

Convection and Substorms

Paradigms of Magnetospheric Phenomenology

Charles F. Kennel

**Geophysical Institute
University of Alaska, Fairbanks**

**Institute of Geophysics and Planetary Physics
University of California, Los Angeles**

**New York Oxford
Oxford University Press
1995**

CONTENTS

1.	Introduction	1
1.1	Geomagnetism	1
1.2	The Discovery of the Solar Wind and the Magnetosphere	5
1.3	Viscous Convection	7
1.4	Reconnection-Driven Convection	10
1.5	Petschek Reconnection	11
1.6	Substorms	13
1.7	Overview	16
1.8	The Equilibrium Magnetosphere	17
1.9	The Convecting Magnetosphere	18
1.10	Auroral and Magnetospheric Substorms	22
2.	The Teardrop Magnetosphere	28
2.1	Introductory Remarks	28
2.2	The Teardrop Model	29
2.3	The Position and Shape of the Magnetopause	29
2.4	The Thickness of the Magnetopause Current Layer	32
2.5	The Position and Shape of the Bow Shock	33
2.6	The Failure of Weak-Field MHD and the "Plasma Depletion Layer"	35
2.7	Standing Slow and Intermediate Waves in the Magnetosheath	36
2.8	Summary	39
3.	The Bell-Like Magnetosphere	40
3.1	Introductory Remarks	40
3.2	Geomagnetic Pulsations	41
3.3	Coupling of Magnetopause Motions to Resonant Alfvén Waves	42
3.4	The Eigenmodes of the Magnetospheric Cavity	43
3.5	Observations of Standing Alfvén Waves	46
3.6	Occurrence and Distribution of Standing-Wave Harmonics	47
3.7	Observations of the Global Mode	49
3.8	Response of the Magnetosphere to Passing Solar Wind Structure	49
3.9	The Response of the Magnetosphere to Interplanetary Shocks	50
3.10	Magnetospheric Response to Solar Wind Tangential Discontinuities	51
3.11	Ionospheric Response to Sudden Pressure Variations in the Solar Wind	52
3.12	Quasiresonant Response to Solar Wind Pressure Pulses	53
3.13	Summary	55
4.	The Viscous Magnetosphere	57
4.1	Introductory Remarks	57
4.2	The Low-Latitude Boundary Layer	57

4.3	Field-Aligned Currents	60
4.4	The Ionospheric Footprint of the Low-Latitude Boundary Layer	62
4.5	Micropulsations Associated with the Kelvin-Helmholtz Instability	64
4.6	Vortex Auroras	66
4.7	Vortex Structures in the Plasma Sheet	67
4.8	The Boundary Layer in the Magnetospheric Tail	68
4.9	Boundary Layer Transport	69
4.10	Summary	70
5.	The Reconnecting Magnetosphere	73
5.1	Introductory Remarks	73
5.2	The Polar Rain	74
5.3	The Polar Wind	75
5.4	The Auroral Oval	76
5.5	The Plasmasphere	78
5.6	Direct Evidence for Dayside Magnetopause Reconnection	78
5.7	Precipitation of Magnetosheath Plasma into the Dayside Ionosphere	80
5.8	Direct Entry of Solar Wind Plasma into the Magnetotail	82
5.9	Convection across the Tail Lobes	86
5.10	Average Tail Reconnection Region	87
5.11	Stratification of the Plasma Sheet Boundary Layer	89
5.12	The Length of the Earth's Magnetic Tail	91
5.13	Interaction of the Two Convection Systems in the Ionosphere	91
5.14	Comparison of Viscosity- and Reconnection-Driven Transport	93
5.15	Discussion	95
6.	Correlation of Geomagnetic Activity with the Solar Wind	96
6.1	Introductory Remarks	96
6.2	Correlation of Geomagnetic Activity with the Interplanetary Magnetic Field	97
6.3	Dependence of the Convection Rate upon the Interplanetary Field	100
6.4	Dependence of the Polar Cap Convection Pattern upon the Interplanetary Field	102
6.5	Dependence of Field-Aligned Currents upon the Interplanetary Field	103
6.6	Time-Dependent Response to the Changing Interplanetary Field	103
6.7	The Viscous Component of Geomagnetic Activity	105
6.8	Summary	106
7.	The Reconnection Substorm	107
7.1	Introductory Remarks	107
7.2	Changes in Magnetopause Position during Substorm Growth Phase	108
7.3	Changes in the Geomagnetic Tail during Substorm Growth Phase	109
7.4	Development of Ionospheric Convection during Growth Phase	112
7.5	Development of Dayside Magnetospheric Convection During Growth Phase	113
7.6	Stimulation of Convection in the Tail Lobes	113
7.7	The "Nearer-Earth Neutral Line" Scenario	116
7.8	Observational Basis of the Nearer-Earth Neutral Line Model	117
7.9	Plasmoids	120
7.10	Traveling Compression Regions	122
7.11	Plasmoid and TCR Timing	123
7.12	Discussion	125

