Mem. S.A.It. Vol. 82, 636

Memorie della

Turbulence, reconnection and cosmic rays in galaxy clusters

A. Lazarian[1] and G. Brunetti[2]

[1] Department of Astronomy, University of Wisconsin-Madison, 475 N. Charter St., Madison, WI, 53706, USA, e-mail: lazarian@astro.wisc.edu
[2] INAF– Istituto di Radioastronomia, via Gobetti 101, 40129 Bologna, Italy

Abstract. Recent years have been marked by substantial changes in our understanding of magnetic turbulence and magnetic reconnection, which, in its turn induced better understanding of cosmic ray diffusion and acceleration. Current models of magnetized turbulence are no more ad hoc constructions, but numerically tested theories. In this very short review we summarize topics presented in two talks given at the conference and provide a brief sketch of the vast and rapidly developing field. We discuss how turbulence decreases the efficient mean free path of the particles in the collisionless plasmas in galaxy clusters and claim that this makes MHD turbulence description applicable to a wider range of scales. We discuss the properties of MHD turbulence and its relation to magnetic reconnection. Finally, we overview how turbulence induces particle acceleration via second order Fermi process and affects first order Fermi acceleration in shocks and reconnection regions.

Key words. Turbulence – Reconnection – Cosmic rays – Particle acceleration

1. Introduction

Mergers between galaxy clusters are the most energetic events in the present day Universe. During these mergers a fraction of the gravitational energy can be converted into fluid motions, i.e. shocks and turbulence, that generate magnetic fields and, through a variety of processes, accelerate relativistic protons and electrons (e.g., Ryu et al. 2003; Cassano & Brunetti 2005; Brunetti & Lazarian 2007; Hoeft & Brueggen 2007; Pfrommer et al. 2008; Skillman et al. 2008; Brunetti et al. 2009; Vazza et al. 2009). In this short review we address some of the basic processes involved, namely, magnetic turbulence in galaxy clusters and the possibility of its observational studies (Sect. 2), magnetic reconnection (Sect. 3), as well as various ways of accelerating cosmic rays (Sect. 4). Our summary is presented in Sect. 5.

2. Turbulence in clusters of galaxies

Astrophysical fluids are characterized by high Reynolds numbers and are known to be turbulent (e.g., Armstrong et al. 1995; Chepurnov & Lazarian 2010; Elmegreen & Scalo 2004; McKee & Ostriker 2007). As properties of turbulent magnetized fluids are very different from laminar ones, the *correct* description of the particle acceleration requires taking into account the fundamental properties of magnetic turbulence as well as the mutual feedback

Send offprint requests to: A. Lazarian of magnetic fields and cosmic rays in the turbulent fluids.

2.1. Properties of intracluster plasmas: instabilities induced by turbulence and effective collisions

Turbulence in galaxy clusters is magnetized. A very important question is whether the MHD description of turbulence is applicable. When Coulomb collisions in the rarefied intergalactic medium (IGM) are considered one has to conclude that the plasma is collisionless. This strongly affects the proparation of compressible modes, cosmic ray acceleration etc (see Brunetti & Lazarian (2007) and ref. therein). In what follows we argue that the degree of collisionality of astrophysical plasmas is underestimated when only Coloumb collisions are taken into account (see Lazarian et al. (2010); Brunetti & Lazarian (2011a)).

It is well known that the mean free path of thermal protons due to Coulomb collisions in the hot IGM is very large, ten to hundred kpc (e.g., Sarazin 1986). Fluids in such a collisionless regime can be very different from their collisional counterparts (Schekochihin et al. 2005, 2006, 2010). Several instabilities (e.g. firehose, mirror, gyroresonance etc) can be generated in the IGM in the presence of turbulence, leading to a transfer of the energy of large-scale compressions to perturbations on smaller scales.

Many instabilities have growth rate which peaks at scales near the particle gyroradius, making very large the scale separation between the energy injection scale and the scale where this energy is being deposited. The scattering induced by instabilities dramatically *reduces the effective mean free path* of thermal ions *decreasing the effective viscosity* of the IGM and making plasmas *effectively collisional* on smaller scales. Indeed, charged particles can be randomized if they interact with perturbed magnetic field. If this field is a result of plasma instabilities, *the process can be viewed as the collective interaction of an individual ion with the rest of the plasma*, which is the process mediated by magnetic field. As a result, the fluid would behave as collisional on scales less that the Coulomb mean free path. This issue has been addressed in Lazarian & Beresnyak (2006) for the case of a collisionless fluid subject to the gyroresonance instability that is driven by the anisotropy of the particle distribution in the momentum space that arises from magnetic field compression; the larger the magnetic field compression, the higher the anisotropy induced and the higher is the instability growth rate. They found that the turbulent magnetic compressions on the scale of the mean free path and less are the most effective for inducing the instability[1]. As the scattering happens on magnetic perturbations induced by the instability, the mean free path of particles decreases as a result of the operation of the instability. This results in the process being self-regulating, i.e. the stronger the turbulence at the scale of injection, the smaller is the mean free path of plasma particles and the larger is the span of scales over which the fluid behaves as essentially collisional.

This induces an interesting picture where the mean free path of plasma protons depends on the level of compressions induced by turbulence and the mean free path is determined not by Columb collisions, but scattering on magnetic field inhomogeneities at the Larmor radius of thermal protons. The peculiar feature of this picture is that the aforementioned magnetic field perturbations are not part of the normal turbulent cascade, but results of compressible turbulent motions at much larger scales. Thermal protons do not scatter each other through electric interactions, but participate in non-local interactions mediated by the perturbed magnetic field. *The higher the level of comressible turbulence, the better is MHD description of the IGM.*

[1] The larger scale compressions do still induce the instability, but their effect is reduced due to their reduced ability to induce large changes of B over the time scale between scattering. The model is further elaborated and improved in Yan & Lazarian (2011).

