Cosmic Electrodynamics

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Electrodynamics and Magnetic Hydrodynamics of Cosmic Plasmas

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Preface

Astrophysics is a highly important part of the modern vision of the world around us. Over the past century, it has transformed the very foundation and basic philosophical concepts on the fundamental laws of nature controlling the structure and evolution of the Universe. One can recall such fascinating astrophysical discoveries as the expansion of the Universe and more recently the accelerated expansion; dark matter and dark energy and so on. This is why astrophysics is studied in hundreds of universities throughout the world; astrophysical courses are taken by students with highly diverse backgrounds, often concentrating on disciplines lacking a direct connection to astrophysics.

This textbook considers primarily those astrophysical and space plasma phenomena, in which electromagnetic interactions play a primary or at least essential role. This textbook has been written based on graduate and undergraduate courses and seminars on "cosmic electrodynamics," "magnetohydrodynamics," "plasma astrophysics," and "radiative processes in astrophysics" that the authors have taught to many generations of students at State Polytechnic University (St. Petersburg, Russia) and New Jersey Institute of Technology (Newark, New Jersey, USA), cumulatively, over more than half a century, in conjunction with the authors' astrophysical studies in the field of theoretical astrophysics, including plasma astrophysics, cosmic rays, solar wind, solar flares, supernova remnants, performed mainly at the above universities, Ioffe Institute (St. Petersburg, Russia), and National Radio Astronomy Observatory (Charlottesville, Virginia, USA). Jointly, we have a long history of teaching these sciences in Russia and the USA, and at some point we felt more and more strongly a deficit of appropriate textbooks to teach our students, which led us to substitute journal papers for use in teaching. We know that many of our colleagues teaching these courses experience similar feelings, so we decided to convert our research and teaching experience to a modern, concise textbook on cosmic electrodynamics and magnetohydrodynamics.

A driver of the textbook writing was, therefore, our willingness to share our teaching experience with our peers and supply them with a textbook representing a core, self-contained reading source, much needed to facilitate delivering undergraduate and graduate courses to students concentrating in the field of astrophysics, solar/stellar Physics, and space physics. The field of cosmic electrodynamics is exceptionally broad, which implies that there is no hope to describe this science field fully and comprehensively within a single textbook. Therefore, it is highly important to clearly formulate the concept of material selection and the approach to depth of presentation.

First of all, we are going to make the case that modern cosmic electrodynamics is a science dealing with a highly nonlinear, nonstationary, turbulent conducting fluid (plasma) in conditions of strong energy release manifesting itself in fast fluid motions, strong magnetic field amplification, and energetic particle generation. We made an attempt to sort out and include only a "fundamental" theory, although not necessarily the "old" one: in many cases we include relatively recent discoveries and developments if we had a good reason to believe that they are reliable and potentially broadly applicable or science transforming.

Furthermore, in application of the theory we restricted ourselves in most cases to analytical solutions of the specific problems discussed: it is the analytical solutions and order-of-magnitude estimates made with them that develop our understanding of sophisticated natural phenomena. Even though we fully appreciate numerical methods and corresponding results and widely use them in our everyday research, we believe that analytical study (solutions and estimates) is the key in developing students' physical understanding and intuition, which is needed to create the science vision, to dig up what is hidden behind observations, and, in particular, to set up sophisticated numerical simulations as well as sort out and interpret their results.

The textbook presents fundamental concepts of the science illustrated by numerous examples of astrophysical applications of the theory. In doing so we try to combine classical concepts with their new developments and clearly demarcate what is well established and what is still under debate. We attempt to present the live science and illustrate how apparently complicated phenomena can be addressed and understood both qualitatively and quantitatively using well-known physics principles and equations applied under appropriate approximations and simplifications. For this purpose a limited number of astrophysical examples are considered in greater detail than it might be expected for most textbooks. In many cases we specifically address the points of agreement or disagreement between the theory and astrophysical observations, employing the latest observational data and modern theory.

