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Cosmic ray propagation in local magnetic fields

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Magneto-hydrodynamic (MHD) turbulence is responsible for the transport of cosmic rays (CRs) in the interstellar medium. Recent models of MHD turbulence show an anisotropic spectrum resulting from the critical balance between the non-linear cascade process and the interaction of oppositely travelling wave packets along the magnetic field lines. The interaction between CRs and magnetic fluctuations involve wave numbers that have to be calculated with respect to the local magnetic field, i.e. the magnetic fields seen by a perturbation of scale k^{-1} which have scales larger than k^{-1}. We have developed kinetic-MHD simulations using the MHD RAMSES code upgraded with a kinetic module describing the particle transport via turbulent Lorentz forces. We have reconstructed the local magnetic fields from the total magnetic field using a Gaussian filter. We have reconstructed the cosine pitch-angle diffusion coefficient for particles propagating in the random Lorentz force produced by the total field and the different local filtered fields. The particles have the same Larmor radius of $r_L = 0.1$ in cube length units and the wave-number r_L^{-1} fall in the inertial range of the turbulence. We found that the particle mean free path is dominated by the transport in local fields with small filter parameters, consistently smaller than $r_L^{3/2}$ in cube length units meaning that perpendicular small scale fluctuations are important in the wave-particle interaction process. The filtering procedure hence helps to isolate the physics of the particles and the MHD anisotropic turbulence interaction.

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1. Introduction

Understanding the properties of cosmic ray (CR) transport in magnetized turbulence is a key issue in the description of the origin of cosmic ray radiation. The transport involves the interaction of CRs with various types of waves that are usually described in the long wavelength magnetohydrodynamic (MHD) limit. The MHD perturbations are part of magnetized turbulent motions that pervade the interstellar medium (ISM) and induce random walks of the CR from their sources to the Earth [1]. The very nature of the MHD turbulence is not well constrained and a matter of very active research [2].

Recent phenomenological models of MHD turbulence have pointed out that the mean magnetic (large scale) field induces a natural anisotropy in the energy transfer. They considered that the source of small scale turbulent motions is produced by the interaction of opposite wave packets travelling along the local mean magnetic field lines. The balance between the interaction timescale and the perpendicular cascade timescale leads to a relation between the parallel and the perpendicular perturbation wave numbers $k_{\parallel} \propto k_{\perp}^{2/3}$ (see [3]). Here the local magnetic field has to be understood in the sense of the large scale magnetic field for the wave packets [4] of scale $1/k$. This turbulence model originally developed in the incompressible limit has been successfully retrieved in the compressible limit using numerical calculations [5].

It appeared soon that a turbulence with a critical balance should not provide efficient cosmic ray transport through the diffusion of the pitch-angle of the particles [1] [6, 7]. This problem arises from the form of the anisotropy: in a Goldreich-Sridhar (hereafter GS) type turbulence the Eddies are elongated along the local magnetic field and a particle with a Larmor radius $r_L \gg 1/k_{\perp}$ do interact with several uncorrelated field lines within one gyro-period. This argument has never been tested with numerical simulations so far but [8] using an approach with an envelope turbulence found an increase of the parallel mean free path by a factor only of a few with respect to the quasi-linear theory in an isotropic turbulence as obtained by [9]. To alleviate the problem of weak cosmic ray transport efficiency in Alfvenic anisotropic turbulence recent work argued for a strong contribution of fast magnetosonic waves which have been shown to follow an isotropic cascade [5, 10, 11]. [12] did extend these works to investigate the perpendicular transport by field line wandering using a non-linear theory for the guiding center motion. In all these previous works the wave numbers are taken with respect to the local magnetic field. However, recent direct numerical calculations involving the particle transport in MHD snapshots have been performed in the global magnetic field reference frame [13, 14].

In this work we consider the propagation of the perturbations along the local magnetic field lines and isolate the particle pitch-angles with respect to the local magnetic fields. This approach helps in understanding the contribution of the different scales composing the total fluctuating magnetic field to the particle transport. Hereafter three different magnetic fields are defined: the global magnetic field $\vec{B}_0$, i.e. the magnetic field at scales larger than the turbulence coherence scale, the total magnetic field $\vec{B}_T$ which combines the global field and the fluctuations at all wavelengths, and the local magnetic field $\vec{B}_l$.

[1] The pitch-angle in the angle between the particle velocity and the magnetic field.

