ARISTOTLE UNIVERSITY OF THESSALONIKI
DEPARTMENT OF PHYSICS
SECTION OF ASTROPHYSICS, ASTRONOMY AND MECHANICS

Laboratory of Astronomy

An institute devoted to research, teaching and popularizing astronomy

THESSALONIKI, MACEDONIA, GREECE
2011

Introduction

The *Laboratory of Astronomy* at the Aristotle University was founded in Thessaloniki in 1943. Since then, without interruption, its members are devoted to promoting research, teaching and popularizing Astronomy in Northern Greece and worldwide. The late academician J. Xanthakis was the first director followed by Academician G. Contopoulos, the late Professor and B. Barbanis and Professor N. K. Spyrou (the current director).

The building hosting the *Laboratory of Astronomy* was constructed by the well known Greek architect P. Karantinos in 1961 and it is located at the center of the University Campus. Offices for the researchers, the graduate students and the staff, teaching and seminar rooms, a Secretan 20 cm optical telescope, and a computational center are housed in this building. In this leaflet a few information is given on the history of the Laboratory of Astronomy and the multiple activities of its staff.

The Laboratory of Astronomy is part of the Section of Astrophysics, Astronomy and Mechanics of the Department of Physics of the Aristotle University of Thessaloniki. Currently, nine faculty members, three post-doctoral fellows and five graduate students are actively working on topics related to various aspects of astronomy and astrophysics, teaching several astronomy and astrophysics courses, and hold monthly public hours throughout the year. The staff of the Laboratory of Astronomy maintains active collaborations with numerous research institutes over Europe and USA. Research is funded by the European Union, the Ministry of Education and the General Secretariat of Research and Technology of Greece and, occasionally, other sources.

***Contact details*:**

Laboratory of Astronomy

Section of Astrophysics, Astronomy and Mechanics

Department of Physics

Aristotle University of Thessaloniki,
GR-54124 Thessaloniki, Greece

Tel: +30 2310 998047,

Fax: +30 2310 995384,

E-mail: grammat@astro.auth.gr,

web page: http://www.astro.auth.gr

Permanent Researchers

Professors
N. K. Spyrou, Director
K. Kokkotas
D. Papadopoulos
M. Plionis
J.-H. Seiradakis
L. Vlahos

Associate Professors
N. Caranicolas

Assistant Professors
N. Stergioulas
C. Tsagas

Associate Researchers
Dr. H. Isliker
Dr. K. Kleidis
Dr. C. Tsironis

PhD Candidates
M. Anastasiou
I. Chatziantonnaki
G. Karanis
A. Kouretsis
N. Papadopoulos
T. Pisokas

Research

1. Plasma Physics: Astrophysical and Laboratory Plasma

❖ Particle transport and acceleration in turbulent, stochastic electromagnetic fields

- The **acceleration of particles** in the heliosphere and in the large scale structures of the universe is a major astrophysical problem. We have been involved in the theoretical development of numerous mechanisms, which can accelerate particles to relativistic energies (e.g. shock waves, turbulence, current sheets, and coherent electromagnetic waves).

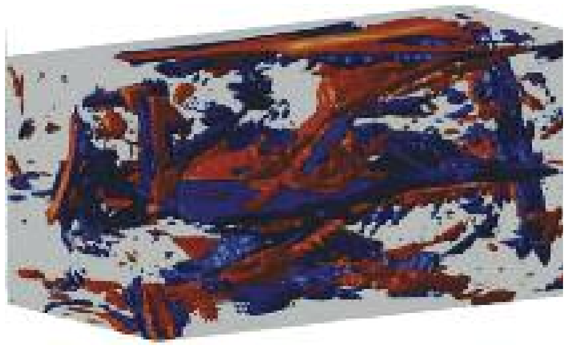


Fig. 1. Stochastic electric fields in turbulent plasma in the solar corona.

- Using the **random walk approach**, we have made thorough studies of the acceleration in strongly turbulent plasmas, in which, occasionally, strong electric fields appear at locations that exhibit a fractal structure, and with the electric field intensities being random. It has been shown that the diffusion of particles in such environments is a very efficient acceleration mechanism in many astrophysical contexts and in particular in the **solar corona**.

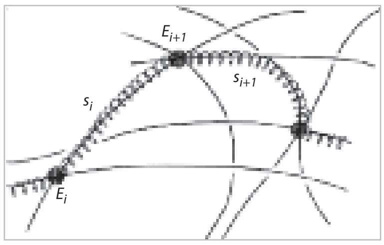


Fig. 2. Sketch of the random walk of a particle in plasma.

- In a third line of research on particle transport and acceleration, we use **test particle simulations** in turbulent electromagnetic field environments, that either are constructed with prescribed statistics, or are taken from numerical magneto-hydrodynamic (MHD) simulations:
  a) In studies of the efficiency of **coronal loops** to accelerate particles, MHD simulations of these loops were used to generate the environment. It was found that the loops are very efficient particle accelerators, to the degree that the energy, in the particle gets so large, that a non-negligible feedback onto the coronal magnetic field must be expected and the magneto-hydrodynamic (MHD) approach must be questioned.
  b) In tokamak **fusion plasmas**, the transport properties of impurities and fast α-particles are very crucial for the achievement of good confinement, and also the behaviour of energetic run-a-way electrons needs to be understood for a proper operation of the devices. So-far, we have determined the transport coefficients (diffusivities) of impurities in turbulent fields at the edge region, for different turbulence models. We also investigated how the transport coefficients depend on the magnetic topology, the level of turbulence, and the anisotropies in the turbulent structures.

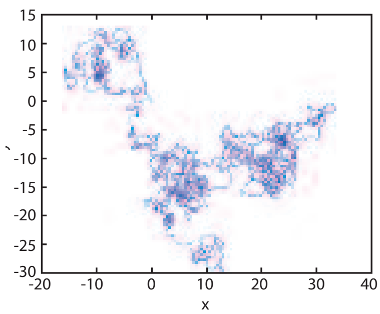


Fig. 3. A typical orbit from test particle simulations of ions in tokamak-like, stochastic magnetic fields.

