

---

# Contents

<b>1</b>	<b>Complex Plasma – Why It Is an Unusual State of Matter?</b>	<b>1</b>
1.1	General Physical Differences Between Complex Plasma and Ordinary Matter .....	1
1.2	General Terminology in Complex Plasma and Ordinary Matter .....	3
1.3	History: Complex Plasmas in Space Physics.....	4
1.4	Problems of Strong Coupling in Plasmas .....	6
1.4.1	Phase Space for Strong Coupling in Ordinary Plasmas ..	6
1.4.2	Physics and Consequences of Large Grain Charges.....	9
1.4.3	Physics and Consequences of Dust Charge Screening ...	11
1.4.4	Phase Space for Strong Coupling in Complex Plasmas .	14
1.5	Openness of Complex Plasma Systems and Long-range Collective Interactions .....	16
1.5.1	Variability of Grain Charges .....	16
1.5.2	Openness of Complex Plasma Systems .....	18
1.5.3	Long-range Unscreened Grain Interactions .....	22
1.6	Plasma Condensation .....	23
1.6.1	First Observations of Plasma Condensation .....	23
1.6.2	Grain Interactions .....	26
1.7	Special Aspects of Complex Plasma Investigations .....	27
1.7.1	Kinetic Level for Dust Investigation in Experiments ...	27
1.7.2	Obstacles in Complex Plasmas .....	30
1.7.3	Interactions of Grain Clouds and Fast Grains with Plasma Crystals .....	32
1.8	Structures and Self-organization in Complex Plasmas .....	36
1.8.1	Observations of Structures in Complex Plasmas .....	36
1.8.2	Self-organization in Complex Plasmas .....	39
1.9	Outlook of the Subsequent Presentation .....	41
	References .....	42

<b>2 Why Complex Plasmas Have Many Applications in Future Technology?</b>	47
2.1 Main Discoveries in Applications of Complex Plasmas . . . . .	47
2.2 Computer Technology . . . . .	48
2.2.1 Simple Principles Used in Computer Technology . . . . .	48
2.2.2 Investigation of Dust Clouds in Etching Devices . . . . .	49
2.3 First Steps to Using Complex Plasma Properties in Computer Industry . . . . .	52
2.3.1 New Laboratory Experiments in Complex Plasmas Inspired by Computer Technology Problems . . . . .	53
2.4 New Surfaces, New Materials . . . . .	54
2.4.1 New Surfaces . . . . .	54
2.4.2 New Materials . . . . .	55
2.4.3 New Magnetic Materials . . . . .	56
2.5 New Energy Production . . . . .	57
2.5.1 Necessity of New Energy Sources . . . . .	57
2.5.2 Controlled Fusion Devices . . . . .	58
2.5.3 Table Size Fusion and Neutron Sources . . . . .	61
2.5.4 Solar Cells . . . . .	62
2.6 Environmental Problems . . . . .	62
2.6.1 Dust is Found Everywhere . . . . .	62
2.6.2 Global Warming . . . . .	63
2.6.3 Noctilucent Clouds . . . . .	63
2.6.4 The Ozone Layer . . . . .	64
2.6.5 Industrial Emissions and Car Exhausts . . . . .	64
References . . . . .	65
<b>3 Elementary Processes in Complex Plasmas</b> . . . . .	67
3.1 Screening of Grain Field in a Plasma . . . . .	67
3.1.1 Elementary Estimates . . . . .	67
3.1.2 Linear Debye Screening . . . . .	69
3.1.3 Non-linear Screening . . . . .	71
3.1.4 Problems to Solve in Grain Screening . . . . .	79
3.2 Charging of Grains in Partially Ionized Plasma . . . . .	86
3.2.1 Introductory Remarks . . . . .	86
3.2.2 Equation for Micro-particle Charging . . . . .	86
3.2.3 Orbital Motion Limited Model . . . . .	88
3.2.4 Extensions of OML Approach . . . . .	93
3.2.5 Role of Potential Barriers in Non-linear Screening for Grain Charging . . . . .	102
3.2.6 Radial Drift Limited Model . . . . .	106
3.2.7 Diffusion Limited Model . . . . .	109
3.2.8 Problems for Modeling of Grain Charging . . . . .	110
3.3 Forces Acting on Ions . . . . .	114
3.3.1 Absorption of Ions on Grains. The Charging Coefficient	114

