

SOCIETA ITALIANA DI FISICA

RENDICONTI
DELLA
SCUOLA INTERNAZIONALE DI FISICA
« ENRICO FERMI »

XXXIX CORSO

Astrofisica del plasma



ACADEMIC PRESS • NEW YORK AND LONDON

SOCIETA' ITALIANA DI FISICA

RENDICONTI
DELLA
SCUOLA INTERNAZIONALE DI FISICA
« ENRICO FERMI »

XXXIX CORSO

a cura di P. A. STURROCK
Direttore del Corso

VARENNA SUL LAGO DI COMO
VILLA MONASTERO

11-30 LUGLIO 1966

Astrofisica del plasma

1967



ACADEMIC PRESS • NEW YORK AND LONDON

ACADEMIC PRESS INC.
111 FIFTH AVENUE
NEW YORK 3, N. Y.

United Kingdom Edition
Published by
ACADEMIC PRESS INC. (LONDON) LTD.
BERKELEY SQUARE HOUSE, LONDON W.1

COPYRIGHT © 1967, BY SOCIETÀ ITALIANA DI FISICA

ALL RIGHTS RESERVED

NO PART OF THIS BOOK MAY BE REPRODUCED IN ANY FORM,
BY PHOTOSTAT, MICROFILM, OR ANY OTHER MEANS,
WITHOUT WRITTEN PERMISSION FROM THE PUBLISHERS.

Library of Congress Catalog Card Number: 67-17120

PRINTED IN ITALY

Introduction.

P. A. STURROCK

Institute for Plasma Research, Stanford University - Stanford, Cal.

In sitting down to write this introduction to the course on « Plasma Astrophysics » in the Enrico Fermi series, my first recollection is of the beautiful setting in which these courses take place. One's first inclination may be to dismiss this as an irrelevancy. Yet, as a scientist, one must admit that there are reasons that the Enrico Fermi series is so successful, and that the environment of the Villa Monastero is one factor which all the courses have in common. At Varenna the pace of life is sufficiently slow that the lecturer faces a class of colleagues and students who are alert, appreciative and critical. Discussions which begin in the lecture room will continue over lunch, on the path to the castle, or beside the lake. Here is an opportunity for a thorough and leisurely exchange of ideas, a place where problems are solved, where friendships are made and renewed.

Such an environment is favorable for any scientific meeting, but it is particularly valuable when the time comes to review—and hopefully advance—one of those areas of science which is something of a « no man's land », either because it overlaps two or more rather well established disciplines, or because it is in a very early stage of development. For both reasons, plasma astrophysics qualifies as a subject appropriate for a course in the Enrico Fermi series, and it was with pleasure that I accepted the invitation of the Italian Physical Society to organize and direct the course given in July of 1966. Nevertheless, such an assignment poses a number of problems.

The first was to decide how the material appropriate to such a course could possibly be fitted into three weeks. Reluctantly I had to decide that it would be necessary to eliminate the extensive and fascinating body of material concerned with solar-terrestrial relations. With the advent of space vehicles to permit the direct observations of conditions in the environment of the earth and in interplanetary space, the observational and also the theoretical material in this branch of science has grown very rapidly in the last few years. This material is reviewed regularly in a series of international

conferences on «space science» which—rightly or wrongly—is coming to be regarded as an autonomous scientific discipline.

The relevance of plasma physics (variations of which are described as «magnetohydrodynamics», «hydromagnetics», «cosmical electrodynamics», etc.) to astrophysics has been clearly recognized for many years. Some of the most important early developments in plasma physics were due to ALFVÉN, COWLING, FERRARO and others, who were concerned with astronomical problems. During the last decade or so, there has been a tremendous development in our knowledge of the plasma state, due primarily to the great effort which has gone into the controlled thermonuclear reactor program. At the same time, astronomers have produced much more detailed information on phenomena such as solar flares, solar radio bursts, supernova remnants and radio galaxies. Moreover, new phenomena have been discovered, the most exciting of which is the mysterious quasar.

In view of these developments, both in plasma physics and in the range of phenomena which involve plasma mechanisms, it is not surprising that the application of plasma physics to astrophysics has fallen into arrears. Complex problems are posed, and much detailed knowledge of plasmas is available, but application of the latter to the former will be a slow and difficult process. It is indeed quite likely that, despite the extensive body of literature on plasma physics which now exists, some quite different developments may be necessary to answer some of the problems posed by astrophysics. As an example one may note that the structure of collision-free shock waves is one of the most intriguing problems of present-day plasma physics, and that interest in this problem is due principally to the role of shock waves in astrophysical situations: the bow shock of the earth, the shock waves produced by a solar flare, and the shock wave outside an expanding supernova shell.