2.2. MHD turbulence: brief summary of theory and main properties of turbulence in the IGM

The last decade has been marked by substantial advances in understanding of magnetic turbulence in the MHD regime (e.g., Goldreich & Sridhar 1995; Lazarian & Vishniac 1999; Cho & Vishniac 2000; Müller & Biskamp 2000; Lithwick & Goldreich 2001; Cho et al. 2002; Cho & Lazarian 2002, 2003; Beresnyak & Lazarian 2010; Kowal & Lazarian 2010).

The presence of a magnetic field makes MHD turbulence anisotropic (Montgomery & Turner 1981; Matthaeus et al. 1983; Higdon 1984; Oughton 2003). The relative importance of hydrodynamic and magnetic forces changes with scale, so the anisotropy of MHD turbulence does too. A landmark event in this was a seminal work by Goldreich & Sridhar (1995) (GS95) which contained ideas that radically changed the further development of the subject. The corner stone of this model was the so-called *critical balance* idea which provided the analytical relation between the fluctuations parallel and perpendicular to the magnetic field. It also contains prophetic statements about mode coupling, providing guidelines for generalization of the model from the incompressible to compressible MHD.

The original model was improved in the subsequent publications. For instance, GS95 uses the closure relations that employ in the global system of reference related to the mean field, which, in fact, is an incorrect system to be used for the critical balance description. In Lazarian & Vishniac (1999) and later publications (e.g., Cho & Vishniac 2000; Maron & Goldreich 2001; Cho et al. 2002) the importance of the *local system of reference*, which is defined by the local direction of the magnetic field of a wave packet, was reviled. The local system of reference was employed in the successful testing of the GS95 model. In addition, Lazarian & Vishniac (1999) generalized the GS95 model for the case when the turbulent injection velocity at the injection scale is less than the Alfvenic velocity.

The predictions of the GS95 model are in rough agreement with numerical simulations (e.g., Cho & Vishniac 2000; Maron & Goldreich 2001; Cho et al. 2002; Beresnyak & Lazarian 2006), although some disagreement in terms of the measured spectral slope was noted. This disagreement produced a flow of papers with suggestions to improve the GS95 model by including additional effects like dynamical alignment (Boldyrev 2005, 2006), polarization intermittency (Beresnyak & Lazarian 2006), non-locality (Gogoberidze et al. 2007). More recent studies in Beresnyak & Lazarian (2009, 2010) indicate that numerical simulations do not have sufficiently extended inertial range to get the actual spectral slope[2] and therefore worries about the "inconsistency" of the GS95 model are premature. Evidence of the GS95 spectrum for the MHD incompressible turbulence was recently obtained by Beresnyak (2011).

We shall add parenthetically that in a number of applications the empirical so-called composite 2D/slab model of magnetic fluctuations is used. In the latter model, which is also known as *two-component model*, it is assumed that fluctuations can be described as a superposition of fluctuations with wave vectors parallel to the ambient large-scale magnetic field (so-called *slab modes*) and perpendicular to the mean field (so-called *two-dimensional modes*). It results in a *maltese cross* structure of magnetic correlations. This model was developed to account for the solar wind observations, which it does well by adjusting the intensity of the two components (e.g. Matthaeus et al. 1990). This theory of 2D fluctuations is consistent with the theory of weak Alfvenic turbulence (e.g., Ng & Bhattacharjee 1996; Lazarian & Vishniac 1999; Galtier et al. 2000) but it can describe Alfvenic turbulence only over a limited range of scales. It may be treated as a parameterization of a particular type of magnetic perturbation dominated by the peculiarities of driving, but recent simulations by Gosh (2011, private communication)

[2] Beresnyak & Lazarian (2010) noticed that the magnetic turbulence is less local compared with the hydrodynamic one and therefore one requires a substantially larger resolution to distinguish the actual spectral slope from the slope affected by the bottleneck.

show that, at best, the model represents a special transient state of a not fully developed turbulence. In addition, slab modes do not arise naturally in turbulence with large-scale driving, as shown by MHD numerical simulations (Cho & Lazarian 2002, 2003). Thus we do not consider this model for clusters of galaxies.

The GS95 model of turbulence can be adopted to describe the Alfvenic part of MHD turbulent fluctuations in galaxy clusters. The model can be generalized also to compressible turbulence and even for supersonic motions numerical calculations show that the Alfvenic perturbations exhibit GS95 scaling (Cho & Lazarian 2002, 2003; Kowal & Lazarian 2010). We note that we consider MHD turbulence where the flows of energy in the opposite directions are balanced. When this is not true, i.e. when the turbulence has non-zero cross-helicity, the properties of turbulence depart substantially from the GS95 model[3]. Solar wind presents a system with imbalanced turbulence. However, the degree of imbalance of turbulence in clusters of galaxies is unclear and we know that in compressible media the imbalance decreases due to reflecting of waves from pre-existing density fluctuations and due to the development of parametric instabililites (Del Zanna et al. 2001). Similarly, we shall not discuss MHD turbulence at high magnetic Prandtl numbers, when the viscosity is much larger than resistivity (e.g., Cho et al. 2002, 2003).

The GS95 model of turbulence combined with several considerations on the macro- and micro-physics of the IGM allows for a basic picture of the properties of turbulence in galaxy clusters (e.g., Brunetti & Lazarian 2007).

