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Turbulence

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ABSTRACT

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1. Theory

(Sobacchi & Lyubarsky 2019) paragraphs:

The most important property of MHD turbulence is its strong anisotropy, with the turbulent eddies becoming strongly elongated in the direction of the background magnetic field at small scales. As first proposed by Goldreich & Sridhar (1995), in the course of the turbulent cascade the ratio of the longitudinal scale of the eddies, $\lambda_\parallel$, to the Alfven velocity remains equal to the ratio of the, perpendicular scale, $\lambda_\perp$,to the turbulent velocity This condition is known as critical balance. From this condition one finds

$$\frac{\lambda_\perp}{\lambda_\parallel} \sim \sqrt{\frac{\lambda_\parallel}{R}} \tag{1}$$

The statement that in collisionless plasmas the anisotropic MHD turbulence decays by heating/accelerating particles along the background magnetic field is general. Indeed, the dissipation occurs at the wave-particle resonances

$$\omega - \boldsymbol{k} \cdot \boldsymbol{v} = n\omega_B \tag{2}$$

where ω and $\boldsymbol{k}$ are the frequency and the wavenumber, $\boldsymbol{v}$ is the particle velocity, ω_B is the Larmor frequency, and n is an integer. The cyclotron resonance condition $n \neq 0$ is satisfied when the longitudinal scale of the wave packet, $\lambda_\parallel$ is of the order of the particle Larmor radius, $r_L = c/\omega_B$. Since $r_L \ll R$, due to the strong anisotropy of the MHD turbulence a particle crosses many wave packerts during one Larmor orbit. It was first noticed by Gruzinov (1998), Quataert (1998), and Quataert & Gruzinov (1999) that in this case the dissipation occurs at the Landau resonance $n = 0$. Since the two physical mechanisms of wave-particle interaction at the $n = 0$ resonance are due to i) the longitudinal electric field of the wave, and ii) the interaction between the effective particle's magnetic moment and the longitudinal magnetic perturbation, one is led to the conclusion that the turbulent energy is primarily dissipated on to the longitudinal particle motion.

It has also been found that the turbulent fluctuations tend to align with one another forming small-scale current sheets (e.g. Beresnyak & Lazarian 2006; Boldyrev 2006;Mason, Cattaneo & Boldyrev 2006), which could be disrupted via magnetic reconnection thus providing an additional dissipation mechanism (e.g. Boldyrev & Loureiro 2017; Loureiro & Boldyrev 2017; Mallet, Schekochihin & Chandran 2017a,b). Note that the background magnetic field, which is much larger than the reconnecting field and lies in the same plane of the current sheet, plays the role of a guide field. Since the magnetic energy is transferred to the plasma particles at the Landau resonance between the particles and the tearing mode that disrupts the current sheet, also in this case one would expect the particles to be heated in the longitudinal direction.

Even if the perpendicular heating is negligible, in a weakly magnetized plasma the fire-hose instability quickly erases any momentum anisotropy (e.g. Parker 1958; Lerche 1966). However, since the fire-hose instability develops once $P_\parallel - P_\perp > B^2/4\pi$, one immediately sees that this instability is not effective if the magnetic-to-plasma energy ratio exceeds $\frac{1}{2}$.

2. Literature

2.1. Non-thermal particles from turbulence

Melrose 1980 Petrosian 2012 Lazarian 2012

2.2. Turbulence in astrophysics

turbulence in stellar coronae Matthaeus 1999, Cranmer 2007

ISM Armstrong 1995, Lithwick & Goldreich 2001

SNRs Weiler & Sramek 1988, Roy 2009

PWN Porth 2014, Lyutikov 2019

BH disks Balbus & Hawley 1998, Brandenburg & Subramanian 2005

jets from AGNs Marscher 2008, MacDonald & Marscher 2018

radio lobes Vogt & Ensslin 2005, O'Sullivan 2009

GRBs Piran 2004, Kumar & Narayan 2009

Galaxy clusters Zweibel & Heiles 1997, Subramanian 2006

2.3. Magnetically dominated turbulence

Sustained relativistic turbulence (force-free) (Thompson & Blaes 1998): extension of Goldreich & Sridhar 1995 to exterme relativistic limit (no plasma inertia; force-free MHD). Anisotropic cascade is formed, dissipation occurs at the scale of current starvation (when not enough charge carriers in plasma to maintain currents from Alfén waves).

(Cho 2005) Inoue 2011 (Cho & Lazarian 2014) (Zrake & East 2016)

Relativistic MHD (Zrake & MacFadyen 2012) (Zrake 2014)

2.4. Bright non-thermal synchrotron and inverse Compton signatures

pulsar magnetospheres and winds Buhler & Blandford 2014

jets from AGNs Begelman 1984

coronae of accretion disks Yuan & Narayan 2014

2.5. Kinetic turbulence

Kinetic turbulence: (Zhdankin et al. 2017b) Letter
(Zhdankin et al. 2017a) Paper
(Zhdankin et al. 2018) System size convergence
(Zhdankin et al. 2019a) electron-proton plasma
(Zhdankin et al. 2019b) radiative turbulence
(Comisso & Sironi 2018) acceleration
(Wong et al. 2019) acceleration
(Nättilä 2019) Runko and turbulence
(Comisso & Sironi 2019) acceleration

2.6. Radiative turbulence

Analytic work on radiative turbulence (Uzdensky 2018) (Zrake et al. 2018); GRBs (Sobacchi & Lyubarsky 2019)

PIC simulations: (Zhdankin et al. 2019b) radiative turbulence

Fokker-Planck equation in momentum space with radiative cooling term (Schlickeiser 1984, 1985); not in original list (Schlickeiser 1989) (Stawarz & Petrosian 2008)

2.7. radiative PIC simulations

Reconnection: (Jaroschek & Hoshino 2009) (Cerutti et al. 2013, 2014b,a) (Kagan et al. 2016b,a) (Hakobyan et al. 2019) (Werner et al. 2019) (Schoeffler et al. 2019)

decay of magnetostatic equilibria (Yuan et al. 2016) (Nalewajko et al. 2018)

pulsar wind (Cerutti & Philippov 2017)

pulsar magnetospheres (Cerutti et al. 2016) (Philippov & Spitkovsky 2018)

Synchrotron and jitter radiative signatures of collisionless shocks (Medvedev & Spitkovsky 2009) (Sironi & Spitkovsky 2009) (Kirk & Reville 2010) (Nishikawa et al. 2011)

Radiative turbulence (Zhdankin et al. 2019c)

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