2. Magneto-hydrodynamic simulations

The MHD simulations are performed using the RAMSES code [15]. The turbulence is driven on the velocity field in a periodic cubic box using the approach detailed in [16]. The magnetic field is interpolated at the position of the particle using a grid volume weighted average of the magnetic field components. In order to derive the local components of the magnetic we applied a filtering of the total magnetic field $\vec{B}$ [4]. The local large scale magnetic field is hence $\vec{B}_\sigma(\vec{r}) = \Sigma_{\vec{r}'}\vec{B}(\vec{r}')F_\sigma(|\vec{r}-\vec{r}'|)$ and we adopted $F_\sigma(|\vec{r}-\vec{r}'|) = K\exp(-|\vec{r}-\vec{r}'|^2/\sigma^2)$ for the filter function and K is chosen as $\Sigma_{\vec{r}'}F_\sigma(|\vec{r}-\vec{r}'|) = 1$. We reconstruct at each grid point a local field of a given σ. The simulations are performed at a resolution of 256^3. The filter parameter $l = \sigma$ is chosen in the range $[2/256, 42/256]$ in box unit size. The scales in the inertial turbulence range fall in the wavenumber interval [256/128, 256/21] (in units of $2\pi/L$) approximatively. Hence, $\vec{B}_\sigma$ with small (large) σ parameters correspond small (large) scale strongly (weakly) anisotropic perturbations. The simulations are performed for a level of moderate turbulence with a mean Alfvénic Mach number $M_a \simeq 0.6$. It is found that the structure function produced from the small scale perturbations of the local fields constructed as $\vec{b}_\sigma = \vec{B} - \vec{B}_\sigma$ (the perturbations in the velocity field are constructed in the same manner) do show an anisotropy corresponding to the GS scaling especially for σ parameters $\leq 8/256$. The structure function has been defined in [4] as $F_b(R,z) = |\vec{b}_\sigma(\vec{r}_1) - \vec{b}_\sigma(\vec{r}_2)|$ (see their figure 11), where R and z are the perpendicular and parallel coordinates in a cylindrical coordinate system associated with the local mean field $\vec{B}_\sigma$.

3. Cosmic Ray transport

The RAMSES code has been upgraded with a particle-in-cell module calculating the particle trajectory under the effect of the Lorentz force following the procedure described in [13]. In figure 1 we present the pitch-angle cosine diffusion coefficients $D_{\mu\mu}$ calculated averaging over all particles as $\langle(\mu(t) - \mu(t=0))^2\rangle/2t$ following the prescription of [17, 13] for applicability of the calculation. As for the variable $\mu \in [-1,1]$, the validity of the calculation is only limited over a restricted time which verifies that the rms deviation from $\mu(t=0)$ should be between 0.01 and 0.1. We selected the value of 0.05 in this work. We use 100 000 particles to reconstruct the diffusion coefficients. All the results in this section are presented for a particle with a Larmor radius $r_L = 0.1$ such that r_L^{-1} falls in the inertial range of the turbulent spectrum. Or, put in another way the wave numbers which correspond to the gyro-resonance with such a Larmor radius are in the interval $[256/128, 256/21]$.

The particles have propagated into the total magnetic field (hence under the effect of the total Lorentz force $\vec{F}_T = q\vec{v}\wedge\vec{B}_T$) but the cosine of the pitch-angle are taken with respect to the total (in red solid line) or the local (other curves) magnetic fields. At first we have found that the diffusion coefficient $D_{\mu\mu}$ with respect to the total magnetic field is consistent with the results obtained by [14]. It provides a particle mean free path of $\lambda_{\parallel,t} = 3/8v\int d\mu(1-\mu^2)^2/D_{\mu\mu} \sim 1.5L$ for a turbulent field with $M_a \simeq 0.6$. Then it is clear that the small σ dominate the pitch-angle scattering. This is not surprising as for small σ the local mean magnetic field converges towards the total magnetic field at the position of the particle (see the above formula in §2). At high σ values the direction of