- Last, we have developed a numerical **Fokker-Planck** solver, which we explore as an alternative tool to model transport, with particular interest in its limitations to describe **anomalous transport** phenomena. In parallel, we work on the development of **fractional transport equations** and their numerical solutions.

Modeling of turbulent systems in space plasmas

Fig. 4. Collapsing currents sheet that leads to the formation of turbulent, fragmented electric fields.

The **solar corona** and **solar wind** are turbulent systems that are widely believed to evolve through the injection of energy at large-scales, the cascading of energy through the inertial range, and the dissipation at small scales. These systems have extensively been studied in the past by using analytical techniques and by performing numerical MHD simulations. Using a **pseudo-spectral** code, which ensures a high numerical accuracy, we have studied the non-linear evolution of collapsing **current sheets** in the **MHD description**, and we have shown that highly fragmented electric fields appear in the course of the collapse. Most importantly, we have shown that the approximations made in the MHD approach are valid only in the very initial phase of the current sheet evolution.

Modeling of turbulent systems in laboratory plasmas

Confined plasmas in **fusion devices**, such as the tokamak, are subject to various instabilities, many of which can lead to a serious reduction of confinement. Of particular interest and related to particle transport are **flute mode** instabilities, instabilities driven by **ion temperature gradients**, and instabilities due to **trapped electrons**. In the framework of **fluid models**, we have studied the non-linear evolution of these instabilities and their implications on particle transport, using **pseudo-spectral** methods for the numerical solution of the fluid equations. In a new project, we numerically solve the MHD equations in polar coordinates, in order to model turbulence in the edge region of tokamak fusion devices.

Complexity models for plasma turbulence

Turbulent systems exhibit complex dynamics on many different scales, with characteristic statistics of e.g. the dissipated energy et c.. **Self-organized criticality (SOC)** models, in the form of cellular automata, are in many cases successful to explain statistical distributions observed in a variety of complex, turbulent systems. Our particular aim in applying SOC models to space and laboratory plasmas is to make the SOC model fully compatible with the underlying physics, and not to use the usual sand-pile analogy.

- In the astrophysical context of **stellar atmospheres**, we have constructed SOC models that are compatible with the resistive MHD description, and which include effects of anomalous resistivity. The SOC models in this form model quantitatively the energy dissipation process, as primarily assigned to magnetic reconnection, and they reproduce the statistical properties of flare as they are observed.

- In the project of the **Integrated Flare Model**, we undertake a modular, unified modeling approach to Solar flares, which includes the modeling of the photospheric driver, the reconstruction of the coronal fields from the photospheric ones, the SOC type evolution of the coronal fields during flares, and the acceleration of particles as well as the emission of X rays.
- In the context of confined plasmas, we have derived a SOC model that is compatible with the physics of micro-instabilities, as they are believed to be dominant in tokamak devices. The model reproduces observed ion temperature profiles in a numerically efficient way, and it makes predictions on the distribution of internal heat-fluxes and the heat out-fluxes.

❖ Non linear interaction of electromagnetic waves with plasma

The nonlinear interaction of **plasma charged particles** with **electromagnetic waves** plays a key role in the description and understanding of particle acceleration and plasma **instabilities** in astrophysical systems and **controlled thermonuclear fusion** devices. In cases where there is a resonance of the Doppler-shifted wave frequency with the cyclotron harmonics, the interaction is stimulated by significant energy exchange between the wave and the particles. Our group research focuses on the following aspects:

- We study the effect of electromagnetic waves on the **dynamics** of magnetized plasmas in terms of the charged-particle orbits. We focus on the characteristics of the energetic and spatial **diffusion** of the resonant electrons across the magnetic field, under the effect of electromagnetic waves of both high and moderate amplitude, where the dynamics of the phase-space is extremely complex.
- We also study the wave-plasma interaction from the viewpoint of the effect of the plasma on the wave, using asymptotic and full-wave methods for the solution of the **wave equation**. The novelty here lies in (a) the generalization of asymptotic methods to include the description of beams with arbitrary electric field profile, (b) the full-wave solution in cases the validity of asymptotic methods is questionable (e.g. mode conversion). As an application, we analyze the wave propagation, absorption and current drive when the **Neoclassical Tearing Mode** (NTM) instability is excited inside a tokamak, focusing on the effect of the **magnetic island** topology on the Electron Cyclotron Current Drive (ECCD) efficiency. Another application is to assess the effect of edge density fluctuations, where, since the distance to the resonance is large, even a small scattering angle may lead to considerable beam broadening and degrade the stabilization effort. Our study includes both asymptotic and full-wave propagation in plasmas with different types of distributions for the density fluctuations.

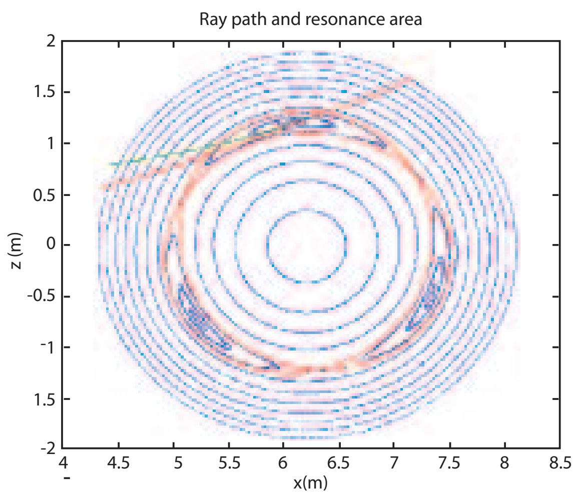


Fig. 5. Asymptotic method solution of electron-cyclotron wave propagation in the presence of overlapping NTMs.