The development of plasma astrophysics is therefore likely to be a three-part dialogue, involving observers, plasma physicists, and those who try to interpret one to the other. The lectures given at Varenna were divided into three such categories, but there was a lively interplay between them, and this is reflected in the ordering of lectures. In so far as lectures can be grouped, the groups correspond to different phenomena.

Professor Reimar LÜST sketched, in a few lectures, the most important concepts and theoretical results of plasma physics, giving us a feeling for the orders of magnitude of the various effects by citing a number of examples from astrophysics. I presented a short account of the theory of electromagnetic waves in plasmas, to supplement the treatment of magnetohydrodynamic waves in LüST's lectures. Professor Russel KULSRUD then spent several lectures in reviewing and classifying the bewildering number of instabilities which have been discovered by plasma physicists. He achieved the almost miraculous feat of bringing his listeners to believe that the subject

is really not so very difficult, and that most instabilities can be understood by fairly simple physical considerations.

Dr. Vaclav BUMBA and Professor Harold ZIRIN together gave a comprehensive account of the wide range of optical observations on which is based our understanding of the structure and motion of the sun's atmosphere and the sun's magnetic field. Although these lecturers never allowed us to lose sight of the difficulties of making these observations, and of the precautions necessary in interpreting the photographs and spectra, we received a lucid introduction to the many fascinating phenomena which occur in the sun. The sun's atmosphere is full of surprises and subtleties and, either directly or indirectly, magnetic field seems to be involved in most of them.

We had hoped that it would be possible for Professor V. L. GINZBURG to participate in the course, but this unfortunately proved not to be possible. We were however fortunate to be able to persuade Dr. André BOISCHOT to join the school at short notice. Furthermore, BOISCHOT kindly agreed to lecture in English, on the understanding that, at the next course on plasma astrophysics, all British and American lecturers would speak in French. BOISCHOT gave a clear account of the many types of radio emission which originate on the sun, and reviewed the current theoretical interpretation of these various types.

In one pair of lectures, I discussed the significance of force-free magnetic field patterns in astrophysics, and the possibility of interpreting quiescent solar prominences in terms of a particular force-free field structure. In another pair of lectures I discussed the requirements of a model of solar flares and proposed a particular model. A substantial fraction of the course was therefore devoted to the sun. However, this seems most appropriate since we have far more detailed observational material about the sun than about any other astronomical body. As each succeeding lecturer enlarged on the many effects of the sun's magnetic field, I was reminded of the remark of Professor Robert LEIGHTON, « If it were not for its magnetic field, the sun would be as dull a star as most astronomers think it is ».

A number of interesting problems involving magnetohydrodynamic concepts, some occurring in the sun and some in other objects, were considered by Professor Leon MESTEL and Professor Eugene PARKER. MESTEL considered the important problem of the possible origin of the magnetic field of stars—the fossil, dynamo and battery theories—and the influence of this field on the early evolution of the protostar and on the possible convection patterns of a developed star. A great deal of interesting work has been done on these problems in recent years, but the problems are formidable and, as MESTEL clearly indicates, much work remains to be done.

PARKER considered the role played by magnetic field in three important areas: the heating of the sun's atmosphere, the solar wind, and the Galaxy.

Although evidence has been available for many years that the Galaxy has a general magnetic field, most of the questions concerning this magnetic field—such as its origin, structure, and dynamical consequences—remain unanswered. PARKER addressed himself to the interesting questions of the influence of magnetic field on gravitational processes and the role of the magnetic field in coupling the pressure of the cosmic ray gas to the Galaxy.

The remainder of the lectures were concerned with the fascinating electromagnetic phenomena which occur in radio galaxies and quasi-stellar radio sources, or « quasars » for short. Lucid and up-to-date reviews of the optical observations and of radio observations were presented by Professor Margaret BURBIDGE and Dr. Peter SCHEUER, respectively. A theoretical discussion of many of the questions raised by these observations was given by Professor Geoffrey BURBIDGE. The problems posed by quasars and radio galaxies have led to theoretical investigations in many branches of physics: for instance, the explosion mechanism has been discussed as a nuclear-physics process, as a relativistic process, as the annihilation of matter and antimatter, and as the result of simultaneous supernova explosions. It seemed appropriate, at this summer school, to discuss these phenomena from a plasma-physics point of view.