Cosmological numerical simulations show that large-scale turbulent motions are generated during the process of cluster formation (Dolag et al. (2005); Iapichino & Niemeyer (2008); Vazza et al. (2011), see also Nagai 2011, Iapichino 2011, Vazza 2011, this conference). These motions, injected at large scales $L_o \sim 300-500$ kpc, are believed to provide the driver for turbulence at smaller scales. The typical velocity of the turbulent eddies at the injection scale is expected to be around $V_L \sim 500-700$ km/s which makes turbulence sub–sonic, but strongly super–Alfvénic. Turbulence at large scales is thus essentially hydrodynamic and – most likely – made of a mix of compressive and incompressive eddies. The cascading of compressive (magnetosonic) modes may indeed couple with that of solenoidal motions (Kolmogorov eddies).

Viscosity in a turbulent and magnetised IGM is strongly suppressed due to the effect of the bending of magnetic field lines and of the perturbations of the magnetic field induced by plasma instabilities (e.g., Sect. 2.1). The important consequence is that an inertial range in the IGM is established – for both solenoidal and compressive modes – down to collisionless scales where a fraction of the turbulent energy is channelled into acceleration/heating of CR and thermal plasma (see Brunetti & Lazarian (2007, 2011a) for discussion). At small scales – in the inertial range – the velocity of turbulent eddies becomes sub-Alfvenic and turbulence is described in the MHD regime. At these scales the coupling between Alfvén and compressible modes gets changed and only slow modes are cascaded by Alfvénic modes (e.g., Goldreich & Sridhar 1995; Lithwick & Goldreich 2001; Cho & Lazarian 2002). The cascading of fast modes is not particularly sensitive to the presence of the other modes, fast modes remain isotropic while the spectrum of other modes becomes anisotropic.

2.3. Spectroscopic ways of turbulence studies

Recent observational advances to constrain turbulence in the IGM focussed on the broadening of lines in the X-ray spectra of galaxy clusters and provide interesting limits in the case of cool-core clusters (e.g., Sanders et al. 2011).

Turbulence in clusters of galaxies can be studied in future using Doppler brodered emission. Here we briefly review techniques originally developed for studies of Doppler

[3] Among the existing theories of imbalanced turbulence (e.g., Lithwick et al. 2007; Beresnyak & Lazarian 2008; Chandran 2008; Perez & Boldyrev 2009), all, but Beresnyak & Lazarian (2008) contradict to numerical testing in Beresnyak & Lazarian (2009, 2010)

broderned emission and absorption lines in the interstellar medium research. These techniques, Velocity Channel Analysis (VCA) and Velocity Correlation Spectrum (VCS) have been developed by Lazarian & Pogosyan (2000, 2004, 2006, 2008) (henceforth LP00, LP04, LP06, LP08, respectively) and successfully used for studying turbulence in diffuse and molecular gas (Lazarian 2009; Padoan et al. 2009; Chepurnov et al. 2010). These techniques can be applied – at some extent – to the case of the IGM and future X-ray telescopes with very good spectroscopic capabilities (eg ASTRO-H) can be used for the studies.

The difference between the VCA and the VCS is how the data is being handled.

In the VCA technique the Position-Position-Velocity data cubes available through spectroscopic observations are analysed by taking spectrum of the velocity slice of the cube. The spectrum of the fluctuations is analysed while changing the thickness of the velocity slice and the analytical description of the statistics of the fluctuations in the PPV slices described in LP00 and LP04 is used to obtain both the spectrum of velocity and the spectrum of density fluctuations.

A different approach is used in the VCS technique, where fluctuations are analysed along the velocity coordinate. For the VCS technique one does not require good coverage of the Position-Position plane and a few spectral lines are sufficient to get the spectra of velocity and density (see Figure 1).

New effects arise when strong absorption lines, which are in a saturated regime, are studied. The procedure for studying of the saturated lines is presented in LP08.

Our study of the effect of finite temperatures for the technique reveals that, unlike the VCA, the temperature broadening does not prevent the turbulence spectrum from being recovered from observations. Indeed, in VCA, gas temperature acts in the same way as the width of a channel. Within the VCS the term with temperature gets factorized and it influences the amplitude of fluctuations (LP06).

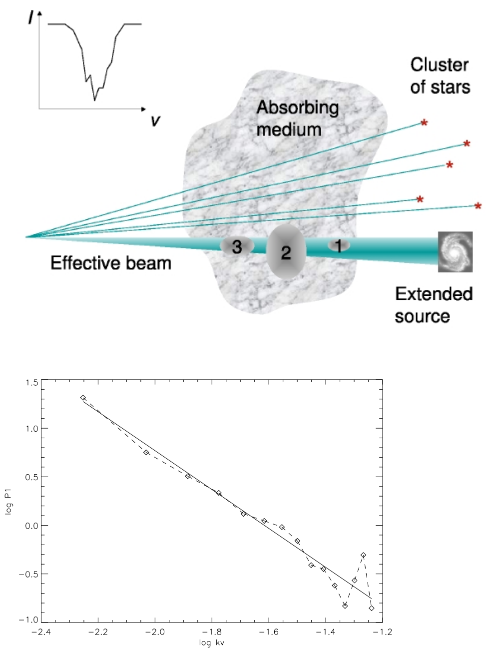

Fig. 1. Illustration of VCS absorption studies of turbulence. *Upper Panel*: Schematic of measuring turbulence with absorption lines from point sources, e.g. stars, and an extended source, e.g. a galaxy. *Lower panel*: Velocity Coordinate Spectrum obtained using sampling of a turbulent volume along 10 lines of sight. The solid line corresponds to the theoretical expectations. Readapted from Chepurnov & Lazarian (2009).

