

UNITEXT for Physics

Giovanni Carraro

Astrophysics of the Interstellar Medium

This book is based on a series of lectures for an Astrophysics of the Interstellar Medium (ISM) master's degree in Astrophysics and Cosmology at Padova University.

From the cold molecular phase in which stars and planetary systems form, to the very hot coronal gas that surrounds galaxies and galaxy clusters, the ISM is everywhere. Studying its properties is vital for the exploration of virtually any field in astronomy and cosmology. These notes give the student a coherent and accurate mathematical and physical approach, with continuous references to the real ISM in galaxies.

The book is divided into three parts. Part One introduces the equations of fluid dynamics for a system at rest and acoustic waves, and then explores the real ISM through the role of thermal conduction and viscosity, concluding with a discussion of shock waves and turbulence. In Part Two, the electromagnetic field is switched on and its role in modulating shock waves and contrasting gravity is studied. Part Three describes dust and its properties, followed by the main stellar sources of energy. The last two chapters respectively address the various components of the ISM and molecular clouds and star formation.

ISBN 978-3-030-75295-8



9 783030 752958

► [springer.com](https://www.springer.com)



1	Fundamental Equations for Ideal Fluids	1
1.1	Introduction: Fluids as Continuous Systems	1
1.2	Continuity Equation	6
1.3	Volume Forces and Surface Forces. Stresses	8
1.4	Equation of Motion (Euler Equation) for Ideal Fluids	11
1.5	Conservation of Total Energy and Thermal Energy	12
1.6	Vorticity in Ideal Fluids. Potential Motion	14
1.7	Numerical Solutions of Hydrodynamical Equations	18
1.8	Synthetic Summary	19
2	Acoustic Waves	21
2.1	Acoustic Waves in an Ideal Fluid at Rest	21
2.2	Velocity of Propagation in a Dispersive Medium	25
2.3	Acoustic Waves in a Patchy Medium at Rest	27
2.4	Acoustic Waves in a Gravity-Dominated Medium	28
2.5	Virial Theorem	31
2.6	Gravitational Collapse of a Sphere	33
2.7	Synthetic Summary	34
	Appendices	35
	References	41
3	Real Fluids	43
3.1	Transport Phenomena	43
3.2	Thermal Conduction	44
3.3	Internal Friction	46
3.4	Navier–Stokes Equation	48
3.5	Energy Dissipation by Internal Friction	50
3.6	Energy Balance in a Real Fluid	51
3.7	Integration of Equations for a Real Fluid	53
3.8	Case of Fluid with Low Viscosity	55
3.9	Similar Motions	58
3.10	Synthetic Summary	59

Appendix	61
References	64
4 The Interstellar Medium	65
4.1 Thermal Balance of Interstellar Gas	65
4.2 Thermodynamic State of Interstellar Gas	69
4.3 Cooling Processes	70
4.4 Heating Processes	75
4.5 Thermal Instability	78
4.6 Synthetic Summary	83
References	84
5 Shock Waves	85
5.1 Supersonic Motion and Discontinuity	85
5.2 Jump Conditions	88
5.3 Shock Waves	91
5.4 Rankine–Hugoniot Conditions for an Ideal Gas	93
5.5 Shock Waves in the Interstellar Medium	96
5.6 Isothermal Shock: Schematic Discussion	98
5.7 Structure of the Relaxation Layer	101
5.8 Observability of Radiative Shocks	102
5.9 Synthetic Summary	104
Appendix	106
Reference	109
6 Turbulence	111
6.1 Experimental Aspects of Turbulence	111
6.2 Stability of Stationary Motion and Turbulence Onset	112
6.3 Notes on the Statistical Description of Turbulence	117
6.4 General Characteristics of Turbulence	121
6.5 Kolmogorov's Theory	122
6.6 Turbulence of the Interstellar Medium	126
6.7 Synthetic Summary	132
References	134
7 Electrodynamics and Magnetohydrodynamics	135
7.1 Plasmas. Debye Screening Length	135
7.2 Plasma Oscillations	138
7.3 A Note on Systems of Measurement Units	141
7.4 Maxwell's Equations	143
7.5 Magnetic Field Equation	146
7.6 Freezing of the Magnetic Field Lines of Force	146
7.7 The Galactic Magnetic Field: Origin and Methods of Measure	150
7.8 Synthetic Summary	151
Appendix	153