The textbook delivers the most essential equations, ideas, and models widely used in modern astrophysics (see the chapter titles as a guide) in the order of increasing complexity of the material: it begins with basic concepts and linear processes including linear eigenmodes (Chaps. 1–3), then considers instabilities, weak and strong nonlinearity, and turbulence (Chaps. 4–6), and finally addresses key astrophysical problems of particle acceleration and transport, magnetic field generation, and electromagnetic radiation including self-consistent nonlinear models (Chaps. 7–12). Later chapters extensively use the material given in earlier chapters. We tried to avoid the opposite cross-referencing of later chapters, but it was not always possible, which once again illustrates that various astrophysical phenomena are tightly connected. Many topics are presented with a full theoretical completeness, although in other cases derivations are truncated or fully omitted depending on the availability of the required theory in complementary reading on the subject (Melrose 1980; Kulsrud 2005; Somov 2006, 2007). For example, the highly important topic of magnetic reconnection is described very briefly, given that it is very well described by Kulsrud (2005) and Somov (2006, 2007).

One of the main focuses of the textbook is detailed application of the theory to astrophysical phenomena. Obviously, we cannot apply all the presented theory to all astrophysical objects and phenomena; thus, we apply some of the theory to some objects/phenomena in such a way to eventually touch upon most (if not all) of the diverse astrophysical objects including stellar interior and atmosphere, solar/stellar flares and winds, interstellar medium, supernova explosions, neutron stars, superbubbles, supernova remnants, pulsar wind nebulae, active galactic nuclei, and gamma-ray burst sources. It may seem that having so many diverse objects implies necessarily that they can be described only superficially given a limited book volume. Nevertheless, this is not the case: many phenomena are presented in all essential detail and a number of cutting-edge examples of comprehensive data analysis and interpretation are given. Complementarily, in most of the cases the derived equations and equation sets are general enough to be immediately used in scientific research work without further consulting original journal papers. This implies that the textbook will be highly useful well beyond the target audience (undergraduate and graduate students)—for active researches in astrophysics, space physics, and, perhaps, geophysics.

To easily learn the textbook, the basic knowledge obtained in general mathematics and physics courses is desirable along with a general astrophysics course. However, understanding of our book does not require any special knowledge beyond that; e.g., the most essential information from plasma physics is given in the textbook itself, although a more specialized and detailed information can be learned from Melrose (1980) and Kulsrud (2005). The book has a long list of recommended bibliography, which can be helpful for both students and researchers as a guideline for deeper study of a topic. The reference list, however, is incomplete: in most cases we included the monographs, textbooks, and review articles, which we actually used in our work on the topic. Not surprisingly, the reader can notice many sources published in Russian, given that this is the main language of both co-authors of the book. Citation of original papers is limited to the cases when we explicitly use the corresponding paper in devising a topic or in case of a few "classical" science-transforming papers. No paper has been ignored intentionally.

Finally, the authors are happy to sincerely thank our colleagues and collaborators V. Abramenko, A. Altyntsev, T. Bastian, M. Bietenholz, A. Bykov, D. Gary, P. Goode, E. Kontar, A. Kuznetsov, V. Melnikov, G. Nita, K. Platonov, J. Stone, A. Tsygan, D. Yakovlev, and V. Yurchishin for their help, highly important discussions, or sharing their observational data, as well as funding agencies NSF, NASA, Russian Ministry of Education and Science, and RFBR, which have partly been supporting our research in the areas closely related to this textbook. We are highly grateful to Professor B. Somov, who reviewed the entire textbook and came up with a number of highly valuable comments, which helped to significantly improve the final manuscript.

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Contents

Notations (Conventions)