3.3.2	Friction of Ions in Gas of Grains. The Drag Coefficient .	117
3.3.3	Other Forces Acting on Ions .....	122
3.4	Forces Acting on Grains .....	124
3.4.1	Ion Drag and Electric Field Forces.....	125
3.4.2	Temperature Gradients and Thermophoretic Force.....	127
3.4.3	Neutral Gas Drag force, Gravity force, and Dust Inertia .....	130
3.5	Forces Acting on Electrons: Characteristic Electric Fields .....	132
3.5.1	Electron Friction in Absorbing Collisions with Grains and Electron Inertia .....	132
3.5.2	Balance of Forces for Electrons .....	134
3.5.3	Electric Fields and Condition for Quasi-neutrality .....	135
	References .....	137
<b>4</b>	<b>Collective Effects in Complex Plasmas .....</b>	<b>141</b>
4.1	Collective Linear Modes .....	141
4.1.1	Dispersion Relations for Low Frequency Modes.....	141
4.1.2	Basic State of Complex Plasmas.....	144
4.1.3	Dispersion Relation for DISW.....	146
4.1.4	Dispersion Relation for DAW .....	150
4.2	Universal Instability of a Complex Plasma .....	153
4.2.1	Instability in the Range of DISW .....	153
4.2.2	Instability in the Range of DAW .....	154
4.2.3	Instability Stabilization in the Range of DAW .....	155
4.2.4	Physics of the Instability .....	156
4.2.5	Instability Rates .....	158
4.2.6	Effects of Finite Size .....	161
4.2.7	Electrostatic Gravitational-like Instability and Modes in Plasma Clusters .....	162
4.2.8	Complex Plasma Structurization .....	164
4.3	Collective Modes Excited by Fast Particles .....	165
4.3.1	Mach Cones: General Remarks and the Cone Angle .....	165
4.3.2	Wave Intensity and Distribution of Wavelengths .....	166
4.3.3	Wave Excitation by Outside Particles Moving near Boundary .....	167
4.4	Observations of Collective Modes .....	168
4.4.1	Introductory Remarks .....	168
4.4.2	Experimental Observations of DISW .....	169
4.4.3	Experimental Observations of DAW .....	177
4.5	Problems to be Solved for Collective Modes .....	183
4.5.1	Structurization Instability and the Finite System Effects .....	183
4.5.2	Surface Waves .....	183
4.5.3	Induced Processes for Collective Modes .....	183
4.5.4	Collective Modes in the External Magnetic Field .....	184

4.5.5	Instabilities in Complex Plasmas . . . . .	184
4.5.6	Non-linear Responses . . . . .	184
4.5.7	Strong Non-linearities and Modulational Interactions . .	184
4.5.8	Kinetic Description of Collective Modes . . . . .	185
4.6	Fluctuations, Collective Pair Interactions, and Pair Correlation Functions . . . . .	185
4.6.1	Relations between Various Fluctuations . . . . .	185
4.6.2	Correlation Functions . . . . .	187
4.6.3	Zero Fluctuations and Collective Pair Interactions of Grains . . . . .	188
4.6.4	Dust Non-collective Charge Fluctuations . . . . .	189
4.6.5	Charge Fluctuations Induced by Dust Fluctuations . .	193
	References . . . . .	193
<b>5</b>	<b>Micro-particle Collective and Non-collective Pair Interactions . . . . .</b>	<b>197</b>
5.1	General Properties of Micro-particle Pair Interactions . . . . .	197
5.1.1	Grain Pair Interactions in Crystals and Clusters . . . . .	197
5.1.2	Two Grains: Electrostatic Energy and Interaction Forces . . . . .	200
5.1.3	Role of Openness of Complex Plasma Systems . . . . .	202
5.1.4	Pair Interaction and Non-linearity in Screening . . . . .	203
5.2	Shadow Non-collective Attraction Forces . . . . .	205
5.2.1	Shadow Attraction Created by Ion Flux . . . . .	205
5.2.2	Shadow Attraction Created by Neutral Flux . . . . .	210
5.2.3	Agglomeration of Grains . . . . .	212
5.2.4	Problems of Non-collective Grain Attraction . . . . .	213
5.3	Collective Attraction for Linear Screening . . . . .	215
5.3.1	Collective Attraction in the Limit $\beta \ll 1$ . . . . .	215
5.3.2	Physics of Collective Attraction . . . . .	217
5.3.3	Attraction of Finite Size Grains . . . . .	218
5.3.4	Natural Boundary Conditions . . . . .	220
5.3.5	Limiting Expressions for Collective Attraction . . . . .	222
5.3.6	Attraction in an Ion Flow for $\beta \ll 1$ . . . . .	224
5.3.7	Attraction in a Magnetic Field for $\beta \ll 1$ . . . . .	225
5.4	Collective Interactions for Non-linear Screening . . . . .	227
5.4.1	Collision-dominated Case $\beta \gg 1$ . . . . .	227
5.4.2	Ionization Proportional to Electron Density . . . . .	228
5.4.3	General Properties of Non-linear Collective Attraction .	231
5.5	Measurements of Screened Potential in Grain-grain Collisions .	234
5.5.1	Experimental Technique . . . . .	234
5.5.2	Collision Experiments . . . . .	236
5.5.3	Problems for Future Experiments . . . . .	242
	References . . . . .	243

