Contents

1	The	Sun's Magnetic Fields	1
	1.1	The Sun as a Star	1
		1.1.1 Legacy of Ancients	1
		1.1.2 Hidden Interior	3
		1.1.3 Magnetic Dipole	4
	1.2	Magnetic Surface	6
		1.2.1 Quiet Sun	7
		1.2.2 Sunspots and Active Regions	8
		1.2.3 Plages	10
		1.2.4 High Latitudes and Polar Regions	11
	1.3	Mass Flows	12
	1.4	Magnetic Skeleton 1	18
	Refe	rences	20
-			• •
2	A Q	uick Look on Small Scale Flux Tubes	21
	2.1	Early Years	21
		2.1.1 First Direct Observational Signs of Magnetic	
		Flux Tubes.	22
		2.1.2 The Sunspot Dilemma	23
	2.2	Elements of Theory for de Facto Flux Tubes	25
	2.3	Numerical Visualization and Observations	28
	2.4	Filamentary Structures in Laboratory and Universe	32 27
	Refe	rences	31
3	Intri	insic Properties of Flux Tubes—Wave Phenomena	39
5	3 1	Equations of Motion or How Are Tube Wayes Excited	30
	5.1	3.1.1 Equation of Motion for a Single Flux Tube	41
		3.1.2 Macroscopic Motions of an Ensemble	
		of Flux Tubes	42
	32	Absorption of Acoustic Wayes—I andau Resonance	45
	3.2	Effects of Noncollinearity of Elux Tubes	48
	5.5	Lifets of Honeoninearity of Flux Tubes	ru

xi

xii

Contents

	24	Errost 7	Chaose of Lincor Oscillations of Magnetic Elvy Type	40
	5.4 2.5	Exact I	theory of Linear Oscillations of Magnetic Flux Tube	49
	3.5	Radiati	on of Secondary waves by Oscillating Flux Tubes	51
	3.6	Scatteri	ing of Acoustic Waves and Maximum Energy Input	53
	3.7	Axisym	metric Oscillations of Flux Tube	54
		3.7.1	Types of $m = 0$ Mode	54
		3.7.2	Equation of Motion for Sausage Oscillations	56
		3.7.3	Dispersion Relation	58
		3.7.4	Sausage and Fast Oscillations in Homogeneous	
			Flux Tube	60
		3.7.5	Effects of Radial Inhomogeneities on Sausage	
			Oscillations	61
	Refer	ences	•••••••••••••••••••••••••••••••••••••••	66
4	Effect	ts of Flu	x Tube Inhomogeneities and Weak Nonlinearity	69
	4.1	Radiall	y Inhomogeneous Flux Tube—Internal Resonances	69
		4.1.1	Anomalous Resonance in Kink Oscillations	69
		4.1.2	Alfvén Resonance	72
	4.2	Bounda	arv Value Problem	75
		4.2.1	Phase-Mixing in Flux Tubes	75
		4.2.2	Phase-Mixed Torsional Wayes	76
		4.2.3	Phase-Mixed Kink Oscillations.	78
	4.3	Longitu	Idinal Resonances	80
		4.3.1	Loss of Radial Equilibrium	81
		4.3.2	Bullwhip Effect	83
	4.4	Standin	g Resonances and the Temperature Jump	87
		4.4.1	Growth of the Oscillation Amplitude—First	
			Resonance	88
		4.4.2	Spectral Density and Strong Enhancement	
			of the Oscillation Amplitude	90
	4.5	Weakly	Nonlinear Waves in Flux Tubes	91
		4.5.1	Nonlinear Kink Oscillations—KdV-Bürgers	
			Equation	91
		4.5.2	Possibility of Solitary Sausage Wave.	96
	Refer	ences		97
5	Flux	Tube D	vnamics in the Presence of Mass Flows	99
C	5 1	Kelvin-	-Helmholtz Instability and Negative-Energy Wayes	99
	5.2	Shear H	Flow Instabilities in Magnetic Flux Tubes	103
	2.2	5.2.1	Specifics of Kelvin–Helmholtz Instability Along	
			Flux Tubes	103
		5.2.2	Flux Tubes and Negative-Energy Waves (NEWs)	104
	5.3	Basic E	Equations of Flux Tube Oscillations	
		with Sł	ear Flows	106