Since the bulk of our information about the explosions is derived from radio observations, the radiation process was discussed in detail by SCHEUER. It seems clear that the most significant radiation process is that of synchrotron radiation, but, as SCHEUER pointed out, there are other possibilities, and details of the synchrotron process and of the structure of radio clouds remain in doubt. In the final lectures, I briefly presented a possible model for the structure of quasars and radio galaxies. If these objects form from intergalactic gas containing a primeval weak magnetic field, some of the gravitational energy released during condensation will be transformed into magnetic energy. It appears that this magnetic energy could be released by the flare mechanism so that the explosions of quasars and radio galaxies may indeed be « galactic flares ».

The Summer School at Varenna was clearly successful in delineating many of the significant plasma phenomena of astrophysics, in presenting the basic plasma physics to which we must turn in attempting to understand these phenomena, and in presenting some of the theories which are currently being developed. It is clear that plasma physics plays an essential role in many important astrophysical phenomena. It is also clear that our understanding of plasma astrophysics is at a very early stage of development. It is likely to be many years still before there is general agreement even on the plasma mechanisms which occur in the atmosphere of the sun, and longer still before all the questions raised in the pages of these proceedings can be considered to be answered. It is most fortunate that these questions, and possible answers, could be raised and discussed at the Villa Monastero in 1966.

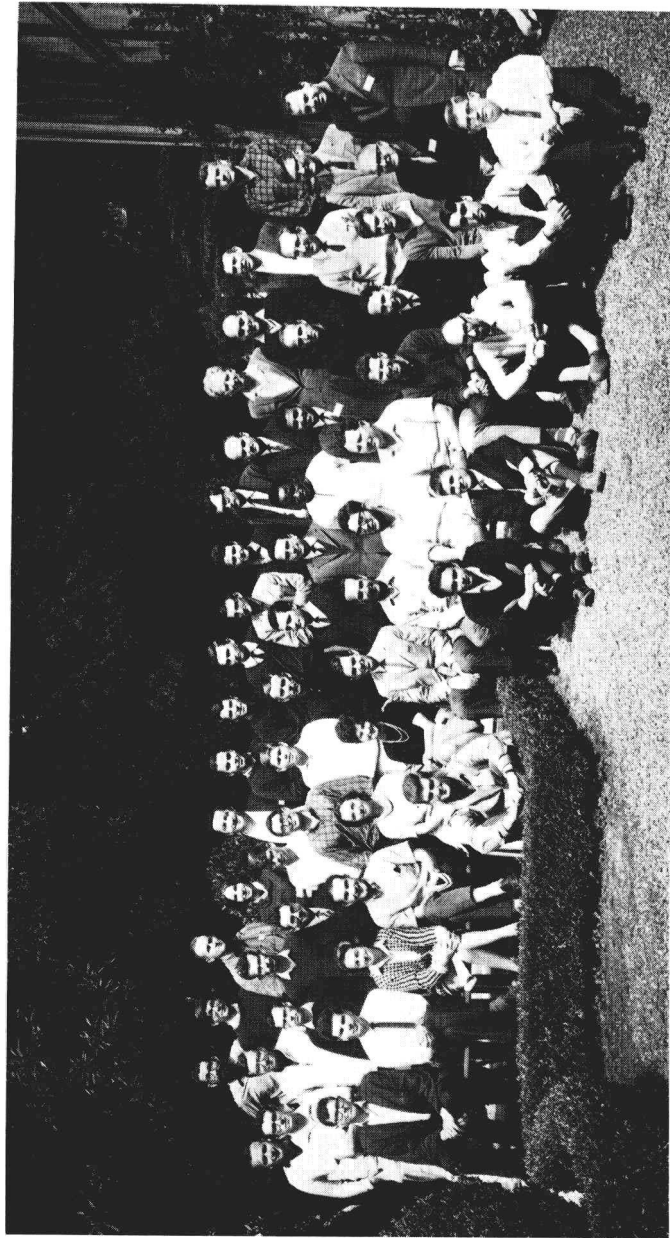
It is my pleasure to take this opportunity to thank those who helped to make the Summer School a success. Thanks are due to my fellow lecturers for the excellence of their lectures, for the enthusiasms with which they were presented, and for the additional effort of preparing these lectures for publication. Special thanks are due to Peter SCHEUER who, in addition to those of lecturer, assumed the burdens and tasks of Secretary. As one of the lecturers, I may say that we in turn are indebted to the students for their perceptively critical but appreciative response to our lectures. Many of the students as well as some of the observers helped in preparing typescripts of the lectures. Detailed acknowledgment is made on the title page of each chapter. In editing these proceedings, I have had the benefit of assistance from Peter SCHEUER and from Mr. Paul FELDMAN, Mr. Donald HALL, Dr. Hugh JOHNSON, Mr. Ronald MOORE and Dr. Sidney SELF.