One can correct for this term[4], which also allows for a new way of estimating the interstellar gas temperature.

Another advantage of the VCS compared to the VCA is that it reveals the spectrum of turbulence directly, while within the VCA the slope of the spectrum should be inferred from varying the thickness of the channel. As the thermal line width acts in a similar way as the channel thickness, additional care (see LP04) should be exercised not to confuse the channel that is still thick due to thermal velocity broad-

[4] To do this, one may attempt to fit for the temperature that would remove the exponential fall off in the spectrum of fluctuations along the velocity coordinate (Chepurnov & Lazarian 2006)

ening with the channel that shows the thin slice asymptotics. A simultaneous use of the VCA and the VCS makes the turbulence spectrum identification more reliable.

Both VCA and VCS are applicable to studies of not only emission, but also absorption lines. We note, that while dealing with emission lines we may face additional complications. For instance, Lazarian & Pogosyan (see LP00, LP04, LP06, LP08) treated the emissivities proportional to the density to the first power. Therefore, in terms of scalings, the emissivities and densities were interchangeable. This is not true, however, when the emissivities are proportional to ρ^2, as is the case of the recombination lines in plasma. The latter regime modifies the analysis. In particular, for the shallow spectrum of density, Chepurnov & Lazarian (2006) showed that the power spectrum of density $P_\rho \sim k^{-\alpha}$ has a shallow spectral index $\alpha < 3$ emissivity spectrum $P_\epsilon \sim k^{\alpha_\epsilon}$ is $\alpha_\epsilon = 2\alpha - 3$ and this index should be used in all the expressions obtained of the VCA and VCS techniques. For the steep power law index of density, the power law indexes of the emissivity and density coinside for sufficiently large wavenumbers k.

3. Reconnection and reconnection diffusion

It is generally believed that magnetic field embedded in a highly conductive fluid preserves its topology for all time due to magnetic fields being frozen-in (e.g., Alfvén 1942; Parker 1979). Although ionized astrophysical objects are almost perfectly conducting, they show indications of changes in topology, "magnetic reconnection", on dynamical time scales (e.g., Lovelace 1976; Priest & Forbes 2000). Reconnection can be observed directly in the solar corona (e.g., Yokoyama & Shibata 1995; Masuda et al. 1994), but can also be inferred from the existence of large-scale dynamo activity inside stellar interiors (e.g., Parker 1993). Also Solar flares (Sturrock 1966) and γ-ray bursts (e.g., Fox et al. 2005; Galama et al. 1998) are usually associated with magnetic reconnection.

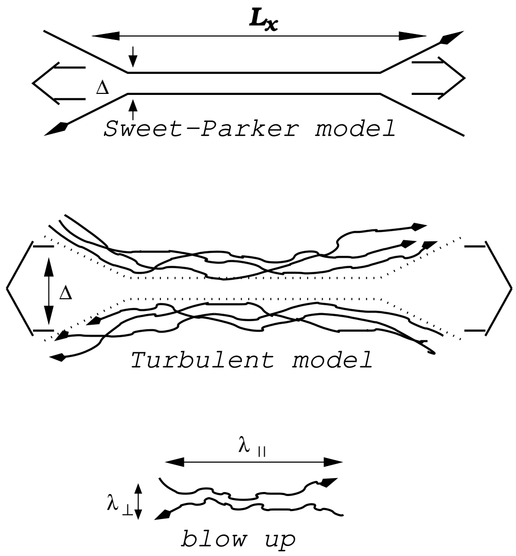

Fig. 2. *Upper plot*: Sweet-Parker model of reconnection. The outflow is limited by a thin slot Δ, which is determined by Ohmic diffusivity. The other scale is an astrophysical scale $L \gg \Delta$. *Middle plot*: Reconnection of weakly stochastic magnetic field according to LV99. The model accounts for the stochasticity of magnetic field lines. The outflow is limited by the diffusion of magnetic field lines, which depends on field line stochasticity. *Low plot*: An individual small scale reconnection region. The reconnection over small patches of magnetic field determines the local reconnection rate. The global reconnection rate is substantially larger as many independent patches come together. From Lazarian et al. (2004). Reproduced by permission of the AAS.

To understand the difference between reconnection in astrophysical situations and in numerical simulations, one should recall that the dimensionless combination that controls the reconnection rate is the Lundquist number[5], defined as $S = L_x V_A/\lambda$, where L_x is the length of the reconnection layer, V_A is the Alfvén velocity, and $\lambda = \eta c^2/4\pi$ is Ohmic diffusivity. Because of the huge astrophysical length-scales L_x involved, the astrophysi-

[5] The magnetic Reynolds number, which is the ratio of the magnetic field decay time to the eddy turnover time, is defined using the injection velocity v_l as a characteristic speed instead of the Alfvén speed V_A, which is taken in the Lundquist number.

cal Lundquist numbers are also huge, e.g. for the IGM they can be as high as 10^{20}, while present-day MHD simulations correspond to $S < 10^4$. As the numerical efforts scale as L_x^4, where L_x is the size of the box, it is feasible neither at present nor in the foreseeable future to have simulations with sufficiently high Lundquist numbers.

Observations have always been suggestive that magnetic reconnection can happen at high speed, in spite of theoretical difficulties to explain the effect. At the same, the phenomenon of solar flares was suggestive that magnetic reconnection may be slow in order to ensure the accumulation of magnetic flux and suddenly gets fast to explain the observed fast release of energy. A model that can naturally explain this and other observational manifestations of magnetic reconnection was proposed in Lazarian & Vishniac (1999) (LV99). The model appeals to the ubiquitous astrophysical turbulence as a universal trigger and controller of fast reconnection.

