Physics of High Energy Plasmas (International Undertaking)

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High Energy Plasmas Undertaking: Funding
Our group effort is an international undertaking in terms of its funding as well as its composition. High Energy Plasmas include both thermonuclear and astrophysical plasmas. In fact, the US Department of Energy, which provides the main source of funding for our Undertaking through the Office of Fusion Energy Sciences has accepted to support the latter field within the Office of Fusion Energy, complementing the support given by High Energy Particle Physics to Astrophysics, since the Symposium on Plasma Astrophysics held at its headquarters in June 2001.

Sample of Research Activities
1) Successes of the “Accretion” Theory in Explaining the Spontaneous Rotation Phenomenon
2) Magnetic Reconnection and Angular Momentum Transport in Theoretical Astrophysics
3) The Ignitor Project
4) Self-Organization and Collective Modes in High Energy Plasmas

1. Successes of the "Accretion" Theory in Explaining the Spontaneous Rotation Phenomenon

While gaining in popularity within the scientific community, the "angular momentum generation" phenomenon and its explanation by the "accretion theory" [[1]] have been confirmed by a new series of detailed experiments both at MIT and in Europe. This phenomenon is observed in axisymmetric plasmas confined by strong magnetic fields and corresponds to the "spontaneous" generation of relatively large plasma velocities up to about 120 km/sec in the toroidal direction, without any active injection of angular momentum.

The "accretion" theory was proposed since the early experimental indications of this phenomenon and was inspired by the theory of millisecond pulsars. Accordingly the explanation given, within this theory, was and is that angular momentum is transferred to the material wall surrounding the plasma by the effects of collective modes excited at the edge of the plasma column and that opposite angular momentum is carried toward the center of the plasma column by a different set of modes. Then a series of predictions could be made that would prove the validity of the theory. (1) The toroidal velocity would have to invert its direction as the plasma column is taken from a regime with a high degree of confinement of the plasma thermal energy (so called H-regime) to a regime of low confinement (so called L-regime). In fact, the modes that, according to the theory, had to be excited at the edge of the plasma column would have opposite phase velocities in the two regimes. (2) Since the inward transport of angular momentum is considered to be at the edge of the plasma column, when the rotation starts it should be observed as localized in the outer part of the plasma column propagating toward the center. (3) Since the inward transport of angular momentum is attributed to plasma modes that are responsible for the outward transport of the nuclei thermal energy the transport characteristic times for the angular momentum and for the nuclei thermal energy should be about equal. (4) The phase velocities of the plasma modes excited at the edge of the plasma column should be in a given characteristic direction (the so called electron diamagnetic velocity) in the H-confinement regime and in the opposite direction in the L-confinement regime. Conversely, the plasma column should rotate contrary to these directions. (5) The modes that can carry the angular momentum toward the center of the plasma column can be suppressed when a strong gradient of the particle density is produced. Therefore the rotation in the central part of the plasma column should disappear when a strong particle density gradient is produced.

A cycle of experiments carried out during the past year has confirmed all these points. In particular, experiments were performed at MIT by the Alcator CMod machine where the transition from the L-regime to the H-regime was programmed so that a state of zero velocity could be reached as the velocity inverted its direction as predicted by the theory. Then as the plasma entered the H-regime, the rotation was seen to start from the outside. The time scales for the inward propagation of the angular momentum and the outward transport of thermal energy were found to be comparable. Moreover, when a strong density gradient was produced on a "shell" within the plasma column, the rotation was observed to disappear within the shell as predicted by the theory. The observation that the modes excited at the edge of the plasma column invert their phase velocities in the transition from the L-regime to the H-regime has been confirmed by further experiments carried out by the JET facility in England.

[[1]]B. Coppi, *Nuclear Fusion* **42**, 1 (2002)

2. Magnetic Reconnection and Angular Momentum Transport in Theoretical Astrophysics

Two major issues in modern theoretical astrophysics are those of providing a consistent framework to describe the rate of destruction of the magnetic field topologies on the grand scale and that of identifying the collective modes that can transport angular momentum in accretion disks radially outward at a rate that is consistent with the needed rate of mass accretion. In both cases, conventional statistical mechanics based on discrete particle collisions is inadequate to give the appropriate description as it leads to diffusion coefficients for the magnetic fields and the angular momentum, respectively, that are several orders of magnitude too small relative to the requirements of the observations. A byproduct of our theoretical work on magnetic reconnection and on angular momentum transport in accretion disks is to have found a close link between the kinds of analyses that are involved in dealing with the two problems. Our involvement with magnetic reconnection goes back to the early days of this field. By now, in space physics, the region where magnetic reconnection events are commonly recognized to take place and to originate auroral substorms is the Earth's magnetotail. The Dynamics of the Geomagnetic Tail that one of us (B. C.) published in 1966 with G. Laval and R. Pellat (*Phys. Rev. Letters*) is the second most quoted paper after the classical paper by Dungey on reconnection.

