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COSMIC RAY TRANSPORT IN THE TURBULENT INTERSTELLAR MEDIUM

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Abstract. Cosmic Rays are an important component of the interstellar medium and likely play a dynamical role in its evolution from large galactic scales to molecular clouds scales. In this short review, we will discuss the interplay between interstellar medium and magnetic fields and cosmic rays in order to identify this role more properly.

Keywords: Cosmic-Rays: Transport, Interstellar medium: interstellar phases-magnetic field-turbulence.

1 Introduction: Cosmic Ray spectra and Cosmic-Rays

Cosmic Rays (CRs) are charged particles composed of 86% of protons, 11% of Helium nuclei and 1% of leptons plus some heavier nuclei as traces. Since a century after their discovery by V.Hess their origin is still highly debated and remains an unsolved issue of modern astrophysics. In this short review we will be interested in galactic CRs, i.e. particles with energies under 10^{17-18} eV, and especially with particles with energies in the range between MeV and TeV. To be more explicit we consider different types of sub-population. Let us first consider low energy CRs (MeV-GeV) protons (for heavier nuclei one has to consider the energy per nucleon) and low energy CR leptons (keV-MeV), we will call them low energy CRs (LECRs) hereafter. These particles are sub-relativistic with an unknown spectrum because of the solar modulation. It is only since the recent results of the two Voyager missions informations about their spectrum start to be collected (Potgieter 2013). LECRs are of prime importance in the interstellar medium (ISM) studies since they contribute to the ionization process readily at the start of several chemical reactions at the base of molecules synthesis. GeV hadrons and MeV leptons may be distinguished as mildly energy CRs (MECRs). These particles are important for the synthesis of light elements that occur in spallation reactions. Their spectrum also badly known because of the solar modulation. Finally, at higher energies particles are in the relativistic regime (we will call them high energy CRs or HECRs). Their spectrum is not sensitive to the solar wind anymore and has been measured since the beginning of cosmic ray studies [*]. HECRs are important because they probe the high-energy galactic sky and the CR sources which are likely connected with the lifecycle of massive stars. HECRs are important also because they loose their energy by collision with the interstellar matter in pion production and hence can trace the dense zones of the ISM: the HII regions and the molecular clouds (MCs). One, may be overlooked, question is the role of these different CR populations in the global and local ISM dynamics. To evaluate this effect, we need first to expose the mathematical formalism of CR transport in turbulent magnetic fluctuations (section 2). Hence, we can discuss ISM-CR connection by considering first the impact of the ISM over CRs by the means of the different transport properties of CR in each ISM phase (section 3) and then the impact of CRs over the ISM by the means of different effects (wave production, galactic magnetic dynamo and spallation in section 4). Note that a special section will discuss the case of CR in interaction with MCs (section 4.4), before concluding. A large part of the materials discussed in this review can be found in a special volume of the memorie della Societa Astronomica Italiana (Marcowith et al 2011).

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[*] http://pdg.web.cern.ch/pdg/2013/reviews/rpp2012-rev-cosmic-rays.pdf

2 A brief introduction to CR transport theories

The CR transport in turbulent fluctuations that pervade the ISM is needless to say a very complex problem in modern astrophysics. This, for several reasons: the basic properties of the turbulence is badly known and quite complex. It involves intermittency and anisotropy with respect to the mean (large scales) magnetic field (noted hereafter B_0). The level of fluctuations δB is not small with respect to B_0 (Ferrière 2001). The properties of the ISM itself are also badly known, the medium is heterogeneous with different temperature, pervaded by multiple shocks and stellar winds and with various degree of ionization. The so-called ISM phases have in details complex geometries. All these effects do have a direct impact over CR transport. Finally, there are several ways CRs can interact with the turbulent ISM through: advection in winds, stochastic acceleration on waves and by multiple shock encountering, resonant and non-resonant interaction (see next). All in all, there are still a large steps to purchase between the description of the microphysics CR interaction with magnetic fields and the macroscopic description of their transport from sources to the Earth.