- In a research line combining the previous ones, we perform a self-consistent analysis of the nonlinear interaction of electromagnetic waves with magnetized plasmas in terms of a closed set of **ordinary dif-**

ferential equations, which consists of the relativistic equations of motion and the wave equation for the vector potential. This description allows for the effects of electron-cyclotron motions in the wave absorption, which cannot be simulated in the context of the linear theory for the wave absorption. An important application under way is the construction of a self-consistent numerical model for NTM dynamics and stabilization with ECRH/ECCD. The primary attempt includes the coupling of different kinds of wave propagation solvers (asymptotic and full-wave) with sophisticated **MHD/kinetic** models (modified Rutherford equation, 3D MHD) for the description of the NTM dynamics, in realistic magnetic geometry including the **non-axisymmetric perturbations** (in the form of magnetic islands) generated by the NTMs.

Electrodynamic properties of large scale structure-formation in the universe

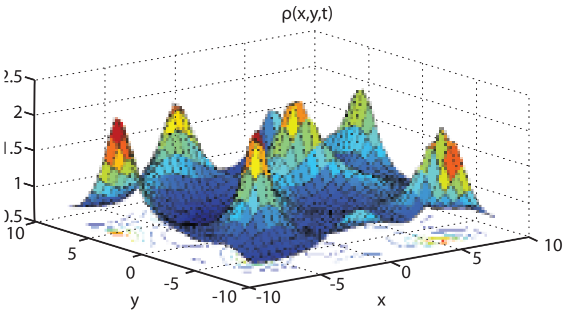


Fig. 6. Density collapse due to the Jeans instability: the instability is associated with magnetic field generation (dynamo) and strong electric activity.

A well known mechanism for the formation of large scale structures in the universe is the Jeans instability, which has extensively been studied in the past. In our own investigations, we numerically solve the **resistive MHD** equations, and we consider the case where a weak initial magnetic field is present. Our particular interest is in the magnetic field generation (dynamo), and in the consequences of the possibly super Dreicer electric fields on the system dynamics and description.

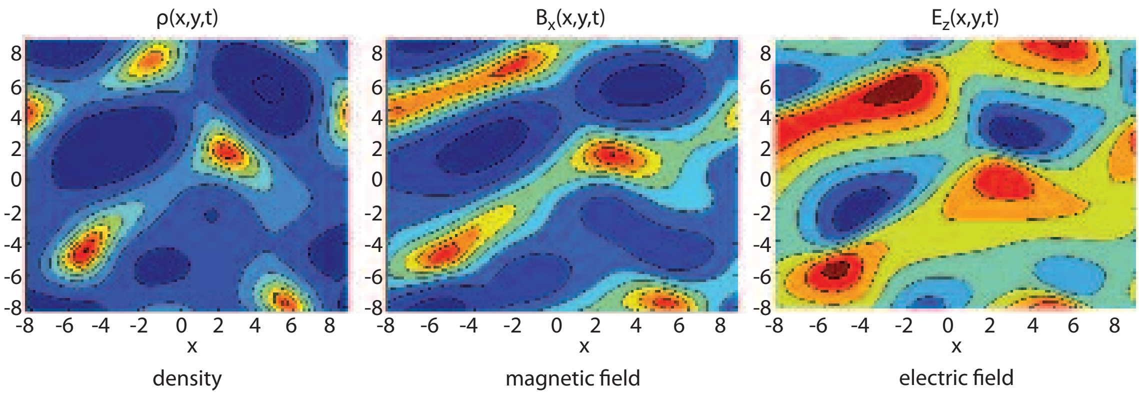


Fig. 7. Collapse due to the Jeans instability: the instability is associated with collapse in density (left), magnetic field generation (dynamo; middle), and strong electric activity (right).

References

Cargill P.J., Vlahos L., Turkmani R., Galsgaard, K., Isliker, H., *'Particle Acceleration in a Three-Dimensional Model of Reconnecting Coronal Magnetic Fields'*, Space Science Reviews **124**, 249 (2006).

Dimitropoulou, M., Georgoulis, M., Isliker, H., Vlahos, L., Anastasiadis, A., Strintzi, D., and Moussas, X., *'The correlation of fractal structures in the photospheric and the coronal magnetic field',* Astron. Astrophys. **505**, 1245 (2009).

H. Isliker, T. Pisokas, D. Strintzi, L. Vlahos, "A self-organized criticality model for ion temperature gradient (ITG) mode driven turbulence in confined plasma" *in press*.

S. Krucker, M. Battaglia, P.J. Cargill, L. Fletcher, H.S. Hudson, A.L. MacKinnon, S. Masuda, L. Sui, M. Tomczak, A.L. Veronig, L. Vlahos, S.M. White, "Hard X-ray emission from the solar corona" Astron. Astrophys. Rev. 16: 155-208 (2008).

Onofri M., Isliker H., Vlahos L., *"Stochastic Acceleration in Turbulent Electric Fields Generated by 3D Reconnection",* Physical Review Letters, **96**, 151102 (2006).

Sandberg, I., Isliker, H. Pavlenko, V., Hizanidis, K., and Vlahos, L., *'Generation and Saturation of Large Scale Flows in Flute Turbulence'*, Physics of Plasmas **12**, 032503 (2005).

Sandberg, I., Isliker, H. Pavlenko, V., Hizanidis, K., and Vlahos, L., *'Fluid simulations of toroidal ion temperature gradient turbulence'*, Physics of Plasmas **13**, 022311 (2006).

Sandberg, I., Isliker, H., Pavlenko, V.P., *'Finite Larmor Radius Effects on the Coupled Trapped Electron and Ion Temperature Gradient Modes',* Physics of Plasmas **14**, 092504 (2007).

Tsironis C., Vlahos L., *"Anomalous transport of magnetized electrons interacting with EC waves"*, Plasma Phys. Control. Fusion, **47**, 131 (2005).

