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A microphysics view of Cosmic Ray propagation in the interstellar medium

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The transport of galactic cosmic rays from the sources to the Earth in the interstellar medium is an essential process for the understanding of several observations: abundances of secondary nuclei produced by spallation reactions, abundances of radioactive elements, diffuse multi-wavelength backgrounds, the lepton cosmic ray spectrum. The transport of cosmic ray in the interstellar medium is controlled by their interactions with magnetic turbulent fluctuations. The review addresses recent analytical and numerical developments in the modeling of the microphysics of magnetic turbulence and charged particle interactions in the interstellar medium. Issues on the cosmic ray escape from the sources is also considered. Finally, the transport of low energy cosmic rays is commented in the view of the problems related to the ionization of interstellar matter.

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1. Introduction

During their journey in the Galaxy cosmic rays (CR) have a random walk in the interstellar medium (ISM). The CR mean free path of GeV CRs deduced from direct observations of secondary to primary [S/P] ratio of the local CR flux is about one parsec and the residence time is about several million years. The mean free path increases with the energy as a power-law with an index still not completely constrained but likely in the range 0.3-0.6. Higher energy CRs (GeV-TeV) distribution can be deduced from X- and gamma-ray observations of the sources and of the diffuse galactic backgounds using modern satellites and ground-based telescopes facilities. The low energy end of the CR spectrum (E < a few GeV) is still largely (but not completely thanks to Voyager 1 and 2 measurements) unveiled due to the solar modulation. This part of the spectrum is important as it concentrates most of the energy density and possibly has a strong but still overlooked effect on the dynamical structures in the ISM [1]. Indirect observations start to provide us with some of the effects of low energy CRs: ionisation, interaction with interstellar dust. But a better understanding of the multi-wavelength source and diffuse emissions requires theoretical inputs beyond the above phenomenological estimates of the mean free path. The description of the particle transport in magnetized turbulence is a very complex problem as it involves a set of fully non-linear implicit integro-differential equations that can be solved using a series of simplify hypothesis (see for instance [2], [4]). The joined developments of heuristic turbulence models and refined particle transport calculations have recently uncovered a problem in the CR confinement in our Galaxy: it appears that the most advanced description of incompressible [1] magnetohydrodynamic (MHD) turbulence [5] (GS) thought to provide a good description of the interstellar magnetized turbulence has been found as being inefficient in scattering charged particles. This drawback is directly connected with the highly anisotropic nature of the cascade that develops along the mean magnetic field in GS model. As the particles are not efficiently scattered they are not well confined by Alfvenic turbulence motions especially in the TeV-PeV energy range ([6], [7]). This is in contraction with the conclusions obtained from the direct S/P ratio measurements. Several remedies have been proposed for this issue. They will be discussed shortly in sections 2 and 3. Another difficulty in the modeling of particle transport in the ISM comes from the multiple sources of turbulent motions that can inject energy into the magnetic perturbations. This is expected to be the case for instance in regions of massive star clusters where multiple MHD perturbations and shocks supply free energy and turbulence (see [8], [9], [10]). Their associated structures (superbubbles) carve large volumes in the galactic disc and are important to consider in the modelling of the local cosmic ray spectrum. Around isolated or groups of supernova remnants the inherent cosmic ray escape should also modified the local turbulent spectrum by producing self-generated waves [11]. These two important aspects will be discussed in section 4. Finally only few theoretical works have addressed the propagation of low energy cosmic rays at present and section 5 will discuss this regime and will present some perspectives.

[1] In a plasma the incompressible regime is obtained in the limit of high beta; i.e. for large ratio of the sound speed to the Alfvén speed. The interstellar medium is known to be compressible although the incompressible description is thought to provide trends of the basic properties of the MHD cascade (see [3]).