The principles of CR transport are based over the solution of the Lorentz equation that controls the CR trajectory (all equations displayed here are in C.G.S units). Considering an electromagnetic turbulent field $\delta\vec{E}, \delta\vec{B}$ embedded in a mean magnetic field $\vec{B}_0$, we have for a particle of charge q, mass m and Lorentz factor γ.

$$\frac{d\vec{p}}{dt} = q\left(\delta\vec{E} + \frac{\vec{p}}{\gamma mc} \wedge (\vec{B}_0 + \delta\vec{B})\right) \ . \tag{2.1}$$

As the fields are random variables so are the particle momentum p and pitch-angle cosine $\mu = \vec{p}.\vec{B}_0/pB_0$. The first, second and third terms on the RHS of Eq. 2.1 are responsible respectively for CR stochastic acceleration, gyro-motion, and both pitch-angle diffusion and perpendicular transports. Hence, the transport process is controlled by the time correlation of the different fluctuating components. As an illustrative example let us consider the time variation of μ, $\dot{\mu}$. The latter can be expressed in terms of the components of $\delta\vec{B}$. The time correlation integrated over the time defines the pitch-angle cosine diffusion coefficient $D_{\mu\mu}$. To derive it, we calculate the correlation of the magnetic forces between time $t = 0$ and time t expressed with the help of their Fourier components defining the turbulence magnetic correlation tensor. In the case of an homogeneous turbulence we have: $\langle \delta B_i(\vec{k}, t)\delta B_j(\vec{k}', 0)\rangle = P_{ij}(\vec{k}, t)\delta(\vec{k} - \vec{k}'), (i, j) = (x, y, z)$, where $\langle . \rangle$ is an ensemble average over, e.g., several magnetic realizations. The correlation function of the magnetic forces is at position $\vec{x}$ and at time t defined as:

$$R_{ij}(\vec{x}, t) = \int d^3\vec{k} P_{ij}(\vec{k}, t) \exp(i\vec{k}.\vec{x}) \ .$$

Actually the exact solution of the above equation is not accessible as 1) P_{ij} is complex and not known in the ISM 2) the tensor R_{ij} depends on the solution $\vec{x}(t)$, it is an integro-differential equation which itself depends on the effect of P_{ij} on the particle trajectory. The most obvious way to short cut the problem is to assume that $\vec{x}$ is given by the unperturbed gyro-motion of the particle around B_0, this is the so-called quasi-linear theory (QLT). It does work only if $\delta B \ll B_0$ and for short timescales (Shalchi 2009). If an approximated form of P_{ij} can be derived and the QLT is assumed it is relatively easy to derive $D_{\mu\mu}$ (Schlickeiser 2002):

$$D_{\mu\mu} = \int dt \langle \dot{\mu}(t)\dot{\mu}(0)\rangle = \int d^3\vec{k} \Sigma_n \alpha_n(\vec{k}) R_n(\vec{k}, t) \ .$$

Here α_n depends on the tensor components P_{ij} and R_n is the resonance function which in the QLT limit and static turbulence reduced to the Landau-Synchrotron resonance $\delta(\omega - k_\parallel v_\parallel - n\Omega)$ between waves of pulsation ω and wavenumber k and particles with velocity v and synchrotron pulsation $\Omega = qB_0/\gamma mc$. In case of HECRs, the important waves are in the magneto-hydrodynamical (MHD) regime and the dominant resonance are obtained for $n = 1$ and gives $kr_L \sim 1$. The coefficient $D_{\mu\mu}$ controls the random walk of μ along the mean magnetic field and hence the spatial parallel diffusion coefficient. This coefficient is hence strongly dependent on the type of waves that travel along the field lines that can resonate with the particles. In fact, another type of resonance with $n = 0$ (the Tcherenkov resonance) appeared to be important as well, as it couples waves and particles as $kr_L < 1$ (Yan & Lazarian (2004), and next section). Finally, the fact that the magnetic field lines are turbulent induces a perpendicular transport due to their wandering. This effect depends on the correlation tensor choice and may induce some non diffusive transport (Shalchi 2009; Kota & Jokipii 2000) like sub-diffusion.