To deal with strong, dynamically important magnetic fields, LV99 proposed a model of fast reconnection in the presence of sub-Alfvénic turbulence (see Figure 2). They identified stochastic wandering of magnetic field-lines as the most critical property of MHD turbulence which permits fast reconnection. As we discuss more below, this line-wandering widens the outflow region and alleviates the controlling constraint of mass conservation. The LV99 model has been successfully tested recently in Kowal et al. (2009) (see also higher resolution results in Lazarian et al. (2010)). The model is radically different from its predecessors which also appealed to the effects of turbulence. For instance, unlike Speiser (1970) and Jacobson & Moses (1984) the model does not appeal to changes of microscopic properties of plasma[6].

The LV99 model justifies the notion of turbulent mixing perpendicular to magnetic field lines. Indeed, LV99 showed that the GS95 model gets self-consistent only in the presence of the turbulence-induced reconnection with the rates predicted in LV99. Otherwise, the formation of the magnetic knots would change the character of the turbulent interactions.

The understanding of fast magnetic reconnection in the presence of turbulence induced the notion of "reconnection diffusion" that was described in Lazarian (2005) and later used for describing different phenomena from star formation to heating of magnetic filaments in IGM (e.g., Santos-Lima et al. 2010; Lazarian et al. 2010). The same concept was implicitly used earlier in Cho et al. (2003) where it was claimed that the heat conductivity of the IGM is influenced by the heat advection by turbulent eddies. Explicit calculations done by Lazarian (2006) show that the heat conduction by turbulent eddies mixing magnetic field perpendicular to the local direction of magnetic field is the dominant way of heat transport in clusters of galaxies. The effect of reduced mean free path of thermal electrons induced by turbulence that we discussed above (Sect. 2) increases the relative importance of thermal transfer via reconnection diffusion. Rigorous arguments justifying the concept of reconnection diffusion can be found in Eyink et al. (2011).

4. Cosmic ray acceleration

Radio observations of galaxy clusters probe particle acceleration by shocks and turbulence in the IGM (Brunetti 2011, this conference for review on physics of cosmic rays (CR) in the IGM). In this Section we briefly discuss the importance of turbulence in the acceleration of CR and the connected issue of CR acceleration induced by magnetic reconnection.

[6] The nearest progenitor to LV99 was the work of Matthaeus & Lamkin (1985, 1986), who studied the problem numerically in 2D MHD and who suggested that magnetic reconnection may be fast due to a number of turbulence effects, e.g. multiple X points and turbulent EMF. However, Matthaeus & Lamkin (1985, 1986) did not observe the important role of magnetic field-line wandering, and did not obtain a quantitative prediction for the reconnection rate, as did LV99.

4.1. Acceleration by magnetic turbulence

The interaction of turbulence and cosmic rays is a vital component of models of CR propagation and acceleration. It has been a concern from the very beginning of CR research (e.g., Ginzbirg 1966; Jokipii 1966; Wentzel 1969). To account for the interaction properly, one must know both the scaling of turbulence, the changes with time of turbulence spectrum due to the damping processes (e.g. with CR), and the interactions of turbulence with various waves produced by CRs.

Clusters of galaxies present magnetic fields of the largest extend and they are also considered on the role of the accelerators of the ultra high energy CR. The acceleration of particles in large (Mpc) regions in galaxy clusters is generally believed to happen via the second order Fermi process as a result of the interaction of particle–turbulence interactions (e.g., Brunetti & Lazarian 2007; Petrosian & East 2008; Brunetti et al. 2008). Similarly, acceleration by magnetic turbulence is a very robust process that is likely be important for Solar flares, gamma ray bursts and many other astrophysical environments (e.g., Hamilton & Petrosian 1992; Miller et al. 1996; Schlickeiser & Dermer 2000; Dermer & Humi 2001).

MHD turbulence is the most important for the acceleration of particles of largest energies and it is vital to use the theoretically justified and numerically tested relations in the studies of particle acceleration. From the start of the work in this direction (e.g., Chandran 2000) it became clear that the earlier models for the acceleration and propagation of energetic particles that were based on ad hoc representation of turbulence are in error of many orders of magnitude as far as Alfvenic perturbations are concerned. Yan & Lazarian (2002, 2004) identified compressible fast modes as the principal agent for CR acceleration by MHD turbulence. As the aforementioned modes, unlike Alfvenic ones, are subject to rather strong damping, the description of the acceleration gets more complicated. In Brunetti & Lazarian (2007) we derived a comprehensive picture of compressible turbulence in galaxy clusters and studies CR acceleration considering all the relevant damping processes, with the results providing good correspondence with observations. More recently we extended this formalism to the case of the reacceleration of CR and of the secondary particles generated in the IGM via pp collisions (Brunetti & Lazarian 2011b).

In addition, the accuracy of the particle acceleration using analytical theory has been improved by extending the quasi-linear theory to the regime of substantial perturbations of magnetic field and applied to the case of Solar flares (Yan & Lazarian 2008; Yan et al. 2008). The improved theory has been successfully tested with direct tracing of CR trajectories in data cubes obtained with results of direct MHD simulations of turbulence (Beresnyak et al. 2011). Future applications of these extensions to the case of galaxy clusters will be important.

Compressible turbulence interacts both with CR and with thermal particles. This interaction may also induce magnetic field perturbations (trough plasma instabilities, e.g. Sect.2) that may further come into play in the particle acceleration process. First attempts in this direction suggest that the fraction of turbulence that goes into CR acceleration increases when turbulent-induced instabilities are taken into account (Brunetti & Lazarian 2011a).