Tsironis C., Vlahos L., *"Effect of nonlinear wave-particle interaction on electron-cyclotron absorption"*, Plasma Phys. Control. Fusion, **48**, 1297 (2006).

Tsironis C., Poli E., Pereverzev G. V., *"Beam tracing description of non-Gaussian wave beams"*, Phys. Plasmas, **13**, 113304 (2006).

Tsironis C., Samaras T., Vlahos L., *"Scattered-field FDTD algorithm for hot anisotropic plasma with application to EC heating"*, IEEE Trans. Antennas Propagat., **56**, 2988 (2008).

Tsironis C., Peeters A. G., Isliker H., Strintzi D., Chatziantonaki I., Vlahos L., *"Electron-cyclotron wave scattering by edge density fluctuations in ITER"*, Phys. Plasmas, **16**, 112510 (2009).

Turkmani, R., Cargill, P.J., Galsgaard, K., Vlahos, L., Isliker, H., '*Particle Acceleration in Stochastic Current Sheets in Stressed Coronal Active Regions'*, Astronomy and Astrophysics **449**, 749 (2006).

Vlahos L., Tsagas C., Papadopoulos D., *"Galaxy formation and cosmic-ray acceleration in a magnetized universe"*, Astrophys. J. **629**, L9 (2005).

2. Cosmology

Cosmology is quickly becoming an observation-based science. The principal drivers over the past fifteen, or so, years have been the large galaxy surveys, the high-precision observation of the Cosmic Microwave Background (CMB) spectrum and the recent supernovae magnitude-redshift measurements. Despite the influx of data, however, the key questions of how the universe begun and how it has evolved to its present state remain open and the subject of debate. Members of the Laboratory of Astronomy at the University of Thessaloniki, have been actively involved in the ongoing quest for answers to these questions and some of the current research interests include:

- **The very early universe**

The high isotropy of the CMB and the success of primordial nucleosynthesis strongly support the idea that our universe is very well described by the simplest cosmological solutions of Einstein's equations: the homogeneous and isotropic Friedmann-Robertson-Walker (FRW) models. Nevertheless, we still have very limited information about the early stages of the creation and although inflation seems compatible with the current observations, the picture of the very early universe is not yet complete. Besides the FRW models, Einstein's equations contain a wealth of solutions that could also describe epochs, or sections, of our universe. Non-Friedmannian cosmologies have long been studied as alternative scenarios of (mainly) the early universe, and going beyond the FRW limits should shed more light to the `agents' and the `forces' that shaped our world. The family of the anisotropic Bianchi models, for example, has been used to understand and explain the weak anisotropy of the observable universe. One of the main questions of contemporary cosmology has been that of the initial singularity, whether or not the latter is unavoidable, or there can be viable models without a singularity at the beginning. We also want to know more about role of the various sources (e.g. baryons, dark matter/energy, electromagnetic fields, gravitational waves, etc) during the early life of the universe and about their interaction; if there is energy transfer between these sources and whether their interplay can favor some at the expense of others. The hope is that this knowledge will help to make the picture of the early universe clearer and more complete.

- **Cosmological magnetic fields**

Magnetic fields have been observed everywhere in the universe. From the Earth, the Sun and the Milky Way, all the way to distant galaxy clusters and high-redshift proto-galactic structures, the magnetic presence has been repeatedly verified. Nevertheless, the origin of cosmic magnetism remains an enigma. We also know relatively little about the evolution and the implications of the large-scale magnetic fields that we observe in the universe today. The dynamo mechanism can amplify and sustain the galactic B-fields, but requires an initial magnetic seed to operate. So, where do we get these seed-fields from? The idea of primordial magnetism is attractive because it could potentially explain all the B-fields observed in the cosmos. Early magnetogenesis, however, is not problem-free. Magnetic seeds generated between inflation and recombination have typical coherence lengths too weak to sustain the dynamo. Inflationary B-fields, on the other hand, are typically too weak to seed the galactic dynamo. As a result, considerable effort has been put into amplifying such inflation-produced magnetic seeds. The majority of the proposed mechanisms, however, solve the problem by introducing, in one way or another, new physics. So, success is usually achieved at the expense of simplicity. Spacetime curvature, through its Ricci or Weyl components, could provide a simple way of amplifying primordial magnetic fields, without breaking away from standard physics or abandoning conventional cosmology. These proposed geometrical mechanisms are purely relativistic and affect inflationary produced, large-scale B-fields. Moreover, the achieved magnetic amplification could be strong enough to reach the dynamo required strengths.

- **Large-scale drift motions the universe**

At the end of the last decade, observations of remote supernovae indicated that the expansion of our universe was accelerating. The same data also suggested that universal acceleration was a relatively recent event, putting the transition from deceleration to acceleration around two billion years ago. The supernovae observations and their interpretation were so unexpected that the effort to explain them has dominated almost every aspect of contemporary cosmology. Dark energy, an unknown and elusive substance, which repels instead of attracting gravitationally, has so far been the most popular answer. As a result, almost all (95%) of the matter in the current `concordance' model, is in some unknown and mysterious form. This has led a number of cosmologists to seek alternative answers. The proposals include changes to the theory of gravity, the introduction of extra dimensions, abandoning the FRW models, or incorporating the large-scale effects of structure formation to the standard model. An attractive aspect of the latter suggestion is its ability to explain the `coincidence problem', namely why the accelerating phase is a relatively recent event, naturally. So far, the large-scale effects of structure formation have been bypassed as negligible. This, however, is a working assumption rather than a verified fact and the number of cosmologists willing to put it to the test is increasing. The opportunity to do so may come from recent independent surveys measuring large-scale, bulk peculiar velocities. The latter are a direct product of structure formation and can affect large sections of space. Our Local Group of galaxies, for example, drifts relative to the smooth Hubble flow at around 600 km/sec. The aforementioned surveys estimated bulk flows of approximately 1000 km/sec on scales ranging from 100 to 1000 Mpc. These numbers far exceed those predicted by the concordance model and potentially put a question mark on its applicability. With these in mind, one would like to know what causes bulk motions of such magnitude and also study their implications for the large-scale kinematics of our universe.

