magnetic field
- Return current of the background plasma
- Back-reaction of cosmic rays

Plasma equations

$$\frac{\partial \mathbf{v}_j}{\partial t} + \mathbf{v}_j \bullet \nabla \mathbf{v}_j = -\frac{\nabla p_j}{m_j n_j} + \frac{q_j}{m_j}\mathbf{E} + \frac{q_j}{m_j c}\mathbf{v}_j \times \mathbf{B},$$

$$\frac{\partial n_j}{\partial t} + \nabla \bullet n_j \mathbf{v}_j = 0,$$

$$\frac{\partial T_i}{\partial t} + \mathbf{v}_i \bullet \nabla T_i + (\gamma - 1) T_i \nabla \bullet \mathbf{v}_i = -(\gamma - 1)\frac{1}{n_i}\mathcal{L}_i(n_i, T_i) + \nu_{ie}^{\varepsilon}(n_e, T_e)(T_e - T_i)$$

$$\frac{\partial T_e}{\partial t} + \mathbf{v}_e \bullet \nabla T_e + (\gamma - 1) T_e \nabla \bullet \mathbf{v}_e = -(\gamma - 1)\frac{1}{n_e}\nabla \bullet \mathbf{q}_e - (\gamma - 1)\frac{1}{n_e}\mathcal{L}_e(n_e, T_e) - \nu_{ei}^{\varepsilon}(n_i, T_e)(T_e - T_i)$$

$j = i, e$

i denotes ions

e denotes electrons

Equations for cosmic rays
(Lontano et al., Phys. Plasmas 2001, 8, 5113)

$$\frac{\partial(R_{cr}\mathbf{p}_{cr})}{\partial t} + \mathbf{v}_{cr} \cdot \nabla(R_{cr}\mathbf{p}_{cr}) = -\frac{\nabla p_{cr}}{n_{cr}} + q_{cr}(\mathbf{E} + \frac{1}{c}\mathbf{v}_{cr} \times \mathbf{B}),$$

- momentum equation,

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_{cr} \cdot \nabla\right)\left(\frac{p_{cr}\gamma_{cr}^{\Gamma_{cr}}}{n_{cr}^{\Gamma_{cr}}}\right) = 0$$

- equation for entropy, and continuity equation,

$$R_{cr} = 1 + \frac{\Gamma_{cr}}{\Gamma_{cr} - 1}\frac{E_{cr}}{m_{cr}c^2}$$

cold $\quad E_{cr} \ll m_{cr}c^2,\ \Gamma_{cr} = \frac{5}{3}$

hot $\quad E_{cr} \gg m_{cr}c^2,\ \Gamma_{cr} = \frac{4}{3}$

Γ_{cr} - the adiabatic index

Zero order state

$$\mathbf{j}_{ret} = q_i n_{i0} \mathbf{u}_{pl} = -\mathbf{j}_{cr0} = -q_{cr} n_{cr0} \mathbf{u}_{cr},$$

$$u_{pl} = \frac{n_{cr0}}{n_{i0}} u_{cr} \ll u_{cr}$$

Results 1
Dispersion relation

$$E_{cr} \ll m_{cr}c^2$$

$$\omega^2 \frac{c^2}{c_A^2} - k^2c^2 = \frac{\omega_{pi}^2 u_{pl}^2 k^2}{(\omega^2 - k^2 C_s^2)} + \frac{\omega_{pcr}^2 u_{cr}^2 k^2}{(\gamma_{cr0}\omega^2 - k^2 c_{scr}^2)},$$

$$u_{pl} = \frac{n_{cr0}}{n_{i0}} u_{cr}$$

$$C_s^2 \to c_s^2$$

$$\frac{\omega_{pi}^2 u_{pl}^2}{\omega_{pcr}^2 u_{cr}^2} = \frac{n_{cr0}}{n_{i0}} \ll 1$$

Results 2
The growth rate and wave number

$$\delta_{\max}^2 = \frac{4\pi j_{cr0}^2}{\rho_{cr0} c^2} \frac{\gamma_{cr0}^{-1} c_A^2}{\gamma_{cr0}^{-1} c_{scr}^2 + c_A^2},$$

$$k_{\max}^2 = \frac{4\pi j_{cr0}^2}{\rho_{cr0} c^2} \frac{\gamma_{cr0}^{-1/2} c_A}{c_{scr}\left(\gamma_{cr0}^{-1} c_{scr}^2 + c_A^2\right)},$$

$$\delta_{\max} = k_{\max}\left(\gamma_{cr0}^{-1/2} c_{scr} c_A\right)^{1/2}.$$

Result 3
The relation between the growth rates

$$\frac{\delta_{\max}}{\delta_{\mathrm{Bell}}} = \frac{2}{\gamma_{cr0}^{1/2}} \left(\frac{n_{i0}}{n_{cr0}} \right)^{1/2}$$ can be $\gg 1$

at $c_A^2 \gg \gamma_{cr0}^{-1} c_{scr}^2$

and

$$\frac{\delta_{\max}}{\delta_{\mathrm{Bell}}} = 2 \left(\frac{n_{i0}}{n_{cr0}} \right)^{1/2} \frac{c_A}{c_{scr}}$$ can be $\gg 1$

at $\gamma_{cr0}^{-1} c_{scr}^2 \gg c_A^2$

Conclusions 1

- **Return current of the background plasma** and the **backreaction of cosmic rays** for one-dimensional perturbations along the magnetic field have taken into account.
- Using the **multi-fluid approach**, streaming and thermal instabilities of the electron-ion astrophysical plasma with homogeneous cold cosmic rays drifting across the background magnetic field were investigated.
- Cosmic-ray backreaction results in a streaming instability with **considerably larger growth rate** than that due to the usually treated return current of the background plasma.
- **The maximal growth rates** and corresponding **wave numbers** have been found.
- It was shown that **the thermal instability** does not dependent on cosmic rays in the model under consideration.
- In the limit of fast thermal energy exchange between electrons and ions, the isobaric and isochoric growth rates have been obtained.