5.4	Dissipa	tive Instabilities of Negative-Energy Kink	
	Oscilla	tions	107
5.5	Radiati	ve Instability of Flux Tube Oscillations	
	in the I	Presence of Flows	110
	5.5.1	Sausage Oscillations	111
	5.5.2	Kink Oscillations	112
5.6	Parity of	of Negative and Positive Energy Waves	113
5.7	Explos	ive Instability of Negative-Energy Waves	115
5.8	Subcrit	ical Mass Flows—Absence of Instabilities	116
	5.8.1	Can the Alfvén Waves Heat the Corona?	117
	5.8.2	Effect of Mass Flows on the Efficiency of Heating	
		by Alfvén Waves	118
5.9	Phase 1	Mixed Alfvén Waves at Sub-alfvénic Mass Flows	120
	5.9.1	Damping Rate and Height of Energy Release	120
	5.9.2	Observable Morphological Effects	122
5.10	The As	symptotic Behavior of the Total Energy Flux	124
5.11	The W	ave Extinction in the Presence of Downflows	126
Refer	ences		134
Colle	ctive Ph	enomena in Rarefied Ensembles of Flux Tubes	137
6.1	Respor	nse of Flux Tubes to Propagation of Sound Waves	137
	6.1.1	Energy Exchange Between the Acoustic	
		Waves and Ensembles of Flux Tubes	138
	6.1.2	Near-Resonance Condition	140
6.2	Nonlin	ear Estimates of the Maximum Energy Input	141
6.3	Axisyr	nmetric Oscillation in Flux Tube Ensembles	145
	6.3.1	Equations of Motion	145
	6.3.2	Dispersion Relation—Resonance	
		and Frequency Shift	147
6.4	The In	teraction of Unsteady Wave Packets	
	with a	n Ensemble of Flux Tubes	151
6.5	Spread	ing of the Energy Absorption Region—"Clouds	
	of Ene	rgy"	154
	6.5.1	Large Wave Packets	155
	6.5.2	Short Wave Packets—Energy Absorption	
		and Release	157
6.6	The E	nergy Transfer from Unsteady Wave Packets	
6.6	The Er to the	mergy Transfer from Unsteady Wave Packets Medium	161
6.6	The E	nergy Transfer from Unsteady Wave Packets	161
6.6	The Er to the	nergy Transfer from Unsteady Wave Packets Medium	161 165

7	Effec	ts of Ma	agnetic Flux Tubes in Helioseismology	167
	7.1	The Ti	me-Distance Tomography	167
		7.1.1	Key Points of Time-Distance Analysis	
			with Magnetic Fields	168
		7.1.2	The Travel Times	169
	7.2	The Ef	fects of Horizontal Flows	171
	7.3	Effects	of Horizontal Magnetic Field	172
	7.4	Effects	of Background Inhomogeneities	174
		7.4.1	Weak Inhomogeneities	174
		7.4.2	Variations of Flow Velocities	175
	7.5	Practic	al Use of the Forward–Backward Information	176
		7.5.1	Symmetry Properties	176
		7.5.2	Reconstruction of Subsurface Flow and Magnetic	
			Fields from Observations	177
	7.6	Magne	tic Corrections in a Vertically Stratified Atmosphere	180
	7.7	Estima	te of the Energy Flux from Time-Distance Analysis	182
		7.7.1	Heat and Magnetic Energy Fluxes.	183
		7.7.2	Contribution of Eddy Fluxes	185
		7.7.3	Reconstruction of Energy Fluxes from Observational	
			Data	186
	7.8	Raman	Spectroscopy of Solar Oscillations	186
		7.8.1	Stokes and Anti-stokes Satellites.	187
		7.8.2	Using Raman Spectroscopy in Observations	190
	Refe	ences.		192
8	Wav	e Pheno	mena in Dense Conglomerate of Flux Tubes	193
	8.1	Propag	ation of MHD Waves in an Ensemble	
		of Clos	sely Packed Flux Tubes	193
		8.1.1	Basic Equations and Dispersion Relation	194
		8.1.2	Spacial Cases	199
	8.2	Dissipa	ative Processes	200
		8.2.1	Weakly Inhomogeneous Medium	201
		8.2.2	Medium with Moderate and Strong	
			Inhomogeneities	203
		8.2.3	Dissipation by Thermal Conduction	204
		8.2.4	Dissipation by Viscosity	206
		8.2.5	Total Dissipation Rate	207
	8.3	Anoma	alous Damping at Small Wavevectors	209
	8.4	Absor	ption of P-Modes by Sunspots and Active	
		Region	s-Observations	211
	8.5	The In	terpolation Formula and Comparison	
		with O	bservations	215
	Refe	rences		220

