## Contents

	Preface		xiii
1	Introduc	tion	1
2	Basic ki	nematic concepts	10
2.1	Magneti	c flux and magnetic helicity	10
2.2	Conserv	ation of magnetic topology	14
2.3	Conditio	ons for magnetic reconnection	17
2.4	Conserv	ation of magnetic helicity in reconnection	21
3	Current	sheets	29
3.1	Resistive MHD		
	3.1.1 TI	he MHD equations	30
	3.1.2 Ec	quilibrium and linear modes	32
	3.1.3 C	onservation laws	37
	3.1.4 R	educed MHD models	38
3.2	Resistive current sheets		
	3.2.1 C	urrent-sheet formation	43
	3.2.2 Ba	asic properties of resistive current sheets	52
	3.2.3 R	efined theory of the current-sheet structure	55
3.3	Driven current-sheet reconnection		
	3.3.1 Sy	vrovatskii's theory of current sheets	60
	3.3.2 D	ynamic structure of Y-points	66
	3.3.3 Sc	caling laws of stationary current-sheet reconnection	69
	3.3.4 Pe	etschek's slow-shock model	75
4	Resistive	e instabilities	81
4.1 The resistive tearing mode			82
	4.1.1 Li	inear tearing instability	85

	4.1.2	Small-amplitude nonlinear behavior	88
	4.1.3	Saturation of the tearing mode	91
	4.1.4	Effect of dynamic resistivity	95
	4.1.5	Neoclassical tearing mode	96
4.2	The double tearing mode		
4.3	The resistive kink mode		
	4.3.1	Resistive kink instability	104
	4.3.2	Small-amplitude nonlinear evolution	106
	4.3.3	Final state of the resistive kink mode	112
4.4	Coale	escence instability	114
4.5	Press	ure-driven instabilities	118
	4.5.1	Interchange and ballooning modes	118
	4.5.2	Nonlinear evolution of pressure-driven modes	125
	4.5.3	Finite pressure effects on tearing modes	128
4.6	Shear	flow instability	129
	4.6.1	Shear flow instability in neutral fluids	130
	4.6.2	Effect of magnetic field on the Kelvin-Helmholtz	
		instability	133
	4.6.3	Instability of a magnetized jet	135
4.7	Instal	bility of a resistive current sheet	137
	471	Threshold condition for tearing instability	137
	-T. / . L	Threshold condition for touring instability	
	4.7.2	Plasmoids	142
5	4.7.2 <b>Dvna</b>	Plasmoids mo theory	142 145
<b>5</b> 5.1	4.7.2 <b>Dyna</b> Kiner	Plasmoids mo theory natic dynamo theory	142 145 148
<b>5</b> 5.1	4.7.2 <b>Dyna</b> Kiner 5.1.1	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions	142 145 148 149
<b>5</b> 5.1	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo	142 145 148 149 151
<b>5</b> 5.1	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3	Plasmoids <b>mo theory</b> natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics	142 145 148 149 151 153
<b>5</b> 5.1	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4	Plasmoids <b>mo theory</b> natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos	142 145 148 149 151 153 155
<b>5</b> 5.1	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes	142 145 148 149 151 153 155 159
<b>5</b> 5.1 5.2	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes i-field MHD dynamo theory	142 145 148 149 151 153 155 159 161
<b>5</b> 5.1 5.2	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes a-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy	142 145 148 149 151 153 155 159 161 161
<b>5</b> 5.1 5.2	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes i-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo	142 145 148 149 151 153 155 159 161 161 164
<b>5</b> 5.1 5.2 5.3	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2 MHI	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes a-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection	142 145 148 149 151 153 155 159 161 161 164 168
<b>5</b> 5.1 5.2 5.3	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2 MHI 5.3.1	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes i-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere	142 145 148 149 151 153 155 159 161 161 164 168 168
<b>5</b> 5.1 5.2 5.3	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2 MHI 5.3.1 5.3.2	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes i-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere The self-consistent MHD dynamo	142 145 148 149 151 153 155 159 161 161 164 168 168 173
<b>5</b> 5.1 5.2 5.3	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mear 5.2.1 5.2.2 MHI 5.3.1 5.3.2 5.3.3	Plasmoids Plasmoids mo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes a-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere The self-consistent MHD dynamo The geodynamo	142 145 148 149 151 153 155 159 161 161 164 168 168 173 179
<b>5</b> 5.1 5.2 5.3	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2 MHI 5.3.1 5.3.2 5.3.3 MHI	Plasmoids Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes i-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere The self-consistent MHD dynamo The geodynamo D turbulence	142 145 148 149 151 153 155 159 161 161 164 168 168 173 179 182
<b>5</b> 5.1 5.2 5.3 5.4	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2 MHI 5.3.1 5.3.2 5.3.3 MHI 5.4.1	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes i-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere The self-consistent MHD dynamo The geodynamo D turbulence Homogeneous MHD turbulence	142 145 148 149 151 153 155 159 161 161 164 168 168 173 179 182 182
<b>5</b> 5.1 5.2 5.3	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mear 5.2.1 5.2.2 MHI 5.3.1 5.3.2 5.3.3 MHI 5.4.1 5.4.2	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes -field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere The self-consistent MHD dynamo The geodynamo D turbulence Homogeneous MHD turbulence Selective decay and energy decay laws	142 145 148 149 151 153 155 159 161 161 164 168 168 173 179 182 182 184
<b>5</b> 5.1 5.2 5.3 5.4	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2 MHI 5.3.1 5.3.2 5.3.3 MHI 5.4.1 5.4.2 5.4.3	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes -field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere The self-consistent MHD dynamo The geodynamo D turbulence Homogeneous MHD turbulence Selective decay and energy decay laws Spatial scaling properties	142 145 148 149 151 153 155 159 161 161 164 168 168 173 179 182 182 182 184 189
<b>5</b> 5.1 5.2 5.3 5.4	4.7.2 <b>Dyna</b> Kiner 5.1.1 5.1.2 5.1.3 5.1.4 5.1.5 Mean 5.2.1 5.2.2 MHI 5.3.1 5.3.2 5.3.3 MHI 5.4.1 5.4.3 5.4.4	Plasmoids mo theory natic dynamo theory Nonexistence theorems and special dynamo solutions The rope dynamo Mean-field electrodynamics $\alpha^2$ - and $\alpha\Omega$ -dynamos Free dynamo modes i-field MHD dynamo theory Nonlinear quenching processes and magnetic buoyancy The solar dynamo D theory of thermal convection Thermal convection in a rotating sphere The self-consistent MHD dynamo The geodynamo D turbulence Homogeneous MHD turbulence Selective decay and energy decay laws Spatial scaling properties Homogenous turbulent dynamo	142 145 148 149 151 153 155 159 161 161 164 168 168 173 179 182 182 182 184 189 197

