Non-linear diffusion of CRs escaping from SNRs in the atomic/molecular ISM

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Introduction

It is admitted that CRs play an important role in the ISM dynamics. Strong shocks in supernova remnants (SNRs) seem to be able to accelerate CRs by diffusive shock acceleration (DSA) up to few hundred of TeV or even to PeV at early times. The generated CRs streaming instability can produces magnetic perturbations propagating in the plasma and affecting back the CRs transport properties.

In this work we study the non-linear diffusion of CRs escaping from SNRs in weakly ionized plasma. We use a 1D C++ fluid code written by Nava et al. (2016) and adapted to the atomic/molecular plasmas which consists in to simultaneously solve two diffusion/advection eqs. for magnetic perturbation energy density and CRs pressure. The dimensionnality of our problem implies to use a flux tube approximation.

Application

Through simulations of CRs sources expansion in the neutral atomic/molecular ISM, we shown that the self-generated CRs turbulence can have an important effect over the CRs propagation and over plasma dynamics.

By equating blue term with green term in master equations presented in the **The model** section, we are currently implementing a sub-grid CRs diffusion coefficient term in the magnetohydrodynamics RAMSES code. See our second poster for more informations.

Generalisation of the method

In order to study a realistic situation we need to take into account the medium properties spatial variations and increase the dimensionnality of our problem leading to a generalized system of equations

$$\frac{\partial P_{\mathrm{CR}}}{\partial t} + \frac{\partial p^3 \mathbf{V_A}}{\partial p^3}\frac{\partial P_{\mathrm{CR}}}{\partial \mathbf{r}} = \frac{\partial}{\partial \mathbf{r}} D \frac{\partial P_{\mathrm{CR}}}{\partial \mathbf{r}} + \frac{4\pi p^4 v(p)}{3}\frac{\partial \mathbf{V_A} p^3}{\partial \mathbf{r}}\frac{\partial P_{\mathrm{CR}}/(\frac{4\pi p^4 v(p)}{3})}{\partial p^3} \tag{1}$$

$$\frac{\partial I}{\partial t} + \frac{\partial \mathbf{V_A} I}{\partial \mathbf{r}} = (\Gamma_g - \Gamma_d) I + Q \tag{2}$$

where $\Gamma_g = -\frac{12\pi}{B_0^2 I}\frac{\partial P_{\mathrm{CR}}}{\partial \mathbf{r}}\frac{\mathbf{B}}{B}$, $P_{\mathrm{CR}} = P_{\mathrm{CR}}(\mathbf{r}, p, t)$, $D = D(\mathbf{r}, p, t)$, $\mathbf{V_A} = \mathbf{V_A}(\mathbf{r}, p)$ and $I = I(\mathbf{r}, k)$.

Conclusion & References

Non-linear diffusion solutions show that a non-negligible amout of turbulence is generated around SNRs especially in the DiM and strongly confine CRs. This effect can have important consequences over the galactic diffusion properties of CRs.

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[2] Malkov M. A., Diamond P. H., Sagdeev R. Z., Aharonian F. A., Moskalenko I. V. : *Analytic Solution for Self-regulated Collective Escape of Cosmic Rays from Their Acceleration Sites*, apj (2013)

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[4] Cioffi D. F., McKee, Bertschinger E. : *Dynamics of radiative supernova remnants*, apj (1988)

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The model

CRs and resonant waves transport along the mean magnetic field lines is described by two transport eqs. given by