- **Electromagnetic fields in curved spacetimes**

According to General Relativity, gravity is not a force but a manifestation of the non-Euclidean geometry of the spacetime. Within this geometrical interpretation of the gravity, electromagnetic fields have a special status. What makes the Maxwell field unique, is the vector nature of its two components. In particular, the electromagnetic field is the only vector source of energy that we know to exist. Just like any other source of energy, the Maxwell field couples to the curvature of the space via the Einstein equations. Because of its vector nature, however, the electromagnetic field `feels' the curvature of the space through the Ricci identities as well. This purely geometrical interaction between the Maxwell and the gravitational field also brings into play the tension properties of the magnetic field lines, leading to a series of nontrivial and sometimes counterintuitive effects. Provided that General Relativity is the correct theory of gravity, one would like to know more about the aforementioned gravito-electromagnetic coupling, especially in situations where the gravitational field is strong (e.g. compact stars, the early universe).

- **Relativistic MHD Phenomena in Plasma Cosmology**

According **to the Standard Model**, after nucleosynthesis the Universe goes on expanding and cooling but nothing of great interest takes place until $t \sim 10^{13}$ $s(z \sim 10^3)$. At that time, the temperature drops to the point where electrons and nuclei can form stable atoms (recombination epoch). During the so-called **radiation epoch**, photons couple strongly with matter, the main constituent of which is in the form **of cosmological plasma**. Interactions between the various constituents of the Universal matter content along this period include radiation-plasma coupling which is described by plasma dynamics. On the other hand, the presence of plasmas plays an important role in shaping the radiation spectrum, something that is fortified by the fact that there appear to exist cosmic magnetic fields. Therefore, although it is not traditional to characterize the radiation epoch by the dominance of plasma interactions, it may well be also called the **plasmas epoch**. It is the time-period during which the electromagnetic interaction dominates among the four fundamental forces.

Although Plasma Physics and Cosmology are two well-established fields of Theoretical Physics, the formulation of magnetohydrodynamics (MHD) in curved spacetimes is a relatively new development. In particular, in spite the fact that MHD processes in flat spacetime gained much attention, only recently we were able to discuss exact spherically symmetric MHD solutions within the context of General Relativity (GR), something that gave rise to efforts of exploring MHD processes in the vicinity of central engines and in Cosmology (plasma epoch). The obtained, so far, results lead the scientist to go even further and search for gravitational instabilities in magnetized cosmological spacetimes either in the Newtonia or GR limit and use them to study the finite-amplitude wave propagation in MHD media.

Research on this area is related to the interaction of the GW as it propagates through a magnetized ideal plasma.

In the linearized theory of gravity the excitation of fast magnetosonic waves by GW have been examined and verified that the GWs do not couple with Alfven waves whenever propagate along the magnetic field but do couple with the magnetosonic waves whereas propagate across the magnetic field. In this case the GW is considered as a small fluctuation to the background Minkowski space-time.

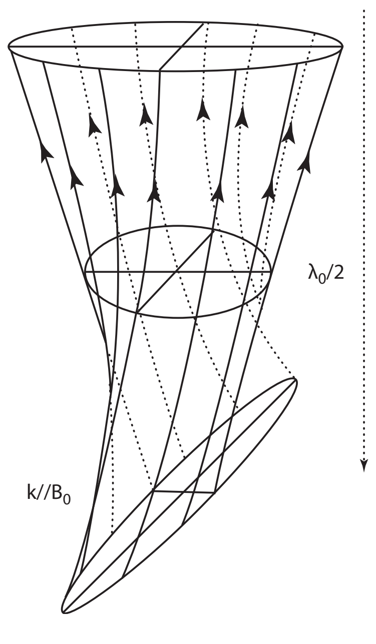


Fig. 8. Sketch of the effect of a large-amplitude GW travelling parallel to a uniform magnetic field frozen into an ambient ideal plasma, k ∥ Bo at an arbitrary time. Here the vertical direction coincides with the direction of wave propagation and of the background magnetic field.

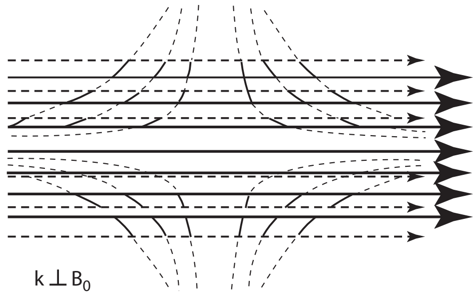


Fig. 9. Sketch of the effect of a GW travelling perpendicular to a uniform magnetic field frozen into an ideal plasma. The tidal motion of the GW is indicated with curved dashed lines. The drawn and, respectively, dashed arrowed lines are the magnetic field lines half a cycle apart. Their individual relative displacements are shown by the bold sections along the tidal curves. Note that the field lines remain straight under the action of the GW.

In the linear theory of gravity, the equations that determine the response of a charged particle moving in a uniform magnetized field to an incident GW have been derived. When the GW propagates parallel to the magnetic field with frequency ω_g, the coupling of a gyrating particle with the GW becomes very strong and the resonance that occur between the GW and the Larmor orbit. In the case that the GW propagates perpendicular to the magnetic field, the interaction becomes extremely efficient at the resonances $\omega = \Omega = eH/mc$ and $\omega = 2\Omega$. and. In both cases, the obtained spectrum of the produced cyclotron radiation becomes comparable to the spectrum of the initially gyrating particle especially in the vicinity of a source producing GWs.