* * *

I wish to thank Professor GERMANÀ for his continual support and the secretaries, Signorine M. ASTORRI, N. FOIADELLI and M. MELLA, who somehow produced comprehensible typescripts from illegible handwriting. In preparing for the Summer School and subsequently in trying to extract typescripts from busy scientists, I have been most ably assisted by Miss Linda MARKS.

Finally, on behalf of all the participants at the Summer School, I wish to thank the Italian Physical Society for providing us with such a memorable environment for our scientific and extra-scientific activities.

SOCIETÀ ITALIANA DI FISICA
SCUOLA INTERNAZIONALE DI FISICA « E. FERMI »
XXXIX CORSO - VARENNA SUL LAGO DI COMO - VILLA MONASTERO - 11-30 Luglio 1966



INDICE

P. A. STURROCK - Introduction pag. XII

Gruppo fotografico dei partecipanti al Corso fuori testo

R. LÜST - Introduction to plasma physics

1. Introduction	pag.	1
2. Single-particle theory	»	2
2'1. The Maxwell equations and the equation of motion . .	»	2
2'2. Drift velocity.	»	3
2'3. Motion in axisymmetric fields	»	5
2'4. Adiabatic invariants.	»	7
3. The macroscopic description	»	11
3'1. Magnetohydrodynamic approximation	»	11
3'2. Two-fluid model	»	15
3'3. Magneto-acoustic waves	»	20
APPENDIX.	»	22

P. A. STURROCK - Waves in plasmas

1. Introduction	»	24
2. Classification of waves.	»	25
3. Wave equation	»	26
4. Waves in a cold collision-free plasma with no magnetic field	»	28
5. Effect of collisions	»	33
6. Effect of magnetic field	»	34
6'1. Propagation transverse to the magnetic field ($\mathbf{k} \cdot \mathbf{B}_0 = 0$)	»	36
6'2. Propagation parallel to the magnetic field ($\mathbf{k} \parallel \mathbf{B}_0$) . . .	»	41
7. Faraday rotation	»	43
8. Whistler waves	»	44

R. M. KULSRUD – Plasma instabilities

1. Instabilities in astrophysics	pag. 46
2. General remarks on instabilities	» 46
2'1. Definition	» 46
2'2. Normal-mode analysis	» 47
2'3. Example of a quasi-mode	» 48
2'4. Nonlinear limit	» 49
3. Low frequency M.H.D. instabilities without resistivity; Rayleigh-Taylor instability	» 49
3'1. General remarks	» 49
3'2. Incompressible case with zero magnetic field	» 50
3'3. Compressibility	» 51
3'4. Nonzero B	» 52
3'5. Interchange instability	» 52
3'6. Example of the interchange instability	» 53
3'7. Comparison of Rayleigh-Taylor and interchange instabilities	» 54
3'8. Combination of Rayleigh-Taylor and interchange stability criteria.	» 54
4. Effect of line-tying and resistivity on the Rayleigh-Taylor instability	» 55
4'1. Zero resistivity	» 55
4'2. $\eta \neq 0$	» 57
5. Tearing instability	» 58
5'1. General remarks	» 58
5'2. Tearing mode theory	» 59
5'3. Linear theory	» 60
5'4. Nonlinear theory of Sweet and Parker	» 61
5'5. Petschek's nonlinear theory of field annihilation	» 62
6. Anisotropic instabilities. Low-frequency M.H.D.	» 64
6'1. General remarks	» 64
6'2. Fire hose instability.	» 64
6'5. Mirror instability	» 65
7. Velocity-space instabilities: high frequency (electrostatic)	» 67
7'1. General remarks	» 67
7'2. Theory.	» 68
7'3. The nonlinear limit and the emission of radio noise	» 70
8. Velocity-space instabilities: electromagnetic	» 71
9. Instabilities in warm plasmas	» 72
APPENDIX: Derivation of eq. (3.17)	» 73