At the same time, the need to describe the magnetic reconnection events observed in laboratory plasmas has led to develop the theory of collective modes that are mesoscopic in nature in that they involve both macroscopic and microscopic scale distances. If macroscopic equations would be used, these modes would have characteristic spatial singularities. Therefore, advanced singular perturbation techniques had to be developed to describe the experimentally observed "singular" modes. These theoretical techniques, in a more complex context, have been shown by us to become necessary when dealing with the angular momentum transport problem in realistically thin accretion disks where the magnetic energy density is significant relative to the thermal energy density. The importance of this circumstance is particularly evident when the formation of jets due to magnetic field topologies maintained by disks is considered. Therefore we have identified the new collective modes that are excited in these disks showing that they are of the singular type, like those explaining reconnection events in the laboratory, and produced the theory for them. We have also demonstrated that the mathematical nature of the involved singularities make non-linear effects important even for relatively small values of the mode amplitudes. Our results have encountered a great deal of interest in the international scientific community, both in plasma physics and in astrophysics (in spite of the difficulties and the unpopularity of having to deal with singular perturbations) as is confirmed by the number of invited papers we have been offered to give. In addition, a chain of collaborations with other institutions that we have started, on the numerical simulation and analysis of thin accretion disks, are producing results.

Two papers have been published in *Physical Review Letters* and *Annals of Physics*, and a third one on the severe limitations of the axisymmetric non singular modes that could fit in thin accretion disks, has been submitted to the *Astrophysical Journal*. The theory of these non singular modes is based on that of the so called "ballooning" modes [2] that one of us (B. C.) had developed years ago for toroidal laboratory plasmas. An updated version of a paper on the importance of nonlinear effects is to be submitted to *Phys. Rev. Letters*.

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[2] B. Coppi. *Phys. Rev. Letters* **39**, 939 (1977)

3. The Ignitor Project

The Ignitor program has been the first proposed and developed with the objective of reaching ignition conditions in laboratory plasmas on the basis of existing technologies and knowledge of plasma physics. At this time, it remains the only experiment capable of attaining ignition in a magnetically confined plasma. A detailed design of the relevant machine has been carried out, the construction of full size prototypes by major European industrial groups has been completed, and the site has been selected, in the Piedmont Region, for the machine's construction and operation. The credit of this site, one of the main nodes of the European electrical grid, reduce considerably both the costs and the times involved.

Consequently, Ignitor has been chosen as one of the three major experiments to be analyzed during an eight month period by the interested US physics community in order to form the basis for the planning of a future path for the US program in the field of fusion burning plasmas. This period has culminated in a workshop at Snowmass (Colorado) in July 2002. The two other experiments are ITER, a multinational enterprise for a large volume, multibillion dollar machine, and FIRE, proposed by a team at Princeton University along the same line (compact size, high magnetic field) as Ignitor. ITER has given up the goal of reaching ignition by retreating to a less ambitious device than that proposed originally, and FIRE has not aimed at ignition given its design characteristics since its inception.

The Italian Government has included Ignitor in its National Research Plan, and has formally invited the U.S. Department of Energy to broaden its collaboration on this program. In fact, most of the physics basis for Ignitor has been developed in the United States. A non-profit Consortium Corporation for the construction of the Ignition facility in the Piedmont region has been established.

On the US side, a panel established by the Fusion Energy Sciences Advisory Committee of the US Department of Energy has published a report concerning experiments on fusion burning plasmas, from which Ignitor emerges with full recognition of its scientific value and originality. Following the Snowmass Workshop, a detailed, written plan for an expanded participation in the Ignitor program that is underway in Italy has been formulated. This plan has been approved by the committees that have examined it and recommended for consideration to the US Department of Energy.

On the scientific front, we have continued to lead the analysis of the major physics issues of fusion burning plasmas at the international level. This is reflected in the publications of our MIT group and of our collaborators in Europe.

We are in the process of proposing an Ignitor-like experiment (called Columbus) to be constructed in the U.S. given the strong interest demonstrated by colleagues both within the scientific community and within the U.S. government for this initiative.

