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Cosmic Ray transport in magnetized turbulence

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The transport of galactic cosmic rays from their production sites in the interstellar medium is essential for the understanding of several observations: secondaries nuclei produced by spallation reactions, abundances of radioactive elements, diffuse multi-wavelength backgrounds. Interaction with magnetic fluctuations in the interstellar medium are the main source of cosmic ray transport. The review addresses the recent analytical and numerical developments in the modelling of magnetic turbulence and charged particle interaction both inside cosmic-ray sources and in the interstellar medium. Issues on the cosmic ray escape from the sources and their radiative signatures in the local interstellar medium will be emphasize. Finally, the transport of low energy cosmic rays will be considered in the view of the problems related to the ionization of interstellar matter and the morphology of the diffuse electron-positron annihilation line.

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1. Introduction

Cosmic rays (CR) have a random walk in the ISM as they propagate between the sources and the Earth. The CR mean free path in the GeV energy domain deduced from the observations of secondary to primary ratio in the CR local flux is about one parsec and increases with the energy as a power-law with an index still not completely constrained but likely in the range 0.3-0.6. Unfortunately the solar modulation prevents any direct observations of the low energy part of the CR spectrum which concentrates most of the energy density and possibly has a strong but still overlooked effect on the dynamical structures in the ISM. Indirect observations start to provide us with some hints about the properties of this part of the CR spectrum: ionisation, effect on interstellar dust. The high energy part of the spectrum is probed by direct X- and gamma-ray observations of both source and diffuse components using modern satellites and ground-based telescopes. But a better understanding of the multi-wavelength source and diffuse emissions requires theoretical inputs (see the early work of [1]). Beyond the previous phenomenological estimates, 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 (see for instance [2]). The joined developments of heuristic turbulence models and refined particle transport calculations have recently end on the problem of cosmic ray confinement in our Galaxy: it appears that the most advanced description of incompressible [1] magnetohydrodynamic (MHD) turbulence [4] thought to provide a good description of the interstellar magnetized turbulence is very 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. As the particles are badly scattered they are badly confined in our Galaxy especially in the TeV-PeV energy range ([5], [6]). Several remedies have been proposed to address this problem. They will be discussed shortly in sections 2 and 3. Another difficulty in the modelling of particle transport in the ISM comes from the multiple sources of turbulent motions. This is expected to be the case in regions of massive star clusters where a network of MHD perturbations and shocks provide supplementary sources of free energy and turbulence (see [7], [8], [9]). Their associated structures (superbubbles) are thought to cover a large fraction of the volume of the galactic disc and hence 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 providing self-generated waves [10]. These two important aspects will be discussed in section 4. Finally only few theoretical work have addressed the propagation of low energy cosmic rays at present. Section 5 will discuss this regime and shall provide some perspectives.

2. Modelling particle transport in stochastic magnetic fields

The random walk character of the cosmic ray (CR) transport in the ISM is inherently associated with the stochastic nature of the magnetic fields that pervade it. A diffusive transport is also expected to occur especially at low energy in the energy space (see the review [11] and the refer-

[1] In a plasma the incompressible regime is obtained in the limit of high beta; ie 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]).

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ences therein). The correlation between the stochastic magnetic fluctuations induces on average a non-vanishing pitch-angle scattering of the particles along the mean field line. The wandering of the field lines due to chaotic turbulent motions contributes to a transport perpendicular to the mean field lines. There are two ways to characterize the correlated effects of magnetic field fluctuations: either by considering a particular turbulence model or by the mean of a fully numerical approach. 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 [12], [16]), the degree of imbalance [2] and possibly intermittency properties. In the latter case, the turbulent spectrum is calculated from a numerical solution that formally can be derived from first principles (as it is the case in particle-in-cell simulations). Considering a non-exhaustive list of turbulent spectra we can first distinguish among their different geometry properties in the wave number space: isotropic or anisotropic. In the latter category fall spectra like the Goldreich-Sridhar model [4], the composite 2D/slab model [17] invoked in the solar wind and the Alfvén wave turbulence spectrum [18] which should be applied in case of weak mean magnetic field. The anisotropy geometry of the GoldreichSridhar has been successfully tested using numerical simulations [19].