8	Motion of a Plasma in a Magnetic Field	157
8.1	Expressions of Magnetic Force	157
8.2	Fundamental Equations of Magnetohydrodynamics	159
8.3	Motion of a Plasma with Respect to Magnetic Lines of Force	161
8.4	Virial Theorem	163
8.5	Application of the Virial Theorem	164
8.6	Ambipolar Diffusion	168
8.7	Synthetic Summary	172
	Appendices	173
9	Magnetohydrodynamic Waves	179
9.1	Classification of MHD Waves	179
9.2	Alfven Waves	181
9.3	MHD Waves: General Discussion	183
9.4	MHD Waves with Generic Propagation Direction	186
9.5	Waves with Particular Direction of Propagation	188
9.6	Alfven Waves Attenuation	190
9.7	Excitation of MHD Waves	193
9.8	Magnetohydrodynamic Shock Waves	194
9.9	Synthetic Summary	198
	Appendices	199
10	Dust from the Interstellar Medium	207
10.1	Introduction	207
10.2	The Extinction of Radiation	208
10.3	Observational Determination of Stellar Extinction	210
10.4	The Extinction Curve of the Diffuse Medium in the Galaxy	211
10.5	Methods for Determining R_V	212
10.6	The Equilibrium Temperature of the Grains	215
10.7	The Temperature of the Small Grains	217
10.8	IR Emission of Galaxies	220
10.9	Synthetic Summary	221
11	HII Regions	223
11.1	Introduction	223
11.2	Ionisation Balance	224
11.3	Energy Balance and Temperature of an HII Region	228
11.4	The Strömgren Sphere	231
11.5	Effect of Dust on the HII Region	232
11.6	Evolution of the HII Region in a Homogeneous Medium	235
11.7	Classification of Ionization Fronts	237
11.8	HII Region Expansion	240
11.9	End of Expansion	243
11.10	Expansion of an HII Region in an In-Homogeneous Medium	246

11.11	Radio Frequency Emission	246
11.12	Infrared Emission	249
11.13	Calculation of the Lines of the Balmer Series	250
11.14	HII Regions Excited by a Cluster	251
11.15	Synthetic Summary	253
	Reference	253
12	Stellar Winds	255
12.1	Introduction	255
12.2	Classification of Winds	258
12.3	Structure and Evolution of a Bubble Produced by a Strong Wind	261
12.4	A Simplified Model for the Radiative Phase	264
12.5	Evolution in Phase D	267
12.6	Observations of the Bubbles	268
12.7	Evolution of the Bubble in an In-Homogeneous Medium	269
12.8	Synthetic Summary	271
	Appendices	271
	References	275
13	Supernovae Remnants	277
13.1	Supernovae	277
13.2	SNR Evolution	278
	13.2.1 Expansion End	284
13.3	Expansion of a SNR in a Patchy Medium	285
	13.3.1 Magnetic Field	288
	13.3.2 Relativistic Particles	288
	13.3.3 Spherical Symmetry	288
13.4	Models of Evolution in a Patchy Medium	289
13.5	Effects of a SNR on the Interstellar Medium	292
13.6	Superbubbles and Supershells	293
13.7	Description of some SNRs	297
13.8	Synthetic Summary	298
	References	298
14	The Interstellar Medium and Its Components	299
14.1	The Structure of the Interstellar Medium	299
14.2	Neutral Gas Diagnostic Techniques: The Line at 21 cm	301
14.3	The Spiral Structure of the Milky Way	304
14.4	Ionized Gas Diagnostic Techniques	305
	14.4.1 Dispersion of Pulsar Signals	306
	14.4.2 Recombination Optical Emission	309
	14.4.3 Absorption at Low Radio Frequencies	310
14.5	The Hot Component: Coronal Gas	310
14.6	The Cold Neutral Component: The Clouds of HI.	312
14.7	The Warm Neutral Component	313

14.8	Synthetic Summary	315
	Appendix	315
	References	318
15	Molecular Clouds	319
15.1	Detection of Molecular Gas	319
15.2	Correlation Between CO Emission and Molecular Gas Mass	321
15.3	The Distribution of H ₂ in the Galaxy	323
15.4	Distribution of H ₂ in Other Galaxies	325
15.5	Clouds Classification and Statistical Properties	325
15.6	Mechanical Equilibrium of Molecular Clouds	328
15.7	Why the Clouds Where Stars Form Are Molecular?	332
15.8	Mechanisms of Molecular Cloud Formation	334
15.8.1	Formation of Clouds by the Compression of Ambient Gas Induced by Shock Waves	334
15.8.2	Cloud Formation by Agglomeration of Smaller Clouds.	335
15.8.3	Cloud Formation Through Medium Instability	336
15.8.4	Summary	339
15.9	Synthetic Summary	339
	Appendix	340
	References	340
16	Star Formation	341
16.1	Observational Data Related to Star Formation	341
16.2	Star Formation in the Presence of a Magnetic Field	346
16.3	The formation of Low-Mass Stars	347
16.4	Low-Mass Star Formation Scenario	348
16.5	Observational Findings	351
16.6	Synthetic Summary	356