4.2. Shock acceleration and turbulence

Here we focus on the importance of turbulence in shock acceleration mechanisms. Shock acceleration is thought to be one of the principal accepted mechanisms of energetic particle acceleration. The shock induces compression and particles trapped between magnetic fluctuations ahead and behind shocks fill the acceleration every time they bounce back and forth between converging fluctuations. This is an efficient way of accelerating particles which results in the energy gain per bouncing to increase as the first power of the ratio of the particle velocity to that of light, i.e. v/c, making this process known as the first order Fermi acceleration.

Shock acceleration in galaxy clusters is believed to contribute the most of the CR (protons), while shock acceleration of CR electrons is the most popular model to explain the origin of radio relics (Enßlin et al. (1998), Ryu 2011, Brüggen 2011, this conference for review).

The necessity of particles to bounce back and forth limits the efficiency of the acceleration of high energy particles through a requirement that the energetic particle should have the Larmor radius less than size of the magnetic fluctuations that they bounce off. Therefore to increase the energy of the accelerated particles one should have strong magnetic field and strong magnetic fluctuations both in the preshock and postshock regions. The situation with the postshock region is relatively simple. Gas passing through the shocks is known to create turbulence (e.g., Giacalone & Jokipii 2007). The turbulence is known to increase the magnetic field energy, enabling particles to scatter efficiently and return to the shock region for further acceleration. For the preshock region, most work was concentrated on instabilities that can enhance magnetic field. The most commonly discussed is the so-called Bell instability (Bell 2004) which is a non-resonant current driven instability, that can increase magnetic field in front of the shock. In Beresnyak et al. (2009) we proposed that a turbulent generation of magnetic field is happening in front of the shock, in the region which is called precursor. The properties of precursor and its formation in front of the shock are described in the literature (e.g., Malkov & Drury 2011). As the precursor interacts with the density inhomogeneities preexisting in the medium in front of the shock, it gets perturbed, creating vorticity and turbulence. New studies of turbulent amplification of magnetic field (e.g., Cho et al. 2009) provide the rates of magnetic field amplification by turbulence. These rates were made use of in Beresnyak et al. (2009) to obtain the values of the turbulent magnetic field that is generated in front of the shock. The corresponding estimates show that the preshock magnetic fields produced via this process are larger than those arising from the Bell instability and that they account for cosmic ray acceleration in galactic supernovae shock up to 10^{15} eV, the so-called "knee" of the cosmic ray spectrum.

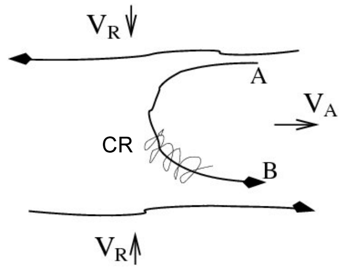

Fig. 3. CR spiral about a reconnected magnetic field line and bounce back at points A and B. The reconnected regions move towards each other with the reconnection velocity V_R. The advection of cosmic rays entrained on magnetic field lines happens at the outflow velocity, which is in most cases of the order of V_A. Bouncing at points A and B happens because either of streaming instability induced by energetic particles or magnetic turbulence in the reconnection region. In reality, the outflow region gets filled in by the oppositely moving tubes of reconnected flux which collide only to repeat on a smaller scale the pattern of the larger scale reconnection. Thus our cartoon also illustrates the particle acceleration taking place at smaller scales.

Further development of this direction presents a very promising avenue of the cosmic ray acceleration research. Interesting boot strap processes are likely to be at work as generation of magnetic fluctuations in front of the shock increases the efficiency of the acceleration, contributing to the development of the precursor.

4.3. Acceleration induced by magnetic reconnection

An important consequence of fast reconnection of turbulent magnetic fields that we discussed in Sect. 3 is the formation of a thick volume filled with reconnected magnetic flux loops. These 3D loops contract, presenting favorable conditions for energetic particle acceleration. This process of first order Fermi acceleration of energetic particles in reconnection regions has been described in de Gouveia

Dal Pino & Lazarian (2005) (see also Fig. 3) for the situation when there is no back reaction of the accelerated particles on the reconnected magnetic flux. Drake et al. (2006) appealed to a similar process within their preferred model of collisionless reconnection and proposed that firehose instability can play a role of the feedback for the accelerated particles.

More recently, the acceleration in reconnection regions has obtained observational support. It was suggested in Lazarian & Opher (2009) that anomalous CR measured by Voyagers are, in fact accelerated in the reconnection regions of magnetopose (see also Drake et al. (2010)). Such a model explains why Voyagers did not see any signatures of acceleration passing the Solar system termination shock. In a separate development, Lazarian & Desiati (2010) appealed to the energetic particle acceleration in the wake produced as the Solar system moves through interstellar gas to explain the excess of cosmic rays of the range of both sub-Tev and multi-TeV energies in the direction of the magnetotail Magnetic reconnection is ubiquitous in astrophysical circumstances and therefore it is expected to induce acceleration of particles in a wide range of astrophysical environments. For instance, the process has been already discussed for the acceleration of particles in gamma ray bursts (Lazarian et al. 2003; Zhang & Yan 2011) and microquasars (de Gouveia Dal Pino & Lazarian 2005). We expect the process to be important for the acceleration of protons and electrons in galaxy clusters.

Numerical 2D simulations presented in Drake et al. (2010) confirmed high efficiency of particle acceleration in regions of magnetic reconnection. However, results in Lazarian et al. (2010) show that the process of acceleration happens rather differently in 2D and 3D situations. The 3D geometry shows a wider variety of acceleration regimes and this calls for much more detailed studies of the acceleration.