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. Dynamical models include a time dependent function in the magnetic correlation tensor (see [20]) 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 magnetic field. 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. The second one is the perpendicular diffusion that is a difference in the type of transport between analytical estimates and calculations (see for instance [21]). 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 monograph of [12] for a more detailed description of these models.

Concerning the transport of CRs in our galaxy probably one of the most advanced analytical work has been proposed by [13] where a resonance broadening procedure (see [14]) is adopted. This provides a non-linear correction to the particle trajectory. The authors considered a Goldreich-Sridhar turbulence. It has been shown here the importance of the slow modes[3] in the estimations of the CR mean free path. The lack of scattering efficiency provided by the resonance with Alfvén waves is compensated (especially at 90 degrees) by the transit-time damping (the resonance with the mirror magnetic field of the wave) due to the slow modes. In the compressible limit the fast magnetosonic waves play an important role but their inclusion requires are careful treatment of

[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) to the total number of waves.

[3]The MHD model has three distinct magnetic modes: the Alfvén mode and the slow and fast magnetosonic modes. The latter are the magnetized limits of the sonic mode. In the incompressible limit the fast mode turns to be a sound wave while the slow modes turns to be a magneto-acoustic mode (see [3]).

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wave damping, highly depend on the ISM phase under consideration. Parallel mean free paths can then be reduced to values of a few parsecs, thus providing a solution to the confinement problem discussed above. Issues are under debates concerning the perpendicular transport. [13] showed the perpendicular transport is highly dependent of the local Alfvénic Mach number (ratio of the turbulent velocity to the Alfvén velocity). Using a semi-analytical approach [15] 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 perpendicular mean free path deduced at energies beyond 10^3 GeV is less than one parsec.

3. Numerical simulations

Considering more closely numerical derivation of the transport coefficients the usual techniques consist in a statistical estimation of the large time limit of the mean square displacement of the particles either using a plane wave approximation development [21], [22] or fast-Fourier transforms [22]. The calculations have been undertaken in different turbulence models: isotropic Kolmogorov turbulence [22], [23], composite slab-2D turbulence [24], anisotropic wave turbulence and Goldreich-Sridhar models [25]. The results are thus highly dependent on the model of turbulence under study. A second approach now is being under development. It involves the calculation of particle transport in a turbulent field that results from direct simulations of the turbulent spectrum; ie without assuming a particular model for the turbulent cascade. This kind of simulations have been recently proposed by [26]. The authors have derived the time evolution of the particle mean square displacement using a MHD code. The latter is used to provide the magnetic field fluctuations spectrum. The results are compared with the analytical solutions obtained in [13]. The simulations show a relative insensitivity to the degree of imbalance of the turbulence. The spatial parallel diffusion coefficient is found to be consistent with analytical estimations. Considering perpendicular transport conclusions appear more limited at present since the simulations did not included large scale perturbations.

4. Sources effects: Cosmic-Ray streaming

Cosmic Rays 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 yet (see the case of enhanced particle distributions in the galactic center [27]). The cosmic ray escape process is poorly known and involves a 3D time dependent investigation of the particle accelerators. In supernova remnants high energy particles should escape first likely at the beginning of the Sedov phase [4]. 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 be

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

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probably say is that due to the high efficiency of the particle acceleration process and in order to obtain a prolonged effect of particle acceleration at the shock, escape has to occur to alleviate shock smoothing [28]. Also at a given time, particles escaping the shock front should drift at velocities larger than the Alfvén speed of the ambient medium (although this assertion has to be verified, see [29]). This drift motion must produce the generation of resonant Alfvén waves that propagate in the opposite direction to the drift. The wave growth can be balanced with non-linear effects that lead to a saturated spectrum [10]. The self-generated waves then contribute to the self-confinement of high energy cosmic rays around the sources over timescales longer than those produced in case of free streaming. This cosmic-ray halo and the modified diffusion coefficient (with respect to typical galactic estimations) can interact with nearby molecular clouds and hence can be probed by gamma-ray instruments [30], Gabici et al in preparation.