- **GW in the early stages of the Universe**

The equation which governs the temporal evolution of a gravitational wave (GW) in curved space-time can be treated as the Schrodinger equation for a particle moving in the presence of an effective potential. When GWs propagate in an expanding Universe with constant effective potential, there is a critical value (k_c) of the co-moving wave-number which discriminates the metric perturbations into oscillating ($k > k_c$) and non-oscillating ($k < k_c$) modes. As a consequence, if the non-oscillatory modes are outside the horizon, they do not freeze out. The effective potential is reduced to a non-vanishing constant in a cosmological model which is driven by a two-component fluid, consisting of radiation (dominant) and cosmic strings (sub-dominant). It is known that the cosmological evolution gradually results in the scaling of a cosmic-string network and, therefore, after some time (Δ_τ) the Universe becomes radiation-dominated. The evolution of the non-oscillatory GW modes during Δ_τ (while they were outside the horizon), results in the distortion of the GW power spectrum from what it is anticipated in a pure radiation-model, at present-time frequencies in the range of $10^{-16}\,Hz < f < 10^5\,Hz$.

Nevertheless, it has been suggested that, there might be a period in the early Universe, in which the matter-content can be modelled by a two-component fluid, consisting of radiation (dominant) and cosmic strings (subdominant). During this radiation-plus-strings stage, the effective potential in the equation, which governs the temporal evolution of a gravitational wave (GW), is constant, leading to a critical co-moving wave-number (k_c), which discriminates the metric perturbations into oscillating ($k > k_c$) and non-oscillating ($k < k_c$) modes. As the cosmological evolution gradually results in the scaling of any long-cosmic-string network, eventually, the Universe enters in the pure-radiation epoch. Following the evolution of the oscillating modes along this transition, we end up with the quantum-gravitational creation of gravitons with a characteristic spectrum. Accordingly, several theoretical as well as observational consequences are discussed, the most important being the amplification of the relic GW signal by, approximately, two orders of magnitude.

Assuming that after the Big-Bang the Universe enters in the inflation period, we examined in an almost de Sitter space-time, the stochastic semiclassical Einstein-Langevin equation with cosmological constant in the TT-gauge in a perturbative way, e.g. as zero-order and first order equations. The zero-order equation gave an exact solution for the scale factor proportional to the cosmological constant Λ corresponding to a continuous expanding universe. Knowing the scale factor(s) and applying order reduction to the inhomogeneous first order equations, we obtained explicit results for the tensor perturbations in the Bunch-Davies vacuum, describing the evolution of the GWs modes in an almost de Sitter Universe. In this scenario, we have computed a retarded Green function and a two point correlation function, which describes how large are the physical perturbations on different time scales.

- **Non linear interaction of gravitational waves with plasma**

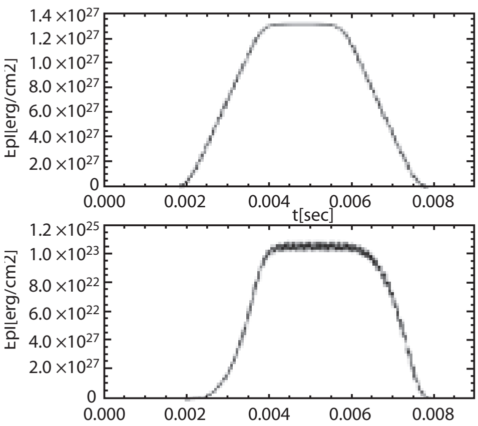


Fig. 10. Energy density in the gravitational wave (top) and in the plasma (bottom) as a function of time.

The interaction of gravitational waves with plasma is a completely non-linear effect, and it is efficient only in the presence of a very strong background magnetic field. A known case where this interaction is expected to be efficient and relevant is in the vicinity of **magnetars**.

To study this interaction in its full non-linearity (including e.g. non-linear saturation effects and feedback mechanisms), we have developed a relativistic MHD solver, for flat background metric, in which we focus on the case of very strong magnetic fields.

- **Thermodynamics of the cosmological structures and of the Universe as a whole**

Current observational data suggest that the observable Universe differs very much from the simple picture of a collection of more or less widely separated galaxies or higher-order cosmological structures, and that the latter differ very much from their optical and radio pictures. The constituting elements of the Universe and, plausibly, the Universe in its large scales, can quite satisfactorily be treated as continuous gravitational systems and, more specifically, as bounded gravitating sources, preferably perfect-fluid sources. As predicted in the *Dynamical-Equivalence Approach* (DEA) in the case of a general-relativistic gravitating bounded perfect-fluid (magnetized or not), the isentropic hydrodynamical flows (and the properly defined hydromagnetic flows) are dynamically equivalent to the geodesic motions in a fully defined virtual perfect-fluid source. In the Newtonian theory of gravity, the generalized mass density producing the above generalized new geodesic motions can be either positive, or negative, or even vanish. This implies the possibility of a spatially increasing, or decreasing, or even non-changing acceleration, depending, beyond the internal physical characteristics of the source considered, on the distance from the center of the source as compared to the so-called inversion distance. This is the distance from the origin separating the regions of dominance of the attractive and repulsive gravity forces in the source. The extra ingredient to the generalized mass density, stemming from the source's internal physical characteristics, results in an extra, negative mass, the so called internal mass, contributing to the geodesic motions in the source, and, thus, clarifying some currently open cosmological issues, like the flat rotation curves in galaxies and the missing-mass problem. As a consequence, a new picture emerges for any cosmological structure as a hot structure extending well beyond its conventional boundaries. For a supercluster of galaxies, the theoretically determined maximal linear dimensions and the matter's absolute temperature are found to be in accordance with the available observational data, and, especially, the fact that no third-order clusters of galaxies have been observed up to now. Applying the above theoretical prototype in the case of a fluid source, magnetized or not, also other phenomena could be explained, like the observed anomalies in the motion of solar-system space probes e.g. the well-known **Pioneer Anomaly effect**, and also **the stellar winds** and **the jets**, both stellar and galactic. Finally, currently, there exist observational indications that the dark matter, namely, the dominant part of the mass of the Universe, presents some **thermodynamical properties**. If so, treating the dark matter as a bounded gravitating perfect fluid source, it is possible to explore the role of the **Universe's thermodynamical content** on its properties like e.g. whether its acceleration is **accelerating or decelerating**, the necessity at all of the **dark energy**, and the necessity at all of the celebrated **cosmological constant**.