3 Impact of magnetic fields and interstellar medium over the transport of cosmic rays

3.1 CR transport in different ISM phases

Considering the different ISM phases is important as the MHD waves that pervade the ISM may be strongly absorbed at some specific scales because of their interaction with the background plasma. Two types of damping can be considered: either collisional and collisionless (Yan & Lazarian 2004). The ratio of the turbulence wavelength λ_T over the thermal proton mean free path ℓ_{mfp} due to collisions determines the dominant damping in the different phases. If the ratio $\rho_1 = \lambda_T/\ell_{mfp} > 1$ (< 1) then the damping is in the collisionless (collisional) regime. ISM phases are decomposed into ionized phases themselves decomposed into hot and warm ISM (HISM, WISM, in fact partially ionized) and neutral phases themselves decomposed into warm ISM (WNM, in fact only partially neutral), cold (CNM) ISM and molecular clouds (MCs) (Jean et al 2009). One can also include the galactic halo (low density, high temperatures) as a particular phase (Yan & Lazarian 2004). The latter authors did addressed in some details the propagation of CR in the ionized phases considering the turbulence to be injected at large scales $\lambda_T \sim 100$ parsecs (pc), likely by the supernova remnants (SNR). They considered the anisotropic phenomenological model of Goldreich & Sridhar (Goldreich & Sridhar 1995) to derive a form of the correlation tensor and hence calculate the diffusion coefficients including the possibility for the turbulent spectrum to be cut off by a phase dependent damping process. (The anisotropy here has to be understood with respect to the mean, large scale magnetic field $\vec{B}_0$, that is the magnetic field presents at scales $\sim \lambda_T$.) Note that due to the anisotropic cascade and the anisotropic damping this cut off scale depends on the angle $(\vec{k}, \vec{B}_0)$. The choice of the GS phenomenology to describe the MHD turbulence in the ISM may be subject of questioning but as the basic properties of this model are recovered in numerical experiments of turbulence (see Cho & Lazarian (2003) and references therein) we will consider it as a fiducial model in this review. Yan & Lazarian (2008) concluded that the CR parallel mean free path $\lambda_{CR,\parallel} \propto 1/D_{\mu\mu}$ is largely controlled by the action of fast-magnetosonic waves (compressible MHD modes) rather than the gyro resonance produced by shearing Alfvén waves, strongly inefficient in CR particle diffusion process in the GS spectrum (Chandran 2000). The CR mean free path in the energy range between 10 GeV and 100 TeV in the ionized phases is limited to be in the range 1-10 pc. Under 10-100 GeV starts the process of self-generated waves to become important (see section 4.1).

The CR perpendicular transport is mostly produced by the magnetic field line wandering due to the interaction of shear Alfvén waves that travel along the field lines. The regime of the perpendicular transport depends on the ratio of the $\rho_2 = \lambda_{CR,\parallel}/\lambda_T$. If $\rho_2 > 1$, the diffusion of CRs depends also on the Alfvénic Mach number $M_A = \delta V/V_A$, the ratio of the turbulent velocity fluctuations at λ_T and the local Alfvén velocity. This ratio controls the stiffness of the magnetic field lines. In particular, Yan & Lazarian (2008) found a suppression of the perpendicular diffusion compared to the parallel one scales as M_A^4 in the sub-Alfvénic ($M_A < 1$) case. They further found that sub-diffusion is negligible for CRs in the Alfvénic turbulence (see the review by Lazarian et al (2012)).

Recent test particle numerical simulations solving the Eq.2.1 under the effect of magnetic fluctuations produced in MHD simulations have started to test the above analytical solutions. The caveats in these simulations is that the turbulence has a limited dynamical extension in the Fourier space and that the different damping processes can not be accounted in a one-fluid MHD description. However the first results tend to confirm the previous findings (Beresnyak et al 2011; Xu & Yan 2013).

3.2 The special case of LE-CRs

As already pointed out in the introduction LECR are of particular importance in the ISM due to their ionization performances. But it appears that the way they are transported is only badly known. It would also be important to understand their propagation in some special environments such as the region where SNR shocks do interact with MC where recent ion radicals measurements concluded to enhancements of the ionization rate (Ceccarelli et al 2011). LECR are characterized by small Larmor radii at scales much lower than the large scale cut off scales discussed above. Hence, LECR are at least transported by perpendicular diffusion produced by the magnetic field line wandering process. One possibility, which needs to be investigated further, is the scattering efficiency in the regime of damped turbulence (at small scales) (Shalchi & Busching 2010). This regime can be of particular importance in partially neutral media (Cho & Lazarian 2003).