Contents

9	Nonli	near Wave Phenomena in Dense	Conglomerate	
	of Flu	1x Tubes		221
	9.1	Nonlinear Equations in Strongly I	nhomogeneous Medium	221
	9.2	Formation of Shocks Across Smal	I-Scale Inhomogeneities	225
		9.2.1 Validation of the Overtur	ning Condition	227
	9.3	Effect of Inhomogeneities on the	Dispersion Properties	
		of the System		228
		9.3.1 Basic Equations		228
		9.3.2 Dispersion Relation		230
		9.3.3 KdV—Bürgers' Equation	with Strong	
		Inhomogeneities		232
	9.4	Numerical Analysis		233
		9.4.1 The Model		233
		9.4.2 Formation of Shock Wav	es	234
		9.4.3 Energy Dissipation		236
	Refer	ences		239
10	Magr	netosonic Streaming		241
	10.1	Secondary Flows—Boundary Lay	er Effects	241
		10.1.1 Acoustic Streaming—His	tory and Nature	
		of Faraday's Effect	-	241
		10.1.2 Secondary Flows in Mag	netohydrodynamics	243
	10.2	Magnetosonic Streaming Due to t	he Action	
		of Ponderomotive Force		244
	10.3	Process of Filamentation and Diff	usive Vanishing	
		of Magnetic Flux Tubes		249
		10.3.1 Diffusive Broadening of	Flux Tube	250
		10.3.2 Quantitative Estimates—	Lifetimes and Spatial	
		Scales of Flux Tubes	•	252
	10.4	Generation of Mass Flows Due to	the Absorption	
		Mechanisms	•	254
	10.5	Numerical Analysis		257
		10.5.1 Basic Equations and Nun	nerical Method	258
		10.5.2 Numerical Results		259
	10.6	Intrinsic Nature of Flux Tube Fra	gmentation	263
	Refer	ences		265
11	Movi	ng Magnetic Features (MMFs)		267
	11.1	Types of MMFs and Their Observ	ved Properties	267
	11.2	Impossibility of the Origin of MN	1F's in Conservative	
		Systems.		269
		11.2.1 The Mechanism		271
	11.3	Nonlinear Kink and Its Evolution	in the Presence	
	•••	of Shear Flows.		272

	11.4	Soliton and Shocklike Formations Along the Flux	
		Tube—Numerical Studies	275
	11.5	Observations and Comparison with Theory	279
	11.6	Ouantitative Analysis	283
	11.7	Unification of Known Types of Moving Magnetic Features	287
	11.8	Impact of MMEs on the Overlying Atmosphere	290
	11.9	Anticorrelation Between Population of MMF's	220
		and Coronal Loop Formation	294
	Refer	ences	298
17	Deee	meeting of Flux Types - Specifics of High Discuss 0	200
14	Reco	nnection of Flux Tubes—specifics of High Plasma β	299
	12.1	Basics of Magnetic Reconnection	299
	12.2	Photospheric Reconnections—No Immediate	
		Gain in Energy	304
		12.2.1 Specifics of Photospheric Reconnections	305
		12.2.2 Flux Tubes Carrying Different Amount	
		of Magnetic Flux	308
		12.2.3 Number of Events—Importance of Noncollinearity	
		of Flux Tubes	311
	12.3	Dynamics of Post-reconnection Products	312
		12.3.1 Self-similarity of Solution	313
		12.3.2 Energy Analysis	315
		12.3.3 Transsonic Motion	316
	12.4	Dynamics of []-shaped Flux Tubes	317
	12.5	Dynamics of \cap -shaped Flux Tube	319
	Refer	ences	323
12	Dest	manufaction Processors Shooles Late and Microflance	225
15	POSI-	Kee Developities Observed in the Distory have Transition	525
	13.1	Regularities Observed in the Photosphere/Transition	225
	12.0	Region	325
	13.2	Post-reconnection Shocks and Hydromagnetic Cumulation	
		of Energy	328
		13.2.1 Head-On Convergence of Shock Fronts	329
		13.2.2 Energy Distribution Between Heat, Jet,	
		and Their Combinations	331
	13.3	Observation of Photospheric Reconnections	
		and Their Impact on Overlying Atmosphere	334
		13.3.1 Microflares, Jets, and Their Combinations	336
		13.3.2 Effects of Converging Supergranular Flows	339
	13.4	Key Elements of Energy Production and Observation	
		of Shocks	341