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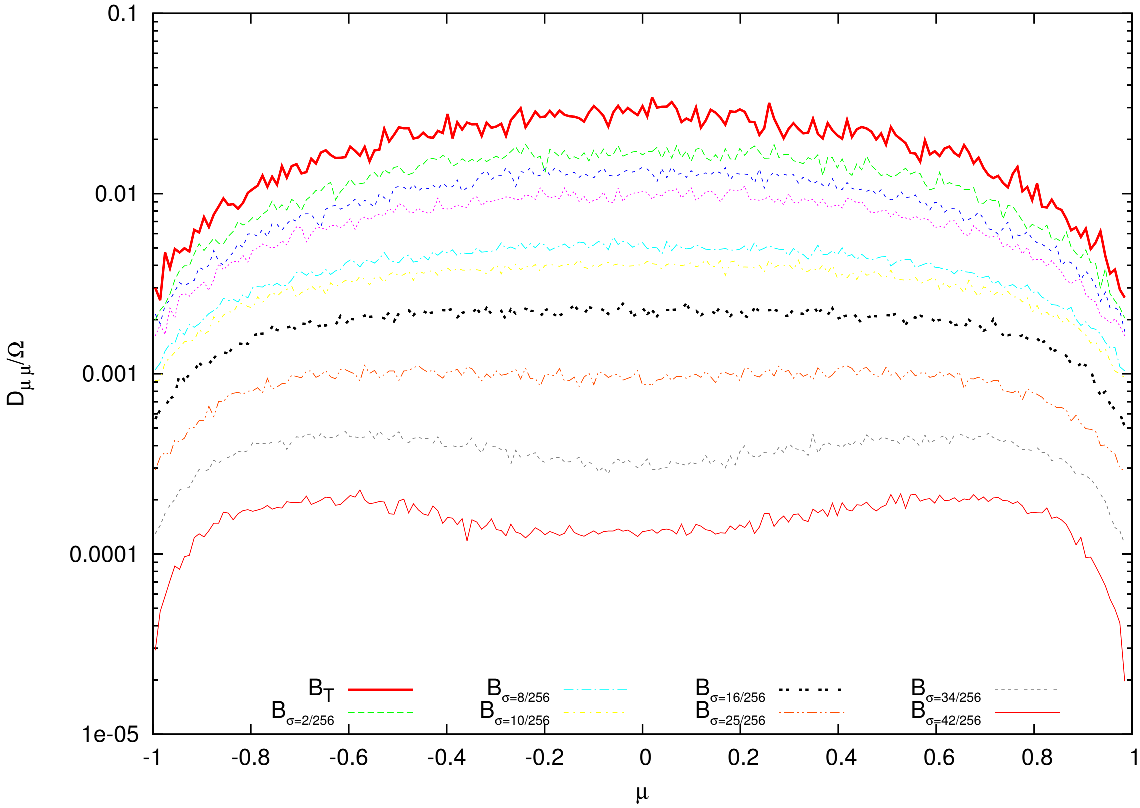

Figure 1: Cosine pitch angle diffusion coefficients in the local magnetic field B_σ for different values of σ spanning the interval 2/256 to 42/256. The Lorentz force is calculated in the total magnetic field. In continuous red is presented the diffusion coefficient obtained in the total magnetic field B_T. The filter parameter corresponding to the particle Larmor radius is approximatively $\sigma = 25/256$ corresponding to the orange dot-dashed curve.

the mean field coincides with the global field B_0 and the pitch-angle scattering drops.

Figure 2 shows the total diffusion coefficient with respect to the cosine of the pitch angle $\mu = cos(\vec{v}, \vec{B})$ taken in the total magnetic field using the total Lorentz force (upper red solid line). The other diffusion coefficients are calculated with respect to the cosine of the pitch angle $\mu_\sigma = cos(\vec{v}, \vec{B}_\sigma)$ taken in the local magnetic fields using the Lorentz force due to the small scale fluctuations at a scale σ, i.e. $\vec{f}_\sigma = q\vec{v} \wedge \vec{b}_\sigma$. Hence, at a given σ the local diffusion coefficients probe the propagation of a particle in a local field (large scale) of intensity B_σ under the effect of (small scale) fluctuations of intensity b_σ.
It appears that beyond filter parameters $\sigma \sim (8-10)/256$ the filtered field lines do not contribute to the transport significantly at large pitch-angles and the diffusion coefficients $D^{\sigma}_{\mu_\sigma\mu_\sigma}(\mu_\sigma \sim 0) < 0.1 D^{\sigma=2}_{\mu_2\mu_2}(\mu_2 \sim 0)$. As $\mu_\sigma \to \pm 1$ also scales in the range $\sigma < (8-10)/256$ do contribute to the pitch-angle scattering the most, i.e. the aisles of the distribution are more pronounced at these values. Also, fluctuations at scales $\sigma = \sigma_{res} = 1/k_{\|_{res}} \simeq 25/256$ associated with the gyro-resonant structures do not produce a strong pitch-angle scattering. In fact it appears that beyond $\sigma \sim 14/256$, the diffusion coefficients drop for any values of μ_σ and are stalling at low values. Fluctuations at