<b>6 Experiments on Plasma Crystals and Long-range Correlations .....</b>	247
6.1 Plasma Crystals .....	253
6.1.1 Crystal Structures Observed .....	253
6.1.2 Observational Techniques .....	256
6.1.3 Structure of Crystals .....	258
6.1.4 Dislocations and Defects .....	268
6.2 Melting and Phase Transitions .....	270
6.2.1 General Description of Phase Transitions .....	270
6.2.2 Phenomenological Description .....	271
6.2.3 Translational and Orientational Order .....	274
6.2.4 Dust Grain Temperatures .....	275
6.3 Paradigms for Plasma Crystal Formation .....	277
6.3.1 Applicability of New Paradigms .....	277
6.3.2 Paradigms for Crystal Formation .....	279
6.3.3 Van der Waals Equations and Collective Interactions ..	281
6.4 Inspiration from Experiments .....	285
References .....	286
<b>7 Mono-layer Plasma Crystals and Clusters .....</b>	289
7.1 Mono-layer Plasma Crystals .....	289
7.1.1 Specific Properties of Mono-layers .....	289
7.1.2 Theory of 2D Dust-lattice Waves .....	293
7.1.3 Experiments on 2D Dust-lattice Waves .....	295
7.1.4 Stimulated Plasma Crystal Sublimation .....	299
7.1.5 Theory of Dust Bending Waves .....	300
7.1.6 2D Dust Shear Waves .....	302
7.1.7 2D Dust-lattice Wave Mach Cones .....	303
7.2 2D Plasma Clusters .....	305
7.2.1 Introductory remarks .....	305
7.2.2 Experiments on Small and 2D Clusters .....	307
7.2.3 Observations and Ordering Rules .....	309
7.2.4 Theory of 2D Clusters .....	314
7.2.5 Boundary-free 2D Clusters .....	320
7.2.6 Numerical Simulations of Boundary-free Clusters ..	326
References .....	330
<b>8 Comments on Other Dust Structures: Concluding Remarks .....</b>	333
8.1 Dust Helical Clusters .....	333
8.1.1 General Remarks .....	333
8.1.2 MD Simulations and Analytical Results .....	335
8.1.3 Problems to Solve .....	336
8.2 Disordered Grain Structures .....	337
8.2.1 Role of Plasma Fluxes .....	337

## XIV    Contents

8.2.2	Structures in Disordered States .....	338
8.2.3	General Features of Disordered Structures .....	341
8.2.4	Dust Void Problems .....	345
8.2.5	Problems for Future Investigations.....	348
8.3	Dust Wall Sheaths.....	349
8.3.1	General Remarks .....	349
8.3.2	Collisionless Dust Wall Sheaths .....	350
8.3.3	Further Problems of Dust Wall Sheath Studies .....	352
8.4	Dust Structures between Walls .....	353
8.4.1	Collision-Dominated Single Flat Layer .....	353
8.4.2	Other Structures between Electrodes.....	354
8.4.3	Problems for Future Research .....	354
8.5	Dust Convection in Structures .....	355
8.5.1	General Remarks .....	355
8.5.2	Problems to Solve .....	357
8.6	Hybrid Dust Structures .....	357
8.7	Micro-gravity Experiments .....	359
8.8	Future Research: Outlook for Complex Plasmas .....	360
8.9	Conclusion .....	362
	References .....	362
<b>Index</b>	.....	365