	13.5 13.6	Explosive Events	344
		of Unipolar Flux Tubes	348
	Refer	ences	350
14	Photo 14.1	Ospheric Network as Energy Source for Quiet Sun Corona Post-reconnection Processes in Arbitrarily Magnetized	351
		Environment	351
		14.1.1 Magnetic Loop Arcades in the Chromosphere14.1.2 Post-reconnection Shocks in Upper	352
	14.0	Atmosphere—Types and Characters	355
	14.2	Heights of Shock Formation.	338
	14.3	Energy Release in the Chromosphere-Transition Region	303
		14.3.1 Qualitative Analysis	267
	14.4	Magnetic Energy Avalanche and the East Solar Wind	368
	Refer	ences	371
	Refer		511
15	Resp	onse of the Corona to Magnetic Activity in Underlying	
	Plage	e Regions	373
	15.1	Magnetic Imprint of Plage Regions in the Corona	373
	15.2	Coronal Dynamics Above Unipolar and Mixed	
		Polarity Plages	375
	15.3	Properties of Braidlike Coronal Structures	378
	15.4	Comparison of Coronal Emission Above Mixed Polarity	
		and Unipolar Plages	381
	15.5	Energy Extraction Mechanisms from the Ensembles	
		of Photospheric Flux Tubes	385
		15.5.1 Mixed Polarity Plage	385
		15.5.2 Unipolar Plage	387
		15.5.3 N-Solitons	389
	Refer	ences	393
16	Elect	rodynamic Coupling of Active Region Corona	
	with	the Photosphere	395
	16.1	The Problem of Multiface Corona	395
	16.2	Emerging Magnetic Flux and Structure Formation	
		in Overlying Atmosphere	397
	16.3	Current Drive Mechanisms Associated with the Emerging	
		Magnetic Flux	403
		16.3.1 Proper Motion	404
		16.3.2 Acoustic Waves	404
		16.3.3 Alfvèn Waves	406

	16.4	Energy Flow Throughout Solar Atmosphere	408
		16.4.1 An Equivalent Circuit—Earlier Attempts	409
		16.4.2 LRC Circuit with Mutual Inductance	
		(Transition Region)	410
	16.5	Energetically Open Circuit	413
	16.6	Evolution of Current Systems	418
		16.6.1 Linear Regime	418
		16.6.2 Nonlinear Regime	419
	16.7	Quantitative Analysis	422
		16.7.1 Examples	423
	16.8	Limiting Currents and Filamentary Structures	426
	Refere	ences	432
17	Fine	Structure of Penumbrae: Formation and Dynamics	433
	17.1	Peculiarities of Sunspot Penumbrae—Observations	433
	17.2	Dynamics of Penumbral Filaments	
		and Ongoing Reconnections	437
	17.3	Formation of Filamentary Penumbrae	441
		17.3.1 Phenomenology of Basic Mechanism	442
		17.3.2 Filamentary Structure of Sunspot	443
		17.3.3 Properties of Individual Filaments	444
	17.4	Screw Pinch Instability and Dark Cores	446
		17.4.1 More on Substructures of Filaments	449
		17.4.2 Effects of Axial Flows	450
	Refer	ences	452
18	Bow	Shocks and Plasma Jetting over Penumbrae	455
	18.1	Response of the Overlying Atmosphere	
		to Penumbral Dynamics	455
		18.1.1 Penumbral Transients—Double Structures and Jets	456
		18.1.2 Viewing Under Different Angles	459
		18.1.3 Brief Summary of Properties	464
	18.2	Phenomenology and Quantitative Analysis	466
		18.2.1 Dynamics of \bigcup -shaped Filaments	467
		18.2.2 Nature of Double Structures	469
	18.3	Bow Shocks	470
	18.4	Energy Release and Lifetime of Bright Transients	473
	Refer	ences	477
19	Self-o	organization in the Corona and Flare Precursors	479
	19.1	Well-Organized Multithreaded Coronal Arcades–Slinkies	479
	19.2	Essential Difference Between "Regular"	
		and Slinky-Producing Flares	482
	19.3	Precursors and Predictability	488

	19.4	Exemplary Case of X-Class Flare and Formation	40.1
	10.5	OI Slinkles	491
	19.5	A national sector of Energy Build Op and Quantitative	405
	10.0	Analysis	495
	19.6	Recurrent Flares and Ecnoes	501
		19.6.1 Landau Damping, Memory, and Spatiotemporal	500
			502
		19.6.2 Echo Effects in Slinkies.	505
		19.6.3 Spatial and Temporal Recurrences in Flares	507
	Refer	ences	510
	~ .		
20	Quies	scent Prominences	513
	20.1	Background—Problem of Stability	513
	20.2	Large-Scale Observed Regularities	516
	20.3	Formation of Prominence Cavity and Helical Structures	521
		20.3.1 The Case of the 16 August 2007 Prominence	525
		20.3.2 Phenomenology of Cavity Formation	526
	20.4	Regular Series of Plumes—Multimode Regime	
		of Rayleigh–Taylor Instability	529
		20.4.1 Practical Use	530
	20.5	Fast-Growing Plumes—Nonlinear Regime	533
		20.5.1 Mushroom Formation	534
		20.5.2 Two-Bubble Competition	537
	20.6	Greenhouse-Like Effect	537
	Refer	ences	540
Ind	ex		543

xix