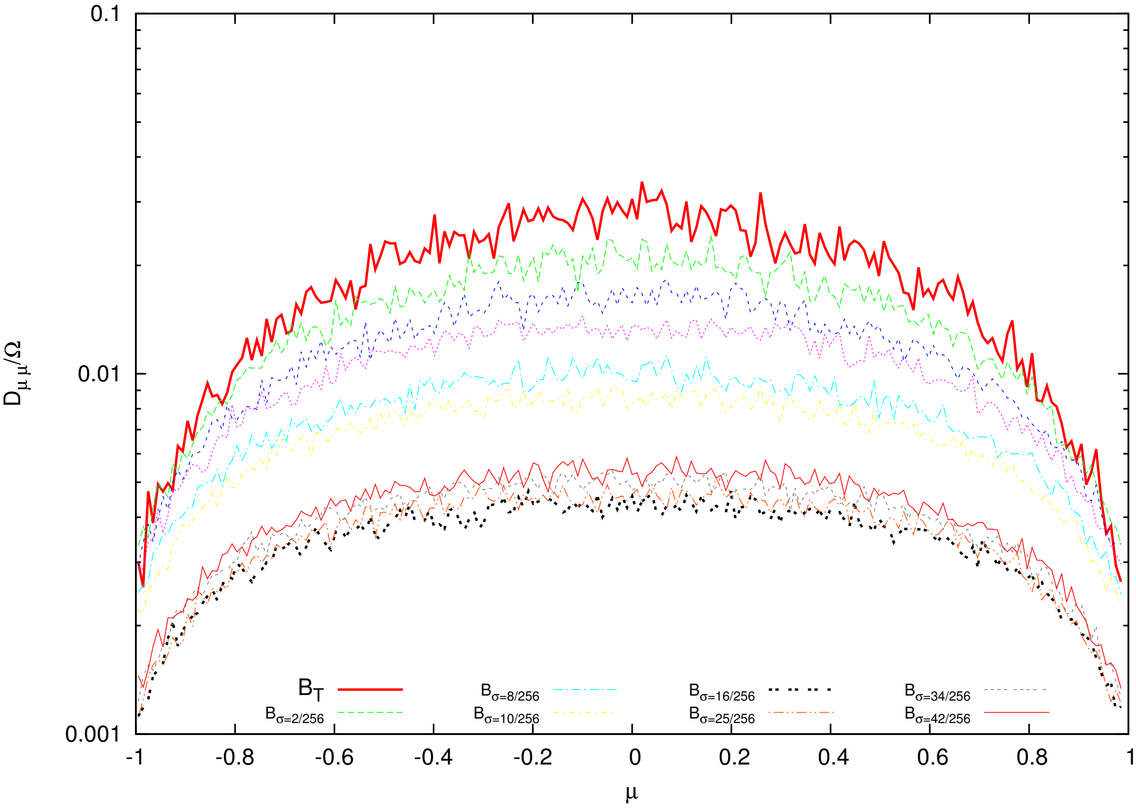

Figure 2: Cosine pitch angle diffusion coefficients in the local magnetic field B_σ for different values of σ spanning the interval 2/256 to 42/256. The Lorentz force is calculated in the local fluctuating magnetic fields. In continuous red is the diffusion coefficient obtained in the total magnetic field B (same as in Fig 1). The filter parameter corresponding to the particle Larmor radius is approximatively $\sigma = 25/256$ corresponding to the orange dot-dashed curve.

small sigmas do dominate the transport of the particles in the local field up to values not strongly different than $(25/256)^{3/2} \sim 8/256 = 2\pi/k_{\perp_{res}}L$. This scaling is associated with the relation between perpendicular and parallel scales in the GS scaling, $\ell_\perp/L = 1/(k_\perp L) = (\ell_\parallel/L)^{3/2}$. Hence one can conclude that the perturbations with scales smaller than $\ell_\perp/L$ are more efficient in producing a pitch-angle scattering along their local mean field: the parallel mean free path deduced along the local field at low σ values is close but a bit larger than the value $\lambda_{\parallel,T}$ calculated above in the total magnetic field. However to confirm that the dominant perturbations for the particle scattering are those at $k_\perp \propto (1/r_L)^{2/3}$ requires an investigation other Larmor radii. These are postponed to a future work.

4. Conclusions

We have developed kinetic-MHD simulations of cosmic ray transport in the turbulent magnetic perturbations. We have calculated the local magnetic fields using a filtering procedure of the total magnetic field at each of the grid points. The random Lorentz force that controls the particle propagation is calculated using different filters. The scales of the filter span the scales in the inertial turbulent range. The contribution of each filtered field to the particle transport is dominated by local fields with $\sigma \sim 1/k_{\perp} < r_L \sim 1/k_{\|_{res}}$ meaning that small scale perturbations are important to account in the wave-particle interaction process.

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