4. Self-Organization and Collective Modes in High Energy Plasmas

The fact that conventional statistical mechanics concepts cannot be applied to the large variety of plasmas that exist in the Universe and that are produced in the laboratory is well known. In fact, collective modes play a key role in the dynamics of the most interesting kinds of plasmas. Some of these have wave-like features and can be treated as quasi-particles using concepts and theories developed in other fields, e.g. condensed matter physics. However, an important, large category of plasma modes do no have wave features, involve both global and microscopic plasma properties and have required the development of original theories to describe both their linear and non-linear evolution. As the experimental methods for the investigation of the microscopic properties of plasmas (so called diagnostics) have progressed, the identification of the most important modes have become possible.

This has been the case, for instance, of a "mesoscopic" mode that was found theoretically by us, that concerns magnetically confined toroidal plasmas with temperatures of thermonuclear interest and whose main excitation factor is the gradient of the longitudinal (along the magnetic field) temperature of the plasma nuclei. This is commonly called ITG-toroidal mode and is widely recognized as being responsible mostly for the rate of transport of the nuclei thermal energy across the magnetic field. This is the most important factor in gauging the confinement properties of a plasma in an optimal magnetic field configuration.

In spite of these achievements, there are major features of confined plasmas in the laboratory and of plasma objects in astrophysics, such as accretion disks, that are becoming increasingly evident but lack an adequate theoretical framework. That is self- organization, by which the plasma microscopic properties, that include for instance, the atomic physics at the edge and relevant nuclear physics at the center of the plasma column in the case of a fusion burning plasma, combine together with the effects of the excited plasma collective modes to produce characteristic global properties that are consistently observed.

In the most elementary case of an axisymmetric, toroidal plasma in which a current is induced and the resulting ohmic heating is the only form of energy input, there are three observations that one of us (B. C.) anticipated to be of general nature by introducing first the "Principle of Profile Consistency" and that have been found to apply to a large diversity of experiments: i) the electron temperature takes a characteristic type of canonical profile; ii) the electron thermal diffusion coefficient has a radial profile that is an increasing function of the distances from the center of the plasma; iii) the applied voltage ("loop voltage") is almost invariant for a very large range of plasma currents ($V \varphi$ 1.5-2 volt). The basic theory of relevant collective modes does not explain these phenomena.

In the case of accretion disks in astrophysics, we have proven that if the angular momentum transport can be described globally by an effective viscosity, which should be considered as a "mesoscopic entity", the radial density profile of the corresponding diffusion coefficient has to be inversely related to that of the plasma surface density. In fact, this is reminiscent of the so called "Alcator scaling" for the energy confinement time τ_E, reflecting the experimental observation that τ_E increases with the particle density.

In the case of magnetically confined plasmas, there have been other phenomena observed that have shown the inadequacy of the theory of isolated collective modes to explain the observations. This is the so called isotopic effect, discovered by us first on the Alcator A machine at MIT, showing that, for instance, a deuterium plasma has a higher confinement time than a hydrogen plasma. The only existing theory is one that one of us (B. C.) formulated a few years after the discovery of the phenomenon and cannot be considered definitive. Another surprise, which was discussed earlier in this section, is that the simplest ("ohmically heated") confined plasmas rotate spontaneously.

In a self-sustained, fusion burning plasma, the reaction rate and the resulting plasma heating by the fusion reaction products is strongly interdependent on the global properties of the temperature and density of the fusing nuclei. Therefore, the resulting entity is eminently self-organized. In this context, we have identified, in our group, important collective modes (quasi-particles) that interact with the MeV particles produced by fusion reactions, alongside with others discovered by other groups, as a first step toward understanding the difference from the plasmas produced by present day experiments. However, the lack of a general framework to describe self-organization, makes it impossible to anticipate the global feature of self-sustained fusion burning plasmas, and this is what accentuates the interest by the scientific community in bringing the relevant experiments to reality.

N.B. - Within our group, there is a significant effort in the numerical simulation of plasmas. In fact, our group is at the forefront of the development of global plasma simulation models using fluid, particle, and hybrid approaches.