5. Summary

The main points of our review can be summarized as follows

- Turbulence is essential for understanding of the IGM. On large scale the description of turbulence obtained in MHD can be used. Compressions induced by turbulence induce instabilities in the IGM, changing the mean free path of thermal ions. This should extend the range over which the MHD description of turbulence is applicable.
- Studies of turbulence in the IGM can get a boost if Doppler-broaderned spectral emission and absorption lines are used. The techniques originally developed and successfully used in the interstellar research, namely Velocity Channel Analysis (VCA) and Velocity Correlation Spectrum (VCS) are promissing for studing of turbulence in the IGM.
- Magnetic reconnection happens fast in turbulent media, which makes the models of MHD turbulence self-consistent. Fast magnetic reconnection makes MHD turbulence somewhat similar to hydrodynamic if one considers turbulent motions perpendicular to the local direction of magnetic field. Such motions can induce a process of "reconnection diffusion" which efficient heat transfer in the IGM.
- Magnetic turbulence is very important for particle acceleration in clusters of galaxies. It can accelerate particles through direct interactions with turbulent fluctuations. However, it can also modify shocks, inducing magnetic field generation in shock precursors and increasing the efficiency of high energy particle acceleration by shocks. In addition, it can enable fast magnetic reconnection which can accelerate particles within the thick reconnection regions.

Acknowledgements. AL thanks the NSF grant AST 0808118, NASA grant NNX09AH78G and the support of the Center for Magnetic Self Organization. GB acknowledge partial support from PRIN-INAF 2008, 2009.

References

Alfvén, H. 1942, Ark. Mat., Astron. o. Fys., 29B, 1

Armstrong, J. W., Rickett, B. J., & Spangler, S. R. 1995, ApJ, 443, 209
Bell, A. R. 2004, MNRAS, 353, 550
Beresnyak, A. 2011, Phys. Rev. Lett., 106, 075001
Beresnyak, A., & Lazarian, A. 2006, ApJ, 640, L175
Beresnyak, A., & Lazarian, A. 2008, ApJ, 682, 1070
Beresnyak, A., & Lazarian, A. 2009, ApJ, 702, 1190
Beresnyak, A., Jones T., & Lazarian, A. 2009, ApJ, 707, 1541
Beresnyak, A., & Lazarian, A. 2010, ApJ, 722, L110
Beresnyak, A., Yan, H., & Lazarian, A. 2011, ApJ, 728, 60
Boldyrev, S. 2005, ApJ, 626, L37
Boldyrev, S. 2006, Phys. Rev. Lett., 96, 115002
Brunetti G., Lazarian A., 2007, MNRAS, 378, 245
Brunetti, G., et al. 2008, Nature, 455, 944
Brunetti, G., et al., 2009, A&A, 507, 661
Brunetti G., Lazarian A., 2011a, MNRAS, 412, 817
Brunetti G., Lazarian A., 2011b, MNRAS, 410, 127
Cassano R., Brunetti G., 2005, MNRAS, 357, 1313
Chandran B.D.G., 2000, Phys. Rev. Lett., 85 (22), 4656
Chandran, B. D. G. 2008, ApJ, 685, 646
Chepurnov A. & Lazarian, A. 2006, arXiv:0611465
Chepurnov, A., & Lazarian, A. 2009, ApJ, 693, 1074
Chepurnov, A., & Lazarian, A. 2010, ApJ, 710, 853
Chepurnov, A., et al., 2010, ApJ, 714, 1398
Cho, J., & Vishniac, E. T. 2000, ApJ, 539, 273
Cho, J., & Lazarian, A. 2002, Physical Review Letters, 88, 245001
Cho, J., Lazarian, A., & Vishniac, E. T. 2002, ApJ, 564, 291
Cho, J., & Lazarian, A. 2003, MNRAS, 345, 325
Cho, J., Lazarian, A., & Vishniac, E. T. 2003, Turbulence and Magnetic Fields in Astrophysics, Lecture notes Physics, 614, 56
Cho, J., et al., 2008, ApJ, 693, 1449
de Gouveia Dal Pino, E. & Lazarian, A. 2005, A&A, 441, 845
Del Zanna, L., Velli, M., & Londrillo, P. 2001, A&A, 367, 705
Dermer, C. D., & Humi, M. 2001, ApJ, 556, 479
Dolag, K., et al., 2005, MNRAS, 364, 753
Drake, J. F., et al., 2006, Nature, 443, 553
Drake, J. F., et al., 2010, ApJ, 709, 963
Eyink, G., Lazarian, A. & Vishniac, E. 2011, ApJ, submitted, arXiv:1103.1882
Elmegreen, B. G., & Scalo, J. 2004, ARA&A, 42, 211
Enßlin T.A., et al., 1998, A&A, 333, 47
Fox, D. B., et al. 2005, Nature, 437, 845
Galama, T. J., et al. 1998, Nature, 395, 670
Galtier, S., Nazarenko, S. V., Newell, A. C. & Pouquet, A. 2000, J. Plasma Phys., 63, 447
Giacalone, J., & Jokipii, J. R. 2007, ApJL, 663, L41
Ginzbirg, V. 1966, Sov. Astr., 9, 877
Gogoberidze, G., Rogava, A., & Poedts, S. 2007, ApJ, 664, 549
Goldreich, P. & Sridhar, S. 1995, ApJ, 438, 763
Hamilton, R. J., & Petrosian, V. 1992, ApJ, 398, 350
Higdon, J.C., 1984, ApJ, 285, 109
Hoeft, M. & Brueggen, M. 2007, MNRAS, 375, 77
Jacobson, A. R., & Moses, R. W. 1984, Phys. Rev. A, 29, 3335
Jokipii, R. 1966, ApJ, 146, 480
Kowal, G., et al., 2009, ApJ, 700, 63
Kowal, G., & Lazarian, A. 2010, ApJ, 720, 742
Iapichino, L., & Niemeyer, J. C. 2008, MNRAS, 388, 1089
Lazarian, A. 2005, Magnetic Fields in the Universe: From Laboratory and Stars to Primordial Structures., AIPC, 784, 42
Lazarian, A. 2006, ApJ, 645, L25
Lazarian, A. 2009, Space Sci. Rev., 143, 357
Lazarian, A., & Vishniac, E. T. 1999, ApJ, 517, 700
Lazarian, A. & Pogosyan, D., 2000, ApJ, 537, 720 (LP00)
Lazarian, A., Petrosian, V., Yan, H., & Cho, J. 2003, arXiv:astro-ph/0301181
Lazarian, A., Vishniac, E. T., & Cho, J. 2004, ApJ, 603, 180