V. BUMBA – Observations of solar magnetic and velocity fields

1. Introduction	» 77
2. Limiting factors of solar observations.	» 77

2'1. Influence of observational conditions and resolution on the results obtained	pag. 77
2'2. Present situation in observations	» 80
3. Magnetic and velocity fields in the solar atmosphere	» 82
3'1. Large-scale distribution of solar magnetic fields	» 82
3'2. A note on the rotation of solar photospheric layers	» 83
3'3. The close relationship of the distribution of solar magnetic and velocity fields	» 85
3'4. On solar granulation	» 87
3'5. Hierarchy of solar magnetic-and-velocity field-distributions	» 88
3'6. Comparison of photospheric and chromospheric dynamical models in a region of weak background fields	» 89
4. Magnetic and velocity fields in active regions	» 90
4'1. Development of a single active region within the supergranular network	» 90
4'2. Development of sunspots	» 97
4'3. Some notes on ephemeral processes and their relation to magnetic- and velocity-field distributions	» 109
4'4. Quiescent filaments	» 114
4'5. Development of coronal condensations	» 115
5. Changes of solar activity	» 116
5'1. Main characteristics of the cycle	» 117
5'2. Basic processes of solar activity	» 118
5'3. Hierarchy of velocity- and magnetic-field distribution and solar activity	» 118
5'4. The asymmetry of development of all solar processes in time	» 120
6. Conclusion	» 120

H. ZIRIN — The solar atmosphere.

1. Introduction	» 124
2. The chromosphere	» 124
3. Monochromatic observations	» 127
4. Chromosphere oscillations	» 132
5. Chromospheric temperatures	» 133
6. General chromospheric model	» 134
7. The solar corona	» 135
8. Coronal condensation over an active region	» 136
9. Atomic processes	» 136
10. Flares	» 138
11. Great flare	» 139

A. BOISCHOT — Solar radio bursts

Introduction	» 142
1. Refraction of the rays	» 146

2. Observation of radio bursts	pag. 147
2'1. Type III	» 147
2'2. Type II	» 150
2'3. Continuum bursts	» 152
3. Presumed origins of these different bursts	» 153
4. Type IV B and noise storms	» 153
 P. A. STURROCK and E. T. WOODBURY – Force-free magnetic fields and solar filaments	 » 155
 P. A. STURROCK – Solar flares	
1. Prologue	» 168
2. Introduction	» 168
3. Requirements of a flare model	» 171
4. Model of the pre-flare state	» 172
5. The high-energy phase of solar flares	» 178
 L. MESTEL – Stellar magnetism	
Introduction	» 185
1. The fossil theory	» 186
1'1. Star formation in magnetic clouds	» 186
1'2. The approach to the main sequence. Hayashi convection and a primeval field	» 191
1'3. Magnetic braking in the Hayashi phase	» 193
1'4. The time for the decay of a strong primeval field	» 201
1'5. Internal and external fields	» 202
1'6. Application to the observed magnetic stars	» 206
2. Dynamo theories	» 211
2'1. Conditions for dynamo action	» 213
2'2. The solar cycle as a nonsteady dynamo	» 216
2'3. Application to magnetic variable stars	» 217
3. The « battery » mechanism	» 219
3'1. The battery process in rotating stars	» 220
3'2. The effect of a primeval poloidal field	» 223
3'3. Observable consequences	» 225
 E. N. PARKER – Cosmic magnetohydrodynamics	
1. Wave generation in the photosphere	» 229
1'1. Energy transmission	» 230
1'2. The generation of sound in a turbulent medium	» 230
1'3. The effect of a magnetic field on acoustic waves	» 232

2. Coronal expansion; momentum equation	pag. 234
3. Coronal expansion; energy equation.	» 238
3'1. Magnetic fields	» 241
3'2. Effect of interstellar pressure	» 242
3'3. Existence of stellar winds	» 243
4. The cosmic-ray gas and the galactic magnetic field	» 243

E. M. BURBIDGE – Optical observation on radio galaxies and quasi-stellar objects

PART I: Radio galaxies	» 250
1. Plasma in galaxies	» 250
2. Spiral structure.	» 251
3. Radio galaxies and related objects	» 252
4. Discussion of individual radio galaxies	» 253
4'1. M 87.	» 253
4'2. NGC 1275	» 254
4'3. M 82.	» 254
4'4. NGC 4038-9	» 255
4'5. Relation between radio-brightness distribution and axis of rotation	» 255
5. Relationship between phenomena in radio galaxies and normal galaxies	» 256
PART II: Quasi-stellar objects.	» 256
6. Line spectra	» 257
7. Continuum spectra	» 259
8. Radio quiet objects	» 260