2. Modelling particle transport in stochastic magnetic fields

The CR random walk in the ISM is produced by the interaction of relativistic particles with stochastic magnetic fields. These interactions produce a scattering of the pitch-angle (the angle between the particle's velocity and the local magnetic field) that induces a spatial transport along the magnetic field mainly (but also in the perpendicular direction). The perpendicular scattering is supplemented by the wandering of the field lines due to chaotic turbulent motions [12, 13, 14]. Finally a diffusive transport is also expected to occur especially at low energies in the energy space (see the review [15] and references therein). Hence, the correlations between the magnetic fluctuations control the CR transport. There are basically two ways to model the correlated effects of magnetic fluctuations: either by considering a particular turbulence model or by the mean of a fully numerical approach (see §3). In the former case, the turbulent spectrum is calculated given an analytical model that aims at reproducing the physics of the turbulent cascade: it involves the time evolution of the turbulence (dynamical models), the wave number spectrum, the geometry of the cascade (see for instance [4], [20]), the degree of imbalancing [2]. In the latter case, the turbulent spectrum is calculated from a numerical solution that formally can be derived from first principles. Considering a non-exhaustive list of turbulent spectra we can distinguish among their different geometry properties in the wave number space: isotropic or anisotropic. In the latter category we find the GS model [5], the composite 2D/slab model [21] invoked in the solar wind and the shear Alfvén wave turbulence [22] which should be applied in the limit of weak magnetic turbulence/strong guiding magnetic field. The anisotropy geometry of the GS model has been successfully tested against numerical simulations [23].

There is a wide literature discussing the calculations of the transport coefficients under various assumptions: dynamic or magnetostatic models, quasi-linear approximation or non-linear calculations (see [4]). Dynamical models include a time dependent function in the magnetic correlation tensor (see [25]) constructed to reproduce the damping of the turbulent fluctuations. In the quasi-linear calculations the diffusion coefficients are constructed with the assumption of unperturbed particle orbits around the mean/background magnetic field [24]. If it provides some analytical solutions the quasi-linear theory have some well-known drawbacks. The first one is the 90 degrees scattering problem, that is the divergence of the spatial particle mean free path once its pitch-angle is approaching 90 degrees due to the vanishing particle pitch-angle scattering. A second problem is the perpendicular diffusion that shows a difference in the type of transport between analytical estimates and numerical calculations (see for instance [26]). These problems have motivated authors to relax the hypothesis of unperturbed orbits in different non-linear models. The reader is invited to report to the well documented monograph of [4] for a more detailed description of these models.

Concerning the transport of CRs in our galaxy, probably one of the most advanced analytical work proposed yet is the calculation of the pitch-angle diffusion coefficient produced in a mixed turbulence of Alfvén waves and magneto sonic waves [3] injected at scales larger than the CR Larmor

[2]The balancing of a turbulent cascade driven by the interaction of oppositely moving wave packets is given by the fraction of forward (or backward) waves reported to the total number of waves.

[3]The MHD model has three distinct magnetic modes: the Alfvén mode and the slow and fast magneto sonic modes.

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radii under consideration by [16]. The calculations are conducted beyond the quasi-linear theory and included a broadening of the wave-particle resonance described in [17] which provides a non-linear correction to the particle trajectory. The central argument of the work is that conversely to the Alfvén wave spectrum, the fast magneto sonic wave spectrum is isotropic and supplies the lack of scattering efficiency provided by the resonance with Alfvén waves. Fast waves do especially interact via the transit-time damping process with CRs (the resonance with the mirror magnetic field of the wave) which in particular is the strongest for pitch-angles at 90 degrees. So, In the compressible limit the fast magneto sonic waves play an important role. But their inclusion requires a careful treatment of wave damping, highly depend on the ISM phase under consideration. Parallel mean free paths can then be reduced to values of a few parsecs in GeV-TeV range, thus providing a possible solution to the confinement problem discussed above. There are some debates concerning the perpendicular transport. [16] showed the perpendicular transport is highly dependent of the local Alfvénic Mach number and the parallel mean free path (ratio of the turbulent velocity to the Alfvén velocity). Using a semi-analytical approach [18] tested different parallel transport models against perpendicular transport in a GS spectrum. The authors found a ratio of the perpendicular to parallel diffusion coefficients in the range $10^{-1} - 10^{-4}$ (from 10 to 10^6 GeV) and an energy independent perpendicular diffusion coefficient at high energy in the case parallel diffusion is obtained from secondary/primary ratio in the cosmic ray flux. The deduced perpendicular mean free path at energies beyond 10^3 GeV is less than one parsec.

In an effort to connect microphysics and phenomenology, based on the above modeling by [16], [19] have derived the CR mean free path depending on the level of turbulence in two distinct ISM phases, i.e. the halo and the disk. The S/P ratios are fitted using the propagation code DRAGON. It is found that the low energy break in the diffusion coefficient around GeV can be reproduced only invoking two different damping scales of the turbulence in the two different phases and no re-acceleration.

