

Contents

Preface — V

- 1 Introduction into MHD turbulence — 1**
 - 1.1 Turbulence around us — 1
 - 1.2 Kolmogorov scaling — 4
 - 1.3 Compressible MHD equations and simulated turbulence — 6
 - 1.4 How MHD cascade is different from hydro cascade? — 7
 - 1.5 Turbulent dynamo — 9
 - 1.6 Magnetohydrodynamics and reconnection — 9
 - 1.7 Observing MHD turbulence — 10
 - 1.8 Applications of MHD turbulent theory — 10
 - 1.9 Cosmic ray transport and acceleration — 11

- 2 Astrophysical dynamo — 13**
 - 2.1 Nonlinear small-scale dynamo — 14
 - 2.1.1 Linear growth stage — 14
 - 2.1.2 Locality of the small-scale dynamo — 16
 - 2.1.3 Numerical results — 17
 - 2.1.4 Efficiency of nonlinear dynamo — 18
 - 2.1.5 Dynamo simulations with intermittent driving — 19
 - 2.2 Dynamo in galaxy clusters — 20
 - 2.2.1 Physical conditions in galaxy clusters — 20
 - 2.2.2 Limitation of dynamo simulations — 22
 - 2.2.3 Analysis of cluster simulations — 24
 - 2.2.4 Cluster magnetic fields — 26

- 3 Incompressible MHD turbulence — 29**
 - 3.1 Equations of incompressible MHD and conservation laws — 31
 - 3.2 From weak to strong turbulence — 33
 - 3.3 Reduced MHD approximation — 35
 - 3.4 Strong turbulence: phenomenology — 36
 - 3.4.1 Dissipation scales — 37
 - 3.4.2 Anisotropy from phenomenological viewpoint — 37
 - 3.4.3 Modifications of GS95 — 39
 - 3.5 Anisotropy from Lagrangian viewpoint — 39
 - 3.6 Parallel spectrum: numerics — 41
 - 3.7 Parallel spectrum observations versus numerics — 43
 - 3.8 Statistical indicators of turbulence — 45
 - 3.9 The scaling convergence argument — 48

3.10	Numerical studies of the spectral slope —	50
3.11	Dynamic alignment models —	55
3.12	Anisotropy scaling study —	58
3.13	Summary of balanced driven MHD turbulence —	59
3.14	Turbulence driven by external current —	59
3.14.1	MHD equations with external current and conservation laws —	60
3.14.2	Linear and nonlinear stages —	61
3.14.3	Empirical findings —	64
3.14.4	Applications of current driven turbulence to astrophysical systems —	65
4	Imbalanced MHD turbulence —	67
4.1	Theoretical considerations —	69
4.1.1	Lithwick, Goldreich, and Sridhar (2007) model, [295] LGS07 —	70
4.1.2	Beresnyak and Lazarian (2008) model, [30] BL08 —	70
4.1.3	Perez and Boldyrev (2009) model, [356] PB09 —	71
4.2	Empirical study in MHD simulations with stochastic driving —	72
4.2.1	Establishment of the stationary state —	75
4.2.2	Parallel structure function —	76
4.2.3	Spectra and anisotropies —	79
4.2.4	Comparison with models —	84
4.3	Empirical study in reduced MHD simulations with energy-controlled driving —	86
4.3.1	Nonlinear cascading and dissipation rate —	86
4.3.2	Imbalanced spectra —	87
4.3.3	Imbalanced anisotropies —	88
5	Compressibility in MHD turbulence —	91
5.1	Decomposition into fundamental modes —	91
5.2	Other ways of decomposition into fundamental modes —	95
5.3	Decomposition into solenoidal and potential modes —	97
5.4	Density scalings —	98
5.4.1	Theoretical considerations —	99
5.4.2	The code —	100
5.4.3	Results —	101
5.4.4	Implications —	102
5.5	Viscosity-dominated regime of MHD turbulence —	103
5.6	Applying results to collisionless fluids —	106
5.7	Toward understanding of relativistic turbulence —	106
5.7.1	Fully relativistic MHD turbulence —	109
5.7.2	Relativistic compressible turbulence: mode decomposition —	110

- 6 Intermittency of MHD turbulence — 117**
 - 6.1 General considerations — 117
 - 6.2 She–Leveque model of intermittency — 118
 - 6.3 Intermittency of incompressible turbulence — 118
 - 6.4 Intermittency of compressible turbulence — 119
 - 6.5 Intermittency of viscosity-damped turbulence — 121

- 7 Turbulence and charged particles — 123**
 - 7.1 Particle diffusion due to stochastic fields — 124
 - 7.1.1 Richardson’s picture of diffusion — 124
 - 7.1.2 Field line diffusion — 125
 - 7.1.3 Limiting cases: very small and very large distances — 126
 - 7.1.4 Inertial range distances – hand-waving derivation — 126
 - 7.1.5 Inertial range distances – Richardson–Alfvén diffusion — 127
 - 7.1.6 Numerical results, asymmetric diffusion — 127
 - 7.1.7 The model of asymmetric diffusion — 130
 - 7.1.8 Implications of asymmetric field line wandering for particle transport — 130
 - 7.2 Turbulence and particle acceleration — 131
 - 7.2.1 Observational evidence for acceleration different from classic DSA — 131
 - 7.2.2 Statistics of general MHD flows and energy transfer — 134
 - 7.2.3 Acceleration by curvature drift — 135
 - 7.2.4 Numerical case study of two types of turbulence — 137
 - 7.2.5 Expected picture for turbulent acceleration in reconnection — 138