6	Noncollis	sional reconnection processes	199
6.1	Two-fluid theory		
6.2	High- $\beta$ v	whistler-mediated reconnection	206
	6.2.1 Tł	ne EMHD approximation	207
	6.2.2 Pr	operties of the reconnection region	208
	6.2.3 Co	palescence of EMHD flux bundles	212
	6.2.4 El	ectron Kelvin-Helmholtz instability of the current	
	lay	yer	215
	6.2.5 Io	n-controlled reconnection dynamics	218
6.3	Low- $\beta$ n	oncollisional reconnection	221
	6.3.1 Tł	ne four-field and three-field models	221
	6.3.2 Li	near stability theory	224
6.4	Nonlinea	ar noncollisional kink mode	229
	6.4.1 El	ectron inertia-dominated reconnection	229
	6.4.2 Ki	inetic Alfvén-wave-mediated reconnection	232
	6.4.3 In	fluence of diamagnetic effects	237
	6.4.4 Cr	riterion for fast reconnection	239
6.5	Sawtootl	h oscillation in tokamak plasmas	241
	6.5.1 Ba	asic experimental observations	241
	6.5.2 Tł	ne safety factor profile	244
	6.5.3 Sta	abilization and onset of sawtooth oscillations	246
	6.5.4 Ol	bservations of the collapse dynamics	248
	6.5.5 Tł	neoretical interpretation of the sawtooth collapse	250
6.6	Laborate	ory reconnection experiments	252
	6.6.1 Tł	ne UCLA magnetic reconnection experiment	253
	6.6.2 Tł	ne PPPL magnetic reconnection experiment	254
	6.6.3 Tł	ne Tokyo University reconnection experiment	256
7	Microsco	opic theory of magnetic reconnection	258
7.1	Vlasov tl	heory and microinstabilities	259
	7.1.1 Li	near Vlasov theory	260
	7.1.2 Qu	uasi-linear theory	265
	7.1.3 M	ode coupling, resonance broadening, and particle	
	tra	apping	268
	7.1.4 Tu	arbulent transport coefficients	272
7.2	Ion-soun	id instability	274
	7.2.1 Li	near stability characteristics	274
	7.2.2 No	onlinear saturation and long-time behavior	278
7.3	Lower-h	ybrid-drift instability (LHDI)	285
7.4	Whistler	anisotropy instability	292
7.5	The colli	isionless tearing mode	296
	7.5.1 Li	near stability theory	298
	7.5.2 No	onlinear saturation	301

Contents

xi

х

## Contents

	7.5.3 The ion tearing mode	304	
7.6	Particle simulation of collisionless reconnection		
	7.6.1 Particle simulation methods	307	
	7.6.2 Collisionless electron dynamics	310	
	7.6.3 Collisionless ion dynamics	312	
	7.6.4 GEM Magnetic Reconnection Challenge	316	
	7.6.5 Three-dimensional simulations	318	
8	Magnetospheric substorms	320	
8.1	The structure of the magnetosphere	321	
	8.1.1 The solar wind	321	
	8.1.2 Magnetopause and bow shock	325	
	8.1.3 The internal structure of the magnetosphere	329	
8.2	Magnetospheric convection	333	
8.3	Magnetopause reconnection		
8.4	Magnetospheric substorms		
	8.4.1 Substorm-related observations	340	
	8.4.2 MHD modeling of substorms	343	
	8.4.3 Collisionless reconnection in the magnetotail	350	
	8.4.4 Nonreconnective substorm model	351	
	8.4.5 Particle acceleration by magnetotail reconnection	353	
Epilogue			
	Bibliography	359	
	Index		

xii