References

Barrow J.D., Tsagas C.G., *New isotropic and anisotropic sudden singularities*, *Class. Quantum Grav.* **22**, 1563 (2005)

Barrow J.D., Maartens R., Tsagas C.G., *Cosmology with inhomogeneous magnetic fields*, *Phys. Rep.* **449**, 131 (2007)

Barrow J.D. and Tsagas C.G, *'Slow decay of magnetic fields in open FRW cosmologies'*. Phys, Rev. D **77** 107302 (2008)

Barrow J.D. and Tsagas C.G., *'On the stability of static ghost cosmologies'* Class. Quantum Grav. **26** 195003 (2009)

Ellis E.F.R. and Tsagas, "*Relativistic approach to nonlinear peculiar velocities and the Zeldovich approximation*" Phys. Rev. D, **66** 124015 (2002)

Isliker H., Sandberg I., Vlahos L., Physical Review D, **74**, 104009 *"Interaction of gravitational waves with strongly magnetized plasmas"*, (2006)

Kleidis K., D.B. Papadopoulos, E.Verdaguer and L.Vlahos, Phys.Rev.D., **78**, 024027 (2008)

Kleidis K., and Spyrou, N.K., "*A conventional approach to the dark-energy concept"*, to appear in "Astronomy and Astrophysics" (2011)

Spyrou, N.K. 2005a, "A *Classical Treatment of the Problems of Dark Energy, Dark Matter, and Accelerating Expansion*" (in Proceedings of the Conference Recent Developments in Gravity (NEB) XI (Mytilini, Lesvos, Hellas, 2-6 June 2004), J.Phys.Conf.Ser. 8, 122-130

Spyrou, N.K., and Tsagas, C., *"Newtonian non-linear hydrodynamics and magnetohydrodynamics"*, Mon. Not. R. Astron. Soc. 388, 187–196, (2008)

Spyrou, N.K., and Tsagas, C.G., "*Magnetohydrodynamic flows as Newtonian-type gravitational motions*", Central European Journal of Physics **8** (6), 989-994 (2010)

Tsagas C.G. "*Magnetic Tension and the Geometry of the Universe*", Phys. Rev. Lett. **86** 5421 (2001)

Tsagas C.G. and Kandus A., *'Superadiabatic magnetic amplification in conventional cosmology'* Phys. Rev. D **71** 123506 (2005)

Tsagas C.G., *'Electromagnetic fields in curved spacetimes'* Class. Quantum Grav. **22** 393 (2005)

Tsagas C.G., *'Magnetic tension and gravitational collapse'* Class. Quantum Grav. 23 4323 (2006)

Tsagas C.G., Challinor A. and Maartens R., *'Relativistic cosmology and large-scale structure'* Phys. Rep. **465** 61 (2008)

Tsagas C.G., *'Gravito-magnetic amplification in cosmology'* Phys. Rev. D **81** 043501 (2010)

Tsagas C.G., *'Large-scale peculiar motions and cosmic acceleration'* Mon. Not. R. Astron. Soc. in press (2010)

Voyatzis G., Vlahos L., Ichtiaroglou S., Papadopoulos D., "*Acceleration of low energy charged particles by gravitational waves",* Phys.Lett.A., **352,** 261 (2006)

3. Gravitational Wave Astronomy and Numerical Relativity

- Research in this area focuses on the study of gravitational wave sources as well as other phenomena in relativistic astrophysics. One main project is the computation of the frequencies of normal modes of oscillation for relativistic stars and black holes. New methods have been developed for the study of various oscillation modes in rapidly rotating stars, in the framework of scalar-tensor gravity and in strongly magnetized stars. A recent result of this effort is the discovery that accreting compact stars in binary systems can be subject to an instability of their rotational modes, becoming a strong persistent source of gravitational waves.

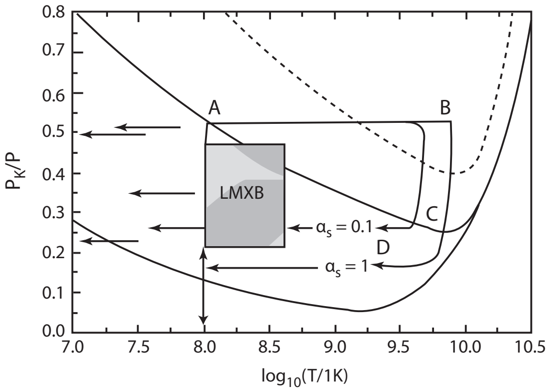


Fig. 11. The instability window of the r-mode instability, limiting the spin of accreting neutron stars.