Conclusions 2

- Our analysis of instabilities induced by cosmic rays is applicable to shocks in a **variety of environments**: ISM, superbubbles, ICM.

- We expect that the **magnetic field is amplified to a larger value** when the backreaction of cosmic rays is present.

- This leads to an **increased confinement of cosmic rays** with excited turbulent motions in the non-linear regime and accordingly to the **acceleration of cosmic rays to higher energies.**

Some of my other cosmic ray studies

1**. A. K. Nekrasov**, Back-reaction instabilities of relativistic cosmic rays, *Plasma Physics and Controlled Fusion,* **55**, 085007, 2013.

In the first geometry, the cosmic-ray current is parallel to the background magnetic field and pertubations, i.e., the following geometry is considered:

$$\mathbf{u}_{cr0} \parallel \mathbf{B}_0 \parallel \mathbf{k}$$

2. **A. K. Nekrasov and M. Shadmehri**, Influence of the back-reaction of streaming cosmic rays on magnetic field generation and thermal instability, *ApJ, 788:47, 2014 June 10*

In the second geometry, the cosmic–ray current is perpendicular to the background magnetic field, which in turn is perpendicular to perturbations. The geometry is:

$$\mathbf{u}_{cr0} \perp \mathbf{B}_0 \perp \mathbf{k}$$

Thank you for your attention!

Back-up slide 1

$$\mathcal{L}_j(n_j, T_j) = n_j^2 \Lambda_j(T_j) - n_j \Gamma_j$$

Λ_{j} and Γ_{j} are the cooling and heating functions

Back-up slide 2

Contribution of cosmic rays

$$H_{cr1} \Rightarrow -\frac{q_{cr}}{m_{cr}} \frac{\partial}{\partial t} \frac{u_{cr}}{c} B_{1x}.$$

$$j_{cr1y} \Rightarrow q_{cr} n_{cr1} u_{cr} = -q_{cr} n_{cr0} u_{cr} \left(\frac{\partial}{\partial t} \right)^{-1} \frac{\partial v_{cr1z}}{\partial z} = -q_{cr} n_{cr0} u_{cr} \frac{1}{L_{cr}} \left(\frac{\partial}{\partial t} \right)^{-1} \frac{\partial H_{cr1}}{\partial z} =$$

$$= q_{cr} n_{cr0} u_{cr} \frac{1}{L_{cr}} \left(\frac{\partial}{\partial t} \right)^{-1} \frac{\partial}{\partial z} \frac{q_{cr}}{m_{cr}} \frac{\partial}{\partial t} \frac{u_{cr}}{c} B_{1x} = \frac{q_{cr}^2 n_{cr0}}{m_{cr}} u_{cr}^2 \frac{1}{L_{cr}} \left(\frac{\partial}{\partial t} \right)^{-1} \frac{\partial^2}{\partial z^2} E_{1y}$$

$$4\pi \left(\frac{\partial}{\partial t} \right)^{-1} j_{cr1y} \Rightarrow \frac{\omega_{pcr}^2 u_{cr}^2}{L_{cr}} \left(\frac{\partial}{\partial t} \right)^{-2} \frac{\partial^2}{\partial z^2} E_{1y}$$

$$4\pi \left(\frac{\partial}{\partial t} \right)^{-1} j_{cr1y} \Rightarrow \varepsilon_{cryy} E_{1y}$$

Back-up slide 3

1. **A. K. Nekrasov**, Back-reaction instabilities of relativistic cosmic rays, *Plasma Physics and Controlled Fusion,* **55**, 085007, 2013.

$$\mathbf{u}_{cr} \parallel \mathbf{B}_0 \parallel \mathbf{k}$$

•Cosmic rays can be both electrons and ions. The drift speed of cosmic rays is directed along the magnetic field.

• In equilibrium, the return current of the background plasma is taken into account.

•One-dimensional perturbations parallel to the magnetic field are considered.

•The dispersion relations are derived for transverse and longitudinal perturbations.

• **It is shown that the back-reaction of magnetized cosmic rays generates new instabilities one of which has a growth rate that can approach the growth rate of the Bell instability.**

•These new instabilities can be stronger than the cyclotron resonance instability.

• **For unmagnetized cosmic rays, the growth rate is analogous to the Bell one.**

•**We compare two models of the plasma return current in equilibrium with three and four charged components. Some differences between these models are demonstrated.**

• For longitudinal perturbations, an instability is found in the case of ultra-relativistic cosmic rays.

Back-up slide 4

1. **A. K. Nekrasov and M. Shadmehri**, Influence of the back-reaction of streaming cosmic rays on magnetic field generation and thermal instability, *ApJ, 788:47, 2014 June 10* . $\mathbf{u}_{cr} \perp \mathbf{B}_0 \perp \mathbf{k}$

•Perturbations are considered to be across the magnetic field.

•The backreaction of cosmic rays resulting in strong streaming instabilities is taken into account.

• **It is shown that, for sufficiently short wavelength perturbations, the growth rates can exceed the growth rate of cosmic-ray streaming instability along the magnetic field, found by Nekrasov & Shadmehri, which is in turn considerably larger than the growth rate of the Bell instability.**

•The thermal instability is shown not to be subject to the action of cosmic rays in the model under consideration.

•The dispersion relation for the thermal instability has been derived, which includes sound velocities of plasma and cosmic rays and Alfv´en and cosmic-ray streaming velocities. The relation between these parameters determines the kind of thermal instability ranging from the Parker to the Field instabilities.