4 Impact of cosmic rays over magnetic fields and interstellar medium

4.1 Wave production

CR sources are known to be strong sites of magnetic field fluctuations production. In particular there are now strong observational, theoretical and numerical arguments in favor of strong magnetic field amplification in young supernova remnants (e.g. see the review by Schure et al (2012)). It appears that the MHD turbulence is generated by the streaming motions of CR accelerated at the SNR shocks in the ISM background plasma. The latter reacts by producing fluctuations that carry a part of momentum of the CRs to limit the effect of streaming. But the process does not stop as the kinetic energy of the matter dominate both CR and magnetic field energy densities. A recent analysis also shows that a return current is settled to counterbalance the CR streaming (Bell 2004; Pelletier et al 2006). In both cases, strong magnetic field fluctuations that can overtake the mean magnetic field are generated, scatter CR, produce faster acceleration and particular transport diffusion coefficients (Marcowith et al 2006; Marcowith & Casse 2010). An important question still under the debate is the way CRs do escape from their sources and pass from zones where the turbulence is self-generated to zones where the CR transport is controlled by MHD turbulence injected at large scales (see the previous section). The transition likely involves further generation of waves by the streaming instability (Malkov et al 2013) that limit the CR diffusion away from the source.

However, self-generated wave are not limited to the sources or to the region close to the sources. Some streaming modes can be produced at the edge of molecular clouds (see section 4.4). The possibility of galactic wind triggered by the streaming motion of escaping CR has been discussed for a long (see Uhlig et al (2012) and the references therein). There, CRs can indirectly induce a heating of the WIM as the waves are subject to non-linear Landau and ion-neutral damping (Weiner et al 2013). In fine, due to the anisotropy of CR in the ISM, a minimum amount of streaming modes are generated. The streaming modes are strongly damped by the background turbulence (the one injected at large scales) and as the CR energy distribution is soft (the flux is $J(E) \propto E^{-2.75}$ above a few GeV) above energies of the order of 10-100 GeV only(Farmer & Goldreich 2004; Yan & Lazarian 2004). This means that the CR parallel mean free path in this tiny energy range (a few hundred MeV-10 GeV) is likely controlled by the self-generated streaming modes. This regime is important as it probes gamma-rays produced by pion decay in the sensitive band of Fermi.

4.2 Large scale magnetic field dynamo

CRs due to their pressure gradient can produce a force that induces fluid motions. This effect can especially be important above the galactic disk where CR escape from the sources into the halo. Due to the CR streaming (see above) the gas and the frozen-in magnetic field lines are pushed away. The latter are distorted due to the differential rotation of the gas in the Galaxy and can reconnect (Parker 1992). The process has been estimated in two-fluid MHD simulations to efficiently convert small-scale magnetic fields of SNR into galactic-scale magnetic fields (Hanasz et al 2004). The resulting magnetic field structure resembles the X-shaped magnetic fields observed in edge-on galaxies. However the galactic dynamo process can also have different origins (discussed in the review by C. Gissinger in these proceedings).

4.3 Spallation

Interaction of GeV CR with the interstellar matter does produce secondary lighter nuclei. These reactions can be diagnosed using line emission in the hard X-ray and soft gamma-ray domains (Tatischeff 2001). Such lines have only been observed up to now in solar flares episodes but not in galactic sources due to the lack of sensitivities of MeV gamma-ray telescopes. This detection would required a huge improvement in instrumental performances. However, it seems not unrealistic to detect diffuse gamma-ray line emission but a Compton telescope with a sensitivity 30 times larger than COMPTEL. At soft X-ray frequencies the fluorescence iron line at 6.4 keV can probe the interaction of a population of LE and MECR with interstellar matter. This seems in particular the case in the Arch clusters in the galactic center (Dogiel et al 2013)

4.4 CR and molecular clouds: ionization, heating and propagation

There are growing evidences that LECR can enhance the ionization rate in diffuse clouds (Indriolo & McCall 2012) whereas the trend is that the ionization rate in dense cores is to be reduced by an order of magnitude (Ceccarelli 2011). However, the proximity of a strong CR source may change this picture (Indriolo et al 2010).