P. A. G. SCHEUER – Radio galaxies and quasi-stellar sources

1. The sky at radio frequencies.	» 262
2. Galactic sources.	» 262
3. Extragalactic sources	» 263
4. Radio structure of sources.	» 264
4'1. Pencil beams	» 265
4'2. Interferometry	» 265
4'3. Aperture synthesis	» 265
4'4. Lunar occultations	» 268
4'5. Interplanetary scintillation.	» 268
4'6. The structure of radio galaxies.	» 268
4'7. The structure of quasi-stellar sources	» 269
4'8. Radio sources as galactic explosions	» 270
5. Polarization of radio sources.	» 273
6. Variation of radio sources with time	» 274

7. Radio spectra	pag. 275
7'1. Summary of observations and introduction	» 275
7'2. Absorption processes in radio sources	» 276
7'3. The low-frequency source in the Crab Nebula	» 279
7'4. The variable radio source 3C 273 B.	» 280
7'5. Radiation processes other than electron synchrotron radiation	» 281
8. Physical conditions in radio galaxies	» 282

P. A. G. SCHEUER – Radiation

1. Introduction	» 289
2. The power radiated by an electron	» 289
3. Spectral distribution of the radiation	» 292
3'1. Inverse Compton scattering	» 293
3'2. Synchrotron radiation	» 293
4. Bremsstrahlung	» 297
5. Other possible emission mechanisms	» 299
6. Relation between the electron energy distribution and the spectrum of a radio source	» 300
7. The minimum energy in a radio source	» 305
8. Arguments that depend on source geometry are weak arguments. Arguments independent of source geometry are strong arguments	» 305

G. R. BURBIDGE – High-energy astrophysics

1. X-ray and γ -ray astronomy	» 307
1'1. The background radiation	» 308
1'2. The discrete sources of X-rays	» 309
2. The nature of the quasi-stellar objects	» 311
2'1. Red-shifts	» 311
2'2. Luminosities and radio fluxes	» 313
2'3. Variations in flux	» 313
2'4. Absorption features	» 315
2'5. Distribution of QSO's	» 316
2'6. The $\log N$ - $\log S$ curve	» 317
2'7. The composition of the quasi-stellar objects	» 318
3. Theories which attempt to account for the energy requirements of the quasi-stellar objects and radio galaxies	» 318
3'1. Supernova theories	» 320

3'2. Stellar collisions	pag. 322
3'3. Massive super-stars	» 323
3'4. The role of magnetic fields in massive objects.	» 325
3'5. Theories using the concept that massive objects have a cosmological origin	» 329
3'6. Quarks as energy sources in massive objects with a cosmological origin	» 330
3'7. Matter-antimatter annihilation	» 333
3'8. Gravitational focussing	» 335
 P. A. STURROCK – A plasma model of quasars and radio galaxies	» 338

Introduction to Plasma Physics (*).

R. LÜST

*Max-Planck-Institut für Physik und Astrophysik
Institut für extraterrestrische Physik - Garching bei München*

1. – Introduction.

A ionized gas is called a plasma if it contains charged particles in such a large number that its properties are essentially influenced and determined by their presence.

In most cases we can regard the plasma as quasi neutral, which means that the number of positive and negative charges are equal. The special properties of a plasma depend on the electrodynamic interaction of the particles with each other and with external fields. Furthermore the hydrodynamical properties are important; hence we have a coupling between hydrodynamical and electrodynamic phenomena.

Plasmas play a very important role in the universe, since the major part of it is in the plasma state except for some planets and their atmospheres. Also magnetic fields are usually present, and often the field strength is high enough for the interaction between the magnetic fields and the plasma to be important.

There are three main reasons for the occurrence of plasma in the universe. First, the atoms are ionized under suitable conditions of temperature and pressure; this is mainly the case in stellar atmospheres and interiors. Furthermore, extensive sources of electromagnetic radiation exist in the universe which can maintain ionization in gases of smaller density. This is important for the ionization in the interstellar regions: In the H I-regions only the metal atoms are ionized while in the outer regions, the H II-regions, hydrogen also is fully ionized. Finally, ionized particles are continually ejected from the stars into interstellar space.

(*) Prepared with the assistance of M. SCHOLER, Max-Planck-Institut für Physik und Astrophysik - Institut für extraterrestrische Physik, and R. PECKOVER, Department of Applied Mathematics and Theoretical Physics, Cambridge.