8.	Bursty Magnetopause Reconnection	127
8.1	Introductory Remarks	127
8.2	Bursts of Energetic Electrons and Ions near the Magnetopause	128
8.3	Flux Transfer Events	129
8.4	Locations of Reconnection Events Generating FTEs	131
8.5	The FTE Contribution to the Overall Convection Potential	132
8.6	Ionospheric Signatures of Impulsive Magnetopause Reconnection	132
8.7	Cusp-Region ULF Waves	135
8.8	Alfvén Waves at the Equatorward Boundary of the Active Cusp	135
8.9	Ion Energy–Latitude Dispersion on Polar Cusp Field Lines	138
8.10	Bursty Ionospheric Flow Events	139
8.11	Transient Dayside Aurora	141
8.12	F-Region Density Patches	143
8.13	Summary	145
9.	Bimodal Plasma Sheet Flow	150
9.1	Introductory Remarks	150
9.2	The Plasma Sheet Pressure Paradox	152
9.3	Statistical Properties of Plasma Sheet Transport	153
9.4	Bursts of Plasma Sheet Flow during Steady Solar Wind Conditions	156
9.5	Bursty Bulk Flow Events	157
9.6	Bimodal Plasma Sheet Flow	158
9.7	High-Speed Flows at Quiet Times	159
9.8	High-Speed Flows and Flux Ropes	160
9.9	High-Speed Flows, Plasmoids, Flux Ropes, and TCRs in the Distant Tail	161
9.10	Dependence of BBF/Plasmoid Properties upon Distance Downtail	162
9.11	Energetic Particle Bursts in the Midtail	164
9.12	Ion Bursts, High-Speed Flows, Boundary Layer Activations, and Bursty Reconnection	166
9.13	East–West Localization of BBF/Plasmoid/Particle Burst Generation Region	167
9.14	Tail Lobe Filaments	168
9.15	Flow Bursts in the Nightside Auroral Ionosphere	170
9.16	The Ionospheric Footprints of Bursty Bulk Flow Events	171
9.17	Comparison of FTE and BBF Flux Transfers	172
9.18	Synthesis	173
10.	Convection for Northward Interplanetary Field	177
10.1	Introductory Remarks	177
10.2	Response of Pre-Existing Polar Cap Convection to Northward Field Shifts	180
10.3	Reconnection of Interplanetary and Tail-Lobe Field Lines	181
10.4	Signatures of Tail-Lobe Reconnection in Polar Orbit	181
10.5	Reverse Convection in the Polar Cap	182
10.6	Field-Aligned Currents	183
10.7	Seasonal and Day–Night Asymmetries of Polar Cap Convection	184
10.8	Global View of Polar Cap Aurora	185
10.9	Ground-Based View of Sun-Aligned Aurora	186
10.10	Evidence that Some Transpolar Arcs Are on Closed Field Lines	187
10.11	Relation between Sun-Aligned Arcs and Convection	188
10.12	Shrinkage of Tail Lobes in Northward Field Conditions	190
10.13	Evolution of Polar Cap Aurora during a Prolonged Northward Field Interval	190