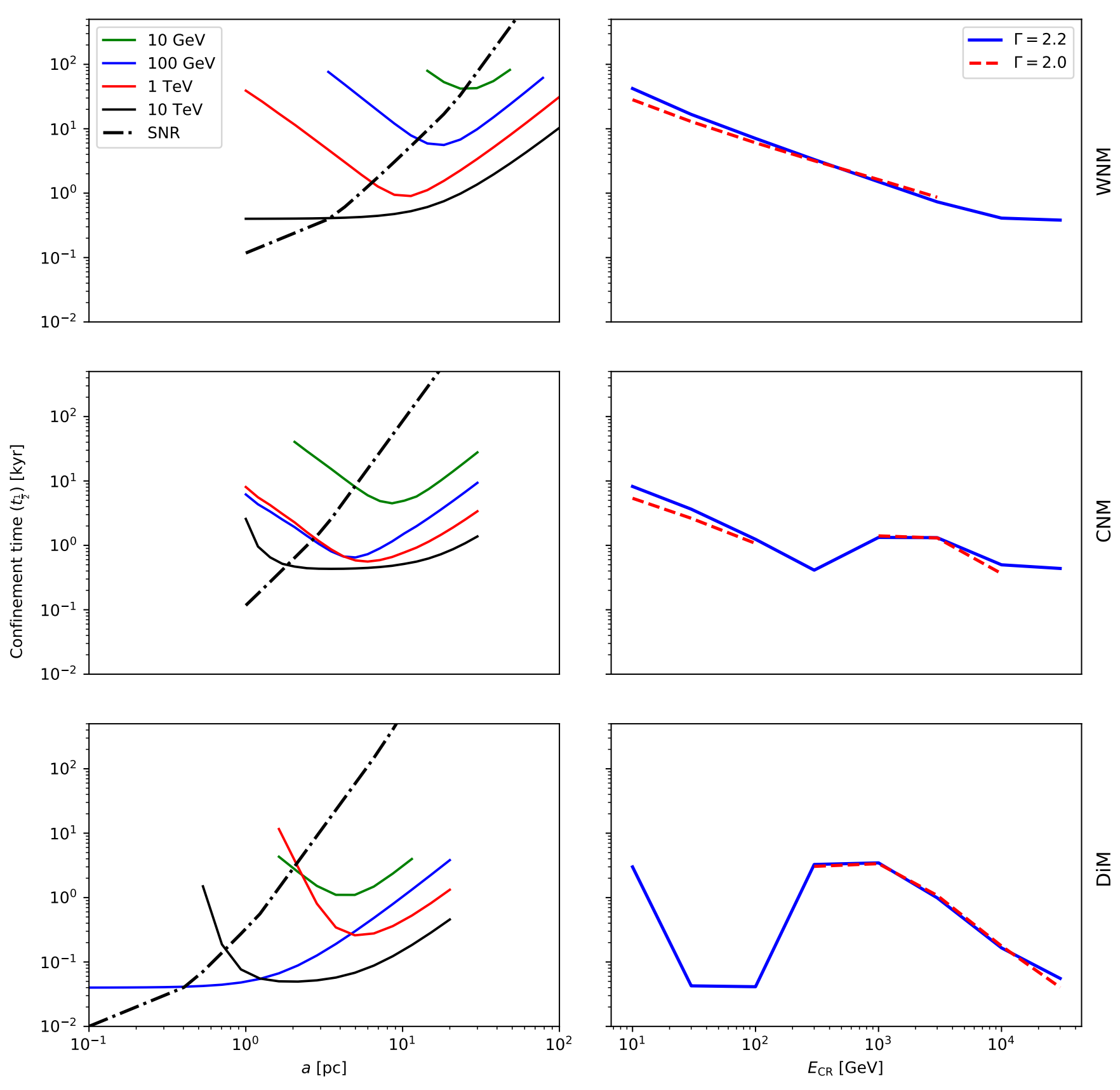
$$\boxed{\frac{\partial P_{\mathrm{CR}}}{\partial t} + V_{\mathrm{A}}\frac{\partial P_{\mathrm{CR}}}{\partial z}} = \boxed{\frac{\partial}{\partial z}\left(D\frac{\partial P_{\mathrm{CR}}}{\partial z}\right)}$$

$$\boxed{\frac{\partial I}{\partial t} + V_{\mathrm{A}}\frac{\partial I}{\partial z}} = \boxed{2\left(\Gamma_{\mathrm{growth}} - \Gamma_{\mathrm{d}}\right) I} + \boxed{Q}$$

