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Astrofisica del plasma

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XXXIX CORSO

a cura di P. A. STURROCK
Direttore del Corso

VARENNA SUL LAGO DI COMO
VILLA MONASTERO
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Introduction.

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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.

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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.

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Introduction to Plasma Physics (*).

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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 electrodynamical 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.