10.14	Polar Cap Convection in Conditions of the Most Extreme Geomagnetic Quiet	191
10.15	Discussion	192
11.	The Nightside Auroral Oval	196
11.1	Introductory Remarks	196
11.2	Magnetic Field Mapping	201
11.3	Dependence of the Auroral "Oval" upon Geomagnetic Activity	202
11.4	Inherent Uncertainty in Mapping the Poleward Aurora	203
11.5	The Diffuse Aurora	204
11.6	Inverted Vs	205
11.7	Auroral Arcs	207
11.8	Diffuse and Discrete Aurora and their Relationship to Field-Aligned Currents	208
11.9	Arc Occurrence and the Interplanetary Field	209
11.10	The Harang Discontinuity	209
11.11	The Relationship between Arcs and Ionospheric Convection	210
11.12	The Relationship between Arcs and Inverted Vs	211
11.13	Ground Observations of Arcs at the Poleward Border of the Auroral Oval	212
11.14	The Poleward Border of the Oval and the Plasma Sheet Boundary Layer	213
11.15	Auroral Kilometric Radiation and the Poleward Aurora	214
11.16	Physical Mapping of the Nightside Oval into the Plasma Sheet	217
11.17	Conjugacy	218
11.18	Concluding Remark	219
12.	The Auroral Substorm	221
12.1	Introductory Remarks	221
12.2	Growth Phase in the Polar Cap	222
12.3	Growth Phase around the Auroral Oval	223
12.4	Classical Evening Sector Growth Phase	225
12.5	Pseudoeexpansions	228
12.6	Precursors to Onset	229
12.7	Onset	230
12.8	Relation of Onset Arc to Other Auroral Oval Structures	231
12.9	The Westward Surge	232
12.10	The Expanding Auroral Bulge	235
12.11	Fine Structure of the Substorm Expansion	236
12.12	Proton Aurora Substorm	236
12.13	The Phases of the Auroral Substorm	238
12.14	The Relationship between the Auroral Bulge and the Poleward Aurora	239
12.15	Activity in the Poleward Arc System	241
12.16	Equatorward Auroral Activity during the Recovery Phase	243
12.17	The End of the Recovery Phase	245
12.18	Synthesis	246
13.	The Geosynchronous Substorm	248
13.1	Development of a Tail-Like Field during the Growth Phase	248
13.2	How Thin Does the Current Sheet Get?	250
13.3	Dipolarization	252
13.4	Dispersionless Injections	253
13.5	The Substorm Current Wedge	254
13.6	Pi 1 and Pi 2 Pulsations and the Timing and Location of Substorm Onset	256
13.7	Generation of Midlatitude Pi 2	258
13.8	Azimuthal Propagation of Dipolarization near Geostationary Orbit	259
13.9	Size of Initial Dipolarization Region	261

13.10	Radial Propagation of Dipolarization	263
13.11	Plasmoids Escaping from the Geostationary Region	264
13.12	Plasma Sheet Dropouts in the Post-Geosynchronous Region	265
13.13	Plasma Sheet Recoveries in the Postgeosynchronous Region	268
13.14	Summary	269
14.	Coordination of the Geosynchronous and Auroral Substorms	272
14.1	Introductory Remarks	272
14.2	The Auroral Expansion and Dipolarization	273
14.3	The Westward Surge and Dipolarization	275
14.4	Multiple Surge Intensification and Oscillatory Dipolarization	276
14.5	Dipolarization and Poleward Arc Brightening	277
14.6	Dependence of Plasma Composition on Solar and Geomagnetic Activity	278
14.7	Dependence of Plasma Sheet Composition on Auroral Activity	279
14.8	Injection of O ⁺ into the Plasma Sheet during Substorm Expansion Phase	280
14.9	Variation of O ⁺ in the Geosynchronous Region During Substorms	281
14.10	Discussion	281
15.	Triggered Substorms	284
15.1	Introductory Remarks	284
15.2	Pseudo-Expansions	284
15.3	Triggering by Interplanetary Shocks and Other Compressions	286
15.4	Triggering by Northward Shifts of the Interplanetary Field	289
15.5	Quasiperiodic Substorm Recurrence	290
15.6	Summary and Discussion	292
16.	On the Relation between Convection and Substorms	294
16.1	Introductory Remarks	294
16.2	Magnetopause Reconnection and the Stimulation of Dayside Convection	297
16.3	The Stimulation of Convection in the Tail	299
16.4	Multiple Tail Reconnection Events	300
16.5	Relation between Auroral and Geosynchronous Substorms	301
16.6	Ambiguity of Plasmoid Timing	303
16.7	Substorms with Two Active Phases	305
16.8	Plasma Sheet Recovery, Plasmoid Formation, and Activation of the Poleward Arcs	306
17.	Epilogue	309
	References	311
	Index	403