3. Numerical simulations

The magnetic fluctuations necessary to produce the CR pitch angle scattering can be generated by the mean of a prescription over the turbulent spectrum calculated in a simulation box. The magnetic perturbations can either be generated using plane wave approximation developments [26, 14] or fast-Fourier transforms [14]. The calculations have been undertaken for different turbulence models: isotropic Kolmogorov turbulence [14, 27], composite slab-2D turbulence [28], anisotropic wave turbulence and GS models [29, 30]. A summary of recent test-particle simulations can be found in [4] table 3.2. The results are thus highly dependent on the model of turbulence under consideration but usually show strong discrepancies with respect to the quasi-linear theory (see again [4]).

A second approach involves the calculation of particle transport in a turbulent field that results from direct simulations of the turbulent spectrum; i.e. without assuming a particular model for the turbulent cascade. Hence this method is expected to provide an "exact" (within the MHD approximation) description of the transport. But the main issue here is the relative limited dynamical range

The latter are the magnetized limits of the sonic mode (see [3]).

of magnetic fluctuations scales that can be described by this type of hybrid kinetic MHD method (usually not more than two orders of magnitudes). However, this kind of simulations have been recently proposed by [31, 32] (see also [33]) using different types of MHD codes (either incompressible or compressible). The results of [31, 32] have been compared with the analytical solutions obtained in [16]. The spatial parallel diffusion coefficient is found to be consistent with analytical estimations. The simulations do not show strong effects produced by imbalanced turbulence. The perpendicular diffusion coefficients derived by [32] show also a good agreement with the analytical estimates obtained in [16] in the limit of large parallel mean free path [4].

4. Cosmic-Ray back-reaction

The works described above have been conducted in the test-particle limit and have neglected the turbulent perturbations that CR may self-generate. In reality CR can trigger a great variety of plasma instabilities. Among, one of the most studied is the streaming instability associated with a local CR pressure gradient. The streaming instability is for instance one of the favorite instability at the origin of the magnetic field amplification at shocks in supernova remnants (see [34] for a review).

4.1 Propagation close to the sources

CRs, especially at high energies are expected to show an inhomogeneous distribution which should peak close to the sources. The spectrum is also expected to be harder since high energy particles have not escape from the Galaxy yet (see the case of enhanced particle distributions in the galactic center [35]). The cosmic ray escape process is poorly known and involves a 3D time dependent calculation of the particle accelerators. In supernova remnants high energy particles should start to escape likely at the beginning of the Sedov phase [5]. However, the exact dynamics of energetic particle escape in supernova remnants depends on several effects: the time evolution of the magnetic field strength generated at the shock front by the accelerated particles, the time dependence of the turbulence properties at the shock, the density of the ambient medium and the fraction of neutrals in this medium, the time history of particle injection at the shock front, etc. What can possibly be said is that due to the high efficiency of the particle acceleration process and in order to obtain a prolongated effect of particle acceleration at the shock, escape has to occur to alleviate strong shock smoothing [36] and regulate the acceleration process [37]. At a given time, particles escaping the shock front should drift at velocities larger than the Alfvén speed in the ambient medium (although this assertion has to be verified case by case, see [38]). This drift motion must produce the generation of resonant MHD waves that propagate in the opposite direction to the drift. The wave growth can be balanced against non-linear effects that lead to a saturated spectrum [11]. The self-generated waves then contribute to the self-confinement of high energy cosmic rays around the sources. The diffusion coefficient around CR sources is strongly energy and time dependent but can be reduced with respect to the local interstellar estimates by

[4] $\lambda_{\parallel} > L$, where L is the scale of the injection of the energy into the turbulent motions. This limit may be more adapted to high energy cosmic rays.

[5] The Sedov expansion phase occurs during once the mass of the advected interstellar material is similar to the ejecta mass of the progenitor star.

several orders of magnitude in some extreme cases. This coefficient also depends on the medium in which the remnant is propagating [39]. This CR halo due to a reduced diffusion coefficient (with respect to typical galactic estimations) can interact with nearby molecular clouds and can produce gamma-ray emission enhancement [40].

4.2 Propagation in the interstellar medium

If scattering off magnetic perturbations injected by large scale turbulence likely dominate the spatial transport of high energy (beyond 100 GeV) CRs, lower energy CRs may trigger self-generated perturbations with sufficient power to dominate the CR propagation in the ISM. Recent works focused on two different types of instabilities. The first instability is again the streaming instability triggered by CR pressure gradients. Such gradients are present at different locations in the ISM: around sources (see above), in the disk-halo interface and more intermittently between arms and inter-arms. Self-generated waves are mostly composed of slab Alfvén waves [6]. These waves contribute to self-confine the particles (hence to couple CRs with the gas) and have various effects: local ISM heating (see the case of the warm ionized medium treated in [41]), spectral breaks in the CR spectrum [42], driving galactic winds [43].
Another instability considered recently is the cyclotron gyro-resonant instability. This instability is induced by an anisotropic distribution of CRs itself induced by the compression due to the turbulence injected at large scales due to the conservation of the particle's magnetic moment [7]. The CRs back react by generating slab type Alfvén waves [44, 45] that do efficiently scatter CRs in the GeV range.