Recent models involving the combination of ionization losses and the effects of magnetic mirroring and focusing in the MC environment. They evaluate the variation of the ionization rate with the hydrogen column density (Padovani & Galli (2011) see also the contribution by M.Padovani to these proceedings). If this approach gives satisfactory qualitative results, it does not include any turbulence. In MCs, the magnetic field is likely turbulent, hence CR can be scattered by several mechanisms involving magnetic fluctuations (Cesarsky & Völk 1978): resonant scattering (see section 3.1), CR trapping and non-resonant CR interaction with long wavelength waves. It is also well-kown since the late 70's (Skilling & Strong 1976; Cesarsky & Völk 1978) that ionization losses trigger the streaming of CRs outside the MC and produce the exclusion of the particles out of the cloud up to an energy of $\sim$ 100 MeV in standard ISM conditions. Considering all these processes one can indeed expect an enhance ionization at the edge of the cloud and a depletion in the cloud cores. But the solution of the CR density in the cloud depends on the solution of CR density in the inter-cloud medium. Recently, Everett & Zweibel (2011) have reconsidered these solutions including the background galactic CR gradient produced by the CR minimum anisotropy. The authors found the above exclusion mechanism to be weaker and predicted a constant CR density in the cloud that can be tested with the help of observations.

As CRs do produce waves and these waves are damped by ion-neutral friction, the medium is locally heated. It appears, in the analysis of Everett & Zweibel (2011), that the heating due to the presence of a galactic CR gradient is in most of the parameter space (see their table 1) sub-dominant over the conduction. Exception may be found in cases of high magnetic fields ($> 30\ \mu$G) and high internal CR pressure ($> 10^{-11}$ erg/cc).

Concerning the penetration of ME and HECRs, the mechanisms considered in the analysis of Cesarsky & Völk (1978) do not in general permit a confinement of CR with energy above a few hundred MeV in the MC over timescales longer than the dominant loss timescales. At high energy, this means that CR cross the cloud before having substantially lost their energy by pp interaction. But the detailed propagation of CRs inside MCs is strongly connected to the properties of the turbulence (geometry, intermittency, coherence length, spectra) that are not well known. Further numerical calculations (see the contribution by P.Hennebelle in these proceedings) may help to specify such quantities and constrain the CR transport coefficients around and in dense cores.

Finally, one should mention recent promising efforts in the modeling of the effect of CR transport on thermal stability of MCs (see the discussion in Shadmehri (2009)). It is found a stabilizing effect that depends on the diffusion coefficient and the ratio of CR pressure to gas pressure. But this linear analysis needs some non-linear extension using numerical simulations.

5 Conclusions

CRs are closely coupled to the magnetic field and gas in the ISM. The magnetic field is essential to confine CRs and to scatter them. If the ISM turbulence follows the Goldreich-Sridhar phenomenology, recent analysis showed the importance of considering the supply of fast magneto-sonic waves in the calculation of the CR parallel mean free path. A good assessment of the properties of each phase is important as clear predictions about the perpendicular transport are now available, but the latter depends strongly on the local Alfvénic Mach number which is not known with good accuracies. Also, these analytical calculations have to be confronted to direct numerical simulations of test CR particles propagating in MHD turbulence even if the latter have some intrinsic dynamical limitations. The CR-magnetic field connection have been considered in various places in the ISM: at large scales in CR wind driven scenario as well as CR induced dynamo and at small scales in CR and MC interaction showing a growing evidence of the strong impact of CRs over their environment. If several pieces of the puzzle have now emerged a global view of the role of CRs in the ISM is still missing. First, CR acceleration at fast SNR shocks involves non-linear complex calculations due to the CR back-reaction over the gas and the magnetic field as a good part of the CR power lies in the HE component (even if the production of magnetic fluctuations induce a softening of the CR distribution). The way CR escape from the sources in also a non-linear problem that only received some recent solutions but limited to 1D, hence 3D simulations seem mandatory to understand these processes. It comes out that the presence of a strong CR source may strongly influences its environment certainly over scales of a few hundred parsecs (see the discussion in Nava & Gabici (2013)). This impact has been somehow overlooked in most of the modeling effort up to now and needs to be accounted to understand the dynamical effects of CR over the ISM and magnetic field structures in our Galaxy as well as the reconstruction of the transport of CR in our Galaxy.

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