Lazarian, A. & Pogosyan, D., 2004, ApJ, 616, 943 (LP04)
Lazarian A., Beresnyak A., 2006, MNRAS, 373, 1195
Lazarian, A. & Pogosyan, D., 2006, ApJ, 652, 1348, (LP06)
Lazarian, A. & Pogosyan, D., 2008, ApJ, 686, 650 (LP08)
Lazarian A., & Opher M., 2009, ApJ, 703, L8
Lazarian, A., & Desiati, P. 2010, ApJ, 722, 188
Lazarian, A., et al., 2010, Space and Planetary Science, doi:10.1016/j.pss.2010.07.020
Lithwick, Y., & Goldreich, P. 2001, ApJ, 562, 279
Lithwick, Y., Goldreich, P., & Sridhar, S. 2007, ApJ, 655, 269
Lovelace, R. V. E. 1976, Nature, 262, 649
Malkov, M. A., & O'C Drury, L. 2001, Rep. Prog. in Physics, 64, 429
Maron, J., & Goldreich, P. 2001, ApJ, 554, 1175
Masuda, S., et al., 1994,Nature, 371, 495
Matthaeus, W. H., Montgomery, D. C., & Goldstein, M. L. 1983, Physical Review Letters, 51, 1484
Matthaeus, W. H. & Lamkin, S. L. 1985, Phys. Fluids, 28, 303
Matthaeus, W. H. & Lamkin, S. L. 1986, Phys. Fluids, 29, 2513
Matthaeus, W. H., Goldstein, M. L., & Roberts, D. A. 1990, J. Geophys. Res., 95, 20673
McKee, C. F., & Ostriker, E. C. 2007, ARA&A, 45, 565
Miller, J. A., Larosa, T. N., & Moore, R. L. 1996, ApJ, 461, 445
Montgomery, D., & Turner, L. 1981, Physics of Fluids, 24, 825
Müller, W-C., Biskamp, D., 2000, PhRvL, 84, 475
Ng, C. S., & Bhattacharjee, A. 1996, ApJ, 465, 845
Oughton, S. 2003, Solar Wind Ten, 679, 421
Padoan, P., et al., 2009, ApJ, 707, L153
Parker, E. N. 1979, Oxford, Clarendon Press; New York, Oxford University Press, 1979
Parker, E. N. 1993, ApJ, 408, 707
Perez, J. C., & Boldyrev, S. 2009, Physical Review Letters, 102, 025003
Petrosian, V., & East, W. E. 2008, ApJ, 682, 175
Pfrommer C., Ensslin T.A., Springel V., 2008, MNRAS, 385, 1211
Priest, E. & Forbes, T. 2000, in: Magnetic Reconnection: MHD theory and applications, Eds. E. Priest & T. Forbes, pp. 612, Cambridge, UK: Cambridge University Press
Ryu, D., et al., 2003, ApJ, 593, 599
Sanders, J. S., Fabian, A. C., & Smith, R. K. 2011, MNRAS, 410, 1797
Santos-Lima, R., et al., 2010, ApJ, 714, 442
Sarazin C.L., 1986, Rev. Mod. Phys. 58, 1
Schekochihin A.A., et al., 2005, ApJ, 629, 139
Schekochihin A.A., Cowley S.C., 2006, PhPl 13, 6501
Schekochihin A.A., et al., 2010, MNRAS, 405, 291
Schlickeiser, R., & Dermer, C. D. 2000, A&A, 360, 789
Skillman S.W., et al., 2008, ApJ, 689, 1063
Speiser, T. W. 1970, Planet. Space Sci., 18, 613
Sturrock, P. A. 1966, Nature, 211, 695
Vazza F., Brunetti G., Gheller C., 2009, MNRAS, 395, 1333
Vazza, F., et al., 2011, A&A, 529, A17
Yan, H., & Lazarian, A. 2002, Physical Review Letters, 89, 1102
Yan, H., & Lazarian, A. 2004, ApJ, 614, 757
Yan, H., & Lazarian, A. 2008, ApJ, 673, 942
Yan, H., Lazarian, A., & Petrosian, V. 2008, ApJ, 684, 1461
Yan, H., & Lazarian, A. 2011, ApJ, 731, 35
Yokoyama, T., & Shibata, K. 1995, Nature, 375, 42
Wentzel, D. G. 1969, ApJ, 156, 303
Zhang, B., & Yan, H. 2011, ApJ, 726, 90