c_s	Sound speed
$v_{\rm A}$	Alfvén velocity
e	Elementary charge; charge of the electron
m_a	Mass of the particle (of sort a)
χ	Coefficient of heat conductivity
κ	Coefficient of thermal diffusivity; diffusion coefficient of accelerated particles
R	Reynolds number
Ra	Rayleigh number
Pr	Prandtl number
$Pe = uL/\kappa$	Pécklet number
$R_\odot$	Radius of solar photosphere
c	Speed of light
h	Plank constant
m_e	Mass of the electron
$k_{\rm B}$	Boltzman constant
ω	Cyclic frequency
ω_B (ω_{Bi})	Gyrofrequency (cyclotron frequency) of a particle (of sort i)
$\mathbf{r}$	Radius-vector of a particle
t	Time
$\mathbf{v}$, $\mathbf{u}$, $\mathbf{V}$, $\mathbf{U}$	Velocities
f, F	Distribution functions
$\mathbf{F}$, $\boldsymbol{\mathcal{F}}$	Forces
T	Temperature
ρ	Mass density or charge density
ρ_e	Charge density (if interfere with the mass density ρ)
σ	Electric conductivity or effective cross-section (typically, with subscripts)
η	Dynamic viscosity
$\nu = \eta/\rho$	Kinematic viscosity
ν_m	Collisional magnetic diffusivity (magnetic viscosity)
$\nu^{\rm eff}$ $\parallel, \perp$	Effective magnetic diffusivities (viscosities)

$\mathbf{A} \cdot \mathbf{B}$	Dot product
$\mathbf{A} \times \mathbf{B}$	Cross product
$\nabla \times \mathbf{B}$	Curl
$\nabla \cdot \mathbf{B}$	Divergence
$\nabla f \equiv \frac{\partial f}{\partial \mathbf{r}}$	Gradient
$\mathbf{B}$, $\boldsymbol{\mathcal{B}}$, $\mathbf{b}$	Magnetic field
$\mathcal{R} = 1.49 \times 10^{13}\,\mathrm{cm}$	Sun to Earth distance (1 AU)
$\mathbf{E}$, $\boldsymbol{\mathcal{E}}$, $\boldsymbol{E}$	Electric field

Physical units in equations are given in [], e.g., [erg]

$P_{\alpha\beta}$	Tensor of the momentum flux density
$\Pi_{\alpha\beta}$	Viscous tension tensor
$\ln \Lambda_{\mathrm{C}}$	Coulomb logarithm
O-mode	Electromagnetic ordinary mode
X-mode	Electromagnetic (fast) extraordinary mode
Z-mode	Electromagnetic (slow) extraordinary mode

Acronyms

AR	Active region
AU	Astronomical unit; 1 AU = 1.49×10^{13} cm
BGK	Bhatnagar–Gross–Krook
CMB	Cosmic microwave background
CME	Coronal mass ejection
CR	Cosmic ray
DM	Dispersion measure
DSR	Diffusive synchrotron radiation
EM	Emission measure
Eq	Equation
FASR	Frequency agile solar radiotelescope (project)
FFF	Force Free Field
GRB	Gamma-ray burst
GS	Gyrosynchrotron
GSR	Gyrosynchrotron radiation
GUI	Graphical user interface
HD	Hydrodynamics
HXR	Hard X-ray
IPM	Interplanetary medium
ISM	Interstellar medium
LCP	Left circular polarization
lhs	Left hand side
MDI	Michelson Doppler Imager
MERLIN	Multi-element radio-linked interferometer network
mfp	Mean free path
MHD	Magnetohydrodynamics
MRI	Magneto-rotational instability
NLFFF	NonLinear force free field
NoRH	Nobeyama radioheliograph
NoRP	Nobeyama radio polarimeters
NST	New solar telescope (Big Bear Solar Observatory, California, USA)

OVSA	Owens Valley Solar Array (Owens Valley Radio Observatory, California, USA)
PIC	Particle-in-cell
PWN	Pulsar wind nebula
RCP	Right circular polarization
rhs	Right hand side
RM	Rotation measure
rms	Root mean square
RHESSI	Reuven Ramaty high energy solar spectroscopic imager
RTR	Resonant transition radiation
SEP	Solar energetic particle(s)
sfu	Solar flux unit
SHH	Soft-hard-harder
SHS	Soft-hard-soft
SN	Supernova
SNR	Supernova remnant
SOHO	Solar and heliospheric observatory
SSRT	Siberian solar radio telescope
SST	Solar sub-THz telescope (Andes, Argentina)
STR	Stochasic theory of radiation
SXR	Soft X-ray
SXT	Soft X-ray telescope
TRACE	Transition region and coronal explorer is a mission of the Stanford-Lockheed institute for space research, and part of the NASA small Explorer program
UT	Universal time
VCR	Vavilov–Cherenkov radiation
WR	Wolf–Rayet (star)