5. Propagation of low energy cosmic rays

Low energy cosmic rays (LECRs); ie protons and ions with MeV-GeV energies and electrons with keV-MeV energies are of particular interest in astrophysics. This part of the CR spectrum harbours the dominant contribution to the cosmic ray energy density. If CRs would have any impact on the structures in the ISM it should come from this part of the spectrum. LECRs contribute also to the ionization of the ISM gas, a process at the very basis of the synthesis of molecules (see [31] and the references therein). As it has been advocated by H_3^+ measurements towards the ξ Persei diffuse cloud [32] the ionization impact of LECRs has been confirmed since by several studies (see [33] and the references therein). Dense clouds show a dispersion of the ionization rate over two order of magnitude as reported by [34]. The ionization rate depends critically on the hardness of the LECR spectrum, which is unknown and likely not homogeneous. It is also mandatory to estimate with a good accuracy the rate of cosmic ray exclusion from dense clouds. The exclusion mechanisms usually invoked are found to be uneffective except for particles with energies $\leq$ 50 MeV/N [35] contributing to an enhancement of the ionization rate at the edge of the molecular clouds. Hence, the question of the CR penetration and ionization (and heating) rate in dense clouds in still under debate (see the discussion in [36]).

Finally another problem related to the propagation of LECRs is the detection of the galactic diffuse annihilation line by INTEGRAL satellite (see [37] and the review by [38]). 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 [39]. 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 [40].

6. Conclusion

The propagation of CRs in the sources and from the sources towards Earth has benefit from a lot of recent analytical and numerical calculations improvements. One the ground of turbulence modelling, refined anisotropic turbulence cascade descriptions have been proposed and sucessfully

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tested by 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 gyroresonance 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 behaviours 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. Another issue, only rarely consider up to now is the propagation of low energy CRs. These particles have a strong role in the dynamics of the structures in the ISM as well as its ionization. A better understanding of the transport properties in these energy regimes are also strongly required in the understanding of the diffuse galactic annihilation line.

References

[1] R.L. Jokipii, 1966, ApJ, 146, 480

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

[3] Y. Lithwick & P. Goldreich, 2001, ApJ, 562, 279

[4] P. Goldreich & S. Sridhar, 1995, ApJ, 438, 763

[5] B.D.G. Chandran, 2000, Phys Rev Letters, 85, 4656

[6] H. Yan & A. Lazarian, 2004, ApJ, 614, 757

[7] A. Bykov, 2001, SSR, 99, 371

[8] E. Parizot et al, 2004, A&A, 424, 747

[9] G. Ferrand & A. Marcowith, 2010, A&A, 510, 101

[10] V. S. Ptuskin et al, 2008, AdSpR, 42, 486

[11] A. Strong, I. Moskalenko, V.S. Ptuskin, 2007, ARNPS, 57, 285

[12] A.Shalchi, 2008, Non-Linear cosmic ray diffusion theories, Springer Verlag

[13] H. Yan & A. Lazarian, 2008, ApJ, 673, 942

[14] H.J. Völk, 1973, Ap&SS, 25, 471

[15] A. Shalchi et al, 2010, ApJ, 725, 2117

[16] R. Schlickeiser, 2002, Cosmic Ray Astrophysics, Springer Verlag

[17] J.W. Bieber, W. Wanner & W.H. Matthaeus, 1996, JGR, 101, 2511

[18] S. Galtier et al, 2002, ApJ, 564, L49

[19] J Maron & P. Goldreich, 2001, ApJ, 554, 1175

[20] J.W. Bieber et al, 1994, ApJ, 420, 494

[21] J. Giacalone & R.L. Jokipii, 1999, ApJ, 520, 204

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[22] F. Casse, M. Lemoine & G. Pelletier, 2002, Phys Rev D, 65, 3002

[23] M. Fatuzzo et al, 2010, ApJ, 725, 515

[24] G. Qin, W.H. Mattheus & J.W. Bieber, 2002, ApJ, 578, L117

[25] A. Marcowith, M. Lemoine & G. Pelletier, 2006, A&A, 453, 193

[26] A. Beresnyak, H. Yan & A. Lazarian, 2011, ApJ, 728, 60

[27] F.A. Aharonian et al, 2006, Nature, 439, 695

[28] D. Caprioli, P. Blasi & E. Amato, 2009, MNRAS, 396, 2065

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

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

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

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

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

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

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

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

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

[38] N. Prantzos et al, 2010, arXiv1009.4620, to be published in Rev Mod Physics

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

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

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