5. Propagation of low energy cosmic rays

Low energy cosmic rays (LECRs); i.e. protons and ions with MeV-GeV energies and electrons with keV-MeV energies are of particular interest in astrophysics. This part of the (hadron) CR spectrum has the dominant contribution to the CR energy density. If CRs would have any impact on the structures in the ISM it should come from this component (maybe to the exception of the sources where high energy CR under some circumstances can dominate the non-thermal pressure of the plasma). LECRs contribute also to the ionization of the ISM gas, a process at the very basis of the synthesis of several molecules (see [46] and the references therein). As it has been advocated by H_3^+ measurements towards the ξ Persei diffuse cloud [47] the ionization impact of LECRs has been confirmed since by several studies (see [48] and the references therein). Dense clouds show a dispersion of the ionization rate over two orders of magnitude as reported by [49]. The ionization rate depends on the hardness of the LECR spectrum critically, which is unknown and likely not homogeneous. It is also important to estimate with a good accuracy the rate of cosmic ray exclusion from dense clouds. The exclusion mechanisms usually invoked are found to be ineffective except for particles with energies $\leq$ 50 MeV/N [50] contributing to an enhancement of the ionization rate at the edge of the molecular clouds. A recent calculation by [51] solving coupled stationary transport equations for waves and CRs concluded that the exclusion operates at energies

[6] Alfvén waves that propagate along the mean magnetic field at a zero pitch-angle.
[7] see the discussion associated with transit time damping process in §S:Model

$E < 100$ MeV/N, irrespective of the cloud model details. But still the question of the CR penetration and ionization (and heating) rate in dense clouds in still under debate (see the discussion in [52]) especially if the clouds are close to a CR accelerator. It can happen also that the accelerator is currently in interaction with the molecular gas. The system W51C a molecular cloud in interaction with a supernova remnant shock has been showed to have enhanced ionization rates by two orders of magnitude with respect to the local ionization rate [53]. This observation provide a direct probe of freshly accelerated LECRs over the shock environment and the local ISM chemistry.
Another aspect related to the propagation of LECRs is the detection of the galactic diffuse annihilation line by INTEGRAL satellite (see [54] and the review by [55]). The positrons which annihilate in flight cannot have an energy that exceeds 3 MeV in order to prevent the annihilation line to be too broad [56]. A detailed analysis has shown the difficulty to confine these low energy particles in our Galaxy invoking the mechanisms already considered for the transport of the high energy CRs. Especially the collisionless processes invoked in section 2 are not efficient enough in confining the MeV positrons relaxed in the ISM [57].

6. Conclusion

The propagation of CRs in the sources and from the sources towards our Earth has benefit from a lot of recent analytical and numerical calculations improvements (not exhaustively reported here). One the ground of turbulence modeling, refined anisotropic turbulence cascade descriptions have been proposed and sucessfully tested using MHD simulations. In this anisotropic cascade only few energy is left to the wave number parallel to the local magnetic field. This produces very inefficient scattering by resonance with Alfvén modes. A way to cure this confinement model has been proposed by considering the effect of the magnetic mirror present in magnetosonic waves. The parallel mean free path of TeV CRs can then be reduced to a few parsecs. These calculations have although to be fully tested by diverse numerical approaches. These include either a prescribed turbulence model or direct MHD simulations. The first results show some consistent behaviors especially with respect to the parallel mean free path calculations. Now, large scale turbulent motions are certainly not the only source of free energy. The impact of injection of streaming modes by particles escaping from the accelerators remain to be fully estimated but already appear to be strongly dependent on the ambient medium due to diverse turbulent damping mechanisms. Another issue, only barely considered up to now is the propagation of low energy CRs. These particles potentially have a strong role in the dynamics of the structures in the ISM as well as its ionization.