where P_{CR} represents the CRs pressure and I is the Alfvén waves magnetic energy density. Red boxes represent the advective terms where the advection velocity is the Alfvén one (V_{A}). The blue box describes the way that CRs are diffused by the plasma turbulence where $D = D_{\mathrm{B}}/I$ corresponds to a non-linear diffusion coefficient depending on the magnetic perturbations energy density. D_{B} is the Bohm diffusion coefficient. The green box discuss the way that magnetic perturbations are generated/damped. Γ_{d} correspond to the waves damping rate while $\Gamma_{\mathrm{growth}} = -V_{\mathrm{A}}\, \partial P_{\mathrm{CR}}/\partial z\, /(2I)$ describes the waves generation by CRs streaming instability dissipation. The black box is a constant term describing the large scale turbulence magnetic energy inferred from observation.

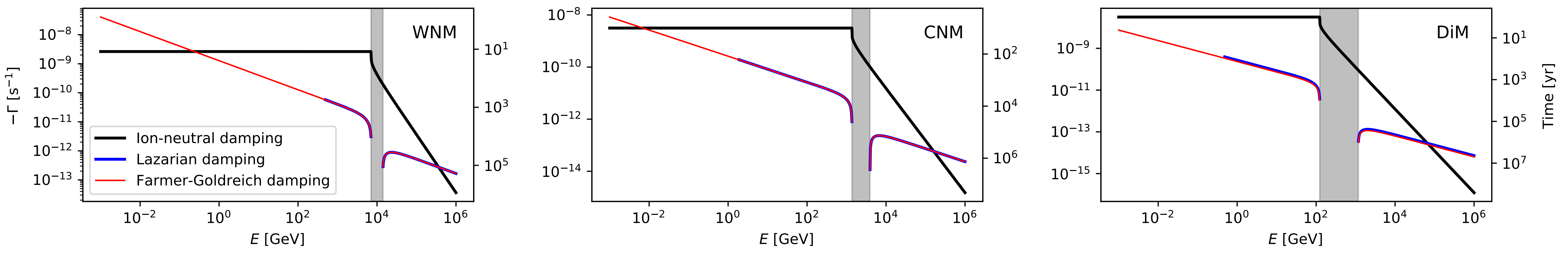
CRs Cloud model

Malkov et al. (2013) defined the CR cloud half-life time $t_{1/2}$ as the time it takes for the CRs integrated pressure in the initial sphere to be divided by two. By calculating this time for each initial CRC radius (see colored lines on the left part of the figure below) and intersecting it with shock radius evolution of SNR in each phase (see black dotted lines on the left part of the figure below) derived from (Cioffi et al. 1988, Truelove & McKee 1999), we can derive the characteristic confinement time as a function of the CRs energy (see blue lines on the right hand part of the figure below).



ISM phases properties

We modelised the CRs leakage problem in three homogeneous atomic/molecular phases of the ISM : Warm Neutral Medium (WNM), Cold Neutral Medium (CNM) and Diffuse Molecular Cloud (DiM). The self-generated Alfvén waves are damped by two processes : Ion-Neutral collisions, Large scale turbulence interaction.



Non-linear diffusion solutions : Numerical approach

Knowing the CRs escape time and the associated SNR shock radius. We simulated CRC expansion for each solution in each phase : WNM (left), CNM (middle), DiM (right). Each numerical solution is calculated at $t_{1/2}/4$ (blue), $t_{1/2}$ (green), $4t_{1/2}$ (red) by solid lines for each CRs energies : 10 (top left), 10^2 (top right), 10^3 (bottom left), 10^4 (bottom right) GeV. For each energy, the top panel represents the CRs spatial pressure distribution and is compared to test particles solutions represented by colored dotted lines. The middle panel represents the CRs pressure gradient. The bottom panel represents the spatial diffusion coefficients due to self-generated turbulence compared to the large scale turbulence one represented by a black large dotted line. Black dotted lines represent the initial conditions of the simulation.