Invited Papers: January 2002 to January 3, 2003

Distinguished Lecture given at the National University of Mexico-Institute for Nuclear Sciences – Mexico City, Mexico, January 2002
“Self-organization Processes, Physics of Burning Plasmas, and Its Relevance to Astrophysics”

Astrophysics Colloquium given at the National University of Mexico-Institute for Astronomy – Mexico City, Mexico, January 2002
“Magnetic Reconnection and Angular Momentum Transport in Astrophysics and in the Laboratory”

International Meeting on Theoretical Plasma Physics (“Sherwood Meeting”) – University of Rochester; April 2002
“The Accretion Theory of the Spontaneous Rotation Phenomenon”

Invited General Presentation given at the International Annual Plasma Theory Meeting on Fusion Research International Meeting on Theoretical Plasma Physics (“Sherwood Meeting”) University of Rochester, NY, April 2002
“The Ignitor Experiment”

Invited Paper given at the Sixth International Symposium on Fusion Nuclear Technology (San Diego, CA, April 2002)
“Technological Solutions and Physics Issues for Meaningful Burning Plasma Experiments”

International Dawson Symposium on Plasma Physics, University of California, Los Angeles, May 2002
“Science Policies in Fusion Research from the Late Sixties to the Present”

Annual Meeting on Plasma Physics of the European Physical Society, Montreux, Switzerland, June 2002. Selected oral paper:
“Singular Bending Modes in Accretion Disks and Magnetic Reconnection”

Third International Sakharov Conference on Physics – Moscow, Russian Academy of Sciences, June 2002 (two invited papers)
“Angular Momentum Transport in Accretion Disks and in Laboratory Plasmas”
“The High Field Approach to Fusion Research”

Snowmass National Workshop on the next generation of fusion burning plasma experiments - Snowmass, CO, July 2002.
“Physics Issues for the First Ignition Experiments”

National Research Council Committee on Fusion Burning Plasma Experiments - Washington D.C., September 2002
"The 'Science First' Approach to Fusion Research"

International Workshop on Galaxies and Chaos - Athens, Greece, September 2002
"Accretion Disk Dynamics" (not given because of a conflict of dates with the NRC committee)

MIT Astrophysics Colloquium – October 2002
"The Issue of Angular Momentum Transport at All Scales in the Universe"

National Meeting of the American Physical Society - Orlando, FL, November 2002
"Unresolved Issues in the Physics of High Energy Plasmas and Expectations from Fusion Burning Experiments"

Italian Cultural Association of Boston, December 2002 (c/o Harvard University).
"E. Fermi and the Significance of the Chicago Pile Experiment" (60^{th} Anniversary Celebration)

International Symposium on Space and Plasma Physics – University of Maryland, January 2003
"Non-linear and Self-Organization Processes in Astrophysical and Laboratory Plasmas"

Invited Papers for 2003
International Conference on "Non-linear Plasmas and Space Exploration: Horizons and Challenges". Space Research Institute (Russian Academy of Sciences); Moscow, January 2003 (forced to cancel participation due to a conflicting commitment.)

Symposium on Current Trends in International Fusion Research – Washington, D.C., March 2003

International Conference on Plasma Astrophysics Moscow Region (June 2003)

International Symposium on "Plasmas in the Laboratory and in the Universe: New Insights and New Challenges" – Villa Olmo (Como-Italy), September 2003

Sample of Publications
"Accretion Theory of Spontaneous Rotation in Toroidal Plasmas" by B. Coppi , *Nuclear Fusion,* **41**, 1 (2002)

"Ballooning Modes in Thin Accretion Disks" by B. Coppi and E.A. Keyes, submitted to the *Astrophysical Journal* and Massachusetts Institute of Technology (R.L.E.) Report PTP-02/02 (2002)

"Angular Momentum Generation: Theory and Recent Experiments" by B. Coppi, paper selected for presentation at the 2002 International Conference on Fusion Energy (I.A.E.A., Lyon, France), published as Paper TH/P1-02 in the Conference Proceedings. (I.A.E.A., Vienna, 2002). An extended version is to be published in *Nuclear Fusion.*

"The 'Science First' Approach to Fusion Research" by B. Coppi, Massachusetts Institute of Technolgy (R.L.E.) Report PTP-02/03. An extended version is to be submitted for journal publication.

"Physical Regimes Accessible to the Ignitor Experiment and Relevant Theoretical Developments" by B. Coppi, A. Airoldi, F. Bombarda *et.al.,* paper selected for presentation at the 2002 International Conference on Fusion Energy (I.A.E.A., Lyon, France), published as Paper FT/P2-10 in the conference proceedings. Submitted to *Nuclear Fusion*.

"Excitation of 'Singular Modes' in Thin Accretion Disks and Relevance of Non-linear Processes" by B. Coppi and P.S. Coppi, updated version to be submitted to *Phys. Rev. Letters*.