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References

[1] P. Girichidis et al, 2014 arXiv1406.4861

[2] M.L. Goldstein, 1976, ApJ, 204, 900

[3] Y. Lithwick & P. Goldreich, 2001, ApJ, 562, 279
[4] A.Shalchi, 2009, Non-Linear cosmic ray diffusion theories, Springer Verlag
[5] P. Goldreich & S. Sridhar, 1995, ApJ, 438, 763
[6] B.D.G. Chandran, 2000, Phys Rev Letters, 85, 4656
[7] H. Yan & A. Lazarian, 2004, ApJ, 614, 757
[8] A. Bykov, 2001, SSR, 99, 371
[9] E. Parizot et al, 2004, A&A, 424, 747
[10] G. Ferrand & A. Marcowith, 2010, A&A, 510, 101
[11] V. S. Ptuskin et al, 2008, AdSpR, 42, 486
[12] L.G. Chuvilgin & V.S. Ptuskin, 1993, A&A, 279 278
[13] P. Duffy et al, 1995, A&A, 302, L21
[14] F. Casse, M. Lemoine & G. Pelletier, 2002, Phys Rev D, 65, 3002
[15] A. Strong, I. Moskalenko, V.S. Ptuskin, 2007, ARNPS, 57, 285
[16] H. Yan & A. Lazarian, 2008, ApJ, 673, 942
[17] H.J. Völk, 1973, Ap&SS, 25, 471
[18] A. Shalchi et al, 2010, ApJ, 725, 2117
[19] C. Evoli & H. Yan, 2014, ApJ, 782, 36
[20] R. Schlickeiser, 2002, Cosmic Ray Astrophysics, Springer Verlag
[21] J.W. Bieber, W. Wanner & W.H. Matthaeus, 1996, JGR, 101, 2511
[22] S. Galtier et al, 2002, ApJ, 564, L49
[23] J Maron & P. Goldreich, 2001, ApJ, 554, 1175
[24] R.L. Jokipii, 1966, ApJ, 146, 480
[25] J.W. Bieber et al, 1994, ApJ, 420, 494
[26] J. Giacalone & R.L. Jokipii, 1999, ApJ, 520, 204
[27] M. Fatuzzo et al, 2010, ApJ, 725, 515
[28] G. Qin, W.H. Mattheus & J.W. Bieber, 2002, ApJ, 578, L117
[29] A. Marcowith, M. Lemoine & G. Pelletier, 2006, A&A, 453, 193
[30] T. Laitinen et al, 2013, ApJ, 764, 168
[31] A. Beresnyak, H. Yan & A. Lazarian, 2011, ApJ, 728, 60
[32] S. Xu & H. Yan, 2013, ApJ, 779, 140
[33] R. Cohet & A. Marcowith, 2015, A&A, in preparation.
[34] K. M. Schure et al, 2012, SSR, 173, 491
[35] F.A. Aharonian et al, 2006, Nature, 439, 695
[36] D. Caprioli, P. Blasi & E. Amato, 2009, MNRAS, 396, 2065

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[37] A.R. Bell et al, 2013, MNRAS, 431, 415

[38] S.J. Schwartz & J. Skilling, 1978, A&A, 70, 607

[39] L. Nava et al, 2015, A&A, in preparation

[40] S. Gabici, F.A. Aharonian & S. Casanova, 2009, MNRAS, 396, 1629

[41] J. Wiener et al, 2013, ApJ, 767, 87

[42] P. Blasi et al, 2012, Phys. Rev. Lett., 109, 1101

[43] V. Zirakashvili et al, 1996, A&A, 311, 113

[44] A. Lazarian & A. Beresnyak, 2006, MNRAS, 373, 1195

[45] H. Yan & A. Lazarian, 2011, ApJ, 731, 35

[46] M. Padovani, D. Galli & A.E. Glassgold, 2009, A&A, 501, 619

[47] B.J. Mc Call et al, 2003, Nature, 422, 500

[48] N. Indriolo, B.J. Fields & B.J. McCall, 2009, ApJ, 694, 257

[49] P. Caselli et al, 1998, ApJ, 499, 234

[50] C.J. Cesarsky & H.J. Völk, A&A, 1978, 70, 367

[51] G. Morlino & S. Gabici, 2015, arXiv150302435

[52] A. Shchekinov, 2005, ARep, 49, 269

[53] C. Ceccarelli et al, 2011, ApJ, 740, L4

[54] G.Weidenspointner et al, 2008, NewAR, 52, 454

[55] N. Prantzos et al, 2011, Rev Mod Physics, 83, 1001

[56] P. Sizun, M. Cassé, S. Schanne, 2006, Phys Rev D, 74, 3514

[57] P. Jean et al, 2009, A&A, 508, 1099