

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