- 8 Reconnection in the presence of MHD turbulence — 141**
 - 8.1 The problem of reconnection — 141
 - 8.1.1 Flux freezing and magnetic topology changes — 141
 - 8.1.2 Sweet–Parker model and its generalization to turbulent media — 141
 - 8.1.3 Temporal and spatial Richardson diffusion — 145
 - 8.1.4 Turbulent reconnection and violation of magnetic flux freezing — 145
 - 8.1.5 Turbulent reconnection in compressible media — 145
 - 8.1.6 Turbulent reconnection in partially ionized gas — 146
 - 8.2 Testing turbulent reconnection — 149
 - 8.3 Understanding turbulent relativistic reconnection — 152
 - 8.4 Generation of turbulence by reconnection — 156
 - 8.4.1 Early-time turbulence in the planar current layer — 157
 - 8.4.2 Compressible simulations with inflow and outflow of turbulence in the current layer — 159
 - 8.5 Observational testing of turbulent reconnection — 161
 - 8.5.1 Solar turbulent reconnection — 161

- 8.5.2 Solar wind, Parker spiral, heliospheric current sheet — **162**
- 8.5.3 Indirect observational evidence — **163**
- 8.5.4 Flares of magnetic reconnection and associated processes — **164**
- 8.6 Comparison of approaches to magnetic reconnection — **165**
 - 8.6.1 Turbulent reconnection and numerical simulations — **165**
 - 8.6.2 Turbulent reconnection versus tearing reconnection — **166**
 - 8.6.3 Turbulent reconnection: 3D reality versus 2D models — **167**
 - 8.6.4 Turbulent reconnection versus turbulent resistivity — **168**
- 9 Turbulent transport of magnetic field and heat — 171**
 - 9.1 Important motivation: star formation problem — **171**
 - 9.2 Diffusion in magnetized turbulent fluid — **173**
 - 9.2.1 Physical picture of reconnection diffusion in the absence of gravity — **176**
 - 9.2.2 Reconnection diffusion in the presence of gravity — **179**
 - 9.3 Reconnection diffusion and the identity of magnetic field lines — **180**
 - 9.3.1 Explosive diffusion of magnetic field lines in turbulent flows — **180**
 - 9.3.2 Spontaneous stochasticity of magnetic field lines and reconnection diffusion — **183**
 - 9.3.3 Reconnection diffusion in partially ionized gas — **184**
 - 9.4 Theoretical expectations and numerical simulations of reconnection diffusion — **185**
 - 9.4.1 Limitations of numerical simulations — **185**
 - 9.4.2 Reconnection diffusion in circumstellar accretion disks — **187**
 - 9.5 Predictions and tests for reconnection diffusion — **188**
 - 9.5.1 Reconnection diffusion in interstellar diffuse gas — **188**
 - 9.5.2 Reconnection diffusion and extreme cases of star formation — **190**
 - 9.5.3 Intuitive understanding of reconnection diffusion — **191**
 - 9.5.4 Reconnection diffusion and alternative ideas — **192**
 - 9.5.5 Transport of heat in magnetized fluid — **194**
 - 9.5.6 MHD and plasma-based descriptions of reconnection diffusion — **199**
- 10 Extracting properties of astrophysical turbulence from observations — 203**
 - 10.1 Studying turbulence with spectral lines — **204**
 - 10.1.1 Statistics of the PPV: velocity channel analysis and velocity coordinate spectrum — **205**
 - 10.2 Synchrotron fluctuations — **219**
 - 10.2.1 Numerical testing of the synchrotron-based techniques and the application to observations — **225**
 - 10.3 Observational signatures of MHD turbulence modes — **226**

- 10.3.1 Anisotropy arising from Alfvénic turbulence: obtaining magnetic field direction and M_A — 226
- 10.3.2 Contribution of different MHD turbulence modes — 227
- 10.4 Relation to CMB foreground studies — 228
 - 10.4.1 Polarized CMB foreground — 228
 - 10.4.2 MHD turbulence for foreground studies — 229
- 10.5 Gradient technique: utilizing the turbulence knowledge to study magnetic fields — 235
 - 10.5.1 Velocity gradients — 235
 - 10.5.2 Synchrotron intensity gradients — 239
 - 10.5.3 Synchrotron polarization gradients — 240
 - 10.5.4 Intensity gradients — 241
 - 10.5.5 Dispersion of gradient directions: obtaining magnetization of the media — 243
 - 10.5.6 Probing magnetic fields with different types of gradients — 244
- 10.6 Synergy of different approaches — 245

Bibliography — 247

Index — 269