- For the study of gravitational wave sources, three-dimensional nonlinear simulations using the full Einstein's equations are performed on supercomputers. Recently, the gravitational wave signature of the collapse of unstable rotating proto-neutron stars to Kerr black holes has been studied and a new way to form supermassive black holes, through the onset of non axisymmetric dynamical instabilities, has been found.
- The results of the computations are useful for the data analysis in the new generation of gravitational wave detectors. There is close collaboration with the VIRGO experiment (through the VIRGO-EGO Scientific Forum) and GEO600 (through the Neutron Star Dynamics Network)

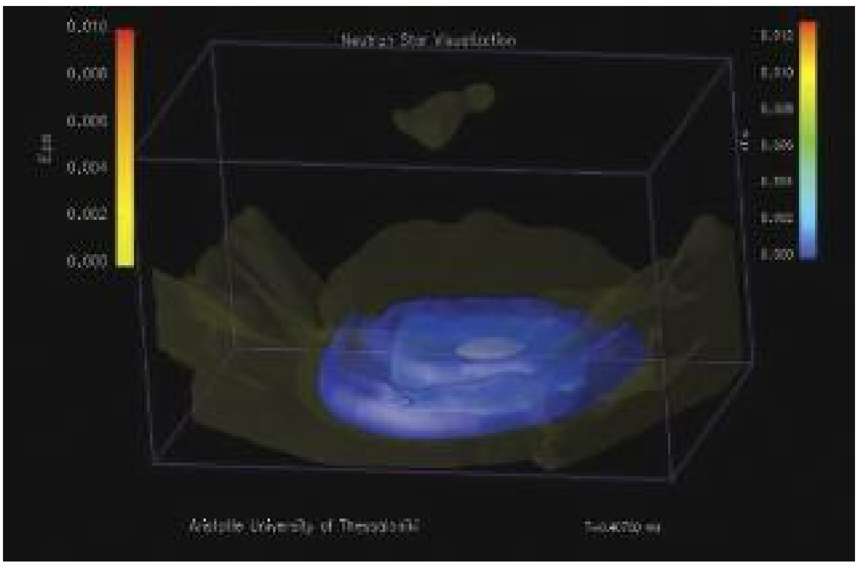


Fig. 12. Three-dimensional simulation of the collapse of a differentially rotating relativistic star in full general relativity.

as well as with the planned LISA experiment. In the case of successful detection of gravitational waves from relativistic stars, the formalism of gravitational wave asteroseismology that has been developed, will allow for a better understanding of the nature of matter in the interior of such stars.

Fig. 13. The VIRGO laser-interferometric gravitational wave detector.

References

Colaiuda A., Beyer H., Kokkotas K.D. ¨*On the QPOs oscillation in Magnetars*¨ Mon. Not. R. Astron. Soc. 396, 1441 (2009).

Gaertig E., Kokkotas K.D., *Oscillations of Rapidly Rotating Relativistic Stars* Phys. Rev. D 78 064063 (2008).

Sotani H., Colaiuda A., Kokkotas K.D., Constraints on the Magnetic Field of Magnetars Mon. Not. R. Astron. Soc. 385 2161-2165 (2008).

Sotani H., Kokkotas K. D., N. Stergioulas, *Alfvén quasi-periodic oscillations in magnetars*, Mon. Not. R. Astron. Soc., 385, L5 (2008).

Stavridis A., Passamonti A., Kokkotas K.D., "Non-radial Oscillations of Slowly and Differentially Rotating Compact Stars", Phys. Rev. D 75, 064019 (2007).

Stergioulas N., Font J., A *Alfvén QPOs in magnetars in the anelastic approximation*, P. Cerdá-Durán, Mon. Not. R. Astron. Soc., 397, 1607 (2009).

Stergioulas N., *Numerical simulations of black hole formation*, Lecture Notes in Physics, 769, 177 (2009).

Vavoulidis M., Stavridis A., Kokkotas K.D., Beyer H., "Torsional Oscillations of Rotating Stars", Mon. Not. R. Astron. Soc. *377, 1553 (2007).*

Vavoulidis M., Kokkotas K.D., Stavridis A. *Crustal Oscillations of Slowly Rotating* Relativistic Stars Mon. Not. R. Astron. Soc. 384, 1711 -1724 (2008).

Zink B., Stergioulas N., Hawke I., Ott C.D., Schnetter E., Müller E., "Formation of Supermassive Black Holes through Fragmentation of Torodial Supermassive Stars", Physical Review Letters, 96, 161101 (2006).

4. Observational Astronomy

- **Neutron Stars**

Using high resolution observations and polarization data at a wide range of high frequencies, the geometry and emission mechanism of pulsar radiation is investigated. The study focuses on the width of the components of the integrated pulses, which, according to theoretical models, should increase from the centre of the pulse to its boundaries. The Observational Astronomy group of the Laboratory of Astronomy participates in the PULSE international cooperation. By using advanced tracing techniques, the cooperation has doubled the number of known neutron stars (pulsars) during the last few years. Special attention has been given to those with a small period of rotation (msec pulsars). One of the highlights of this work is the tracing and study of a double pulsar system, which is used to unfold properties predicted by General Relativity. For this work, the PULSE cooperation has been awarded the 2005 Descartes prize for research.

- **Neutral hydrogen in nearby and infrared galaxies**

A sample of nearby galaxies has been studied in order to investigate their global properties (extent, mass, dynamics, etc.). A computer model was used in order to extract these parameters from the observed data. The main aim of this investigation is to determine the amount of missing mass in these galaxies.

- **Radio continuum (Galactic centre, SNR, gamma-ray sources)**

Using radio continuum observations at several frequencies, the galactic center and other interesting regions in our Galaxy have been investigated. Particularly successful results were obtained at high frequencies towards the galactic centre where the polarization properties of the region have been extensively studied. The main aim of this research is to determine the properties of the massive source in the centre of our Galaxy, its mass and spatial distribution. The overall magnetic field of the region is under investigation.

- **Variable stars**

Studies of flare stars and RS CVn stars, using the 30 inch Cassegrain telescope of the Stephanion Observatory or the 1.2m Kryonerion telescope are undertaken, in collaboration with international teams using ground or space instruments covering a wide range of frequencies. The data have been used to model the stars' atmospheric activity, including stellar spots. The spots that are usually found on the surface of certain categories of stars are studied in order to calculate their period of rotation. For some objects (such as the SS433 microquasar), we search for relations between the periodicities observed and the physical properties of these objects. The problem of the generation of explosions on the surfaces of flaring stars is approached with the collaboration of many Observatories and by different astronomical observations. The temperature and the spectral index are documented for a wide range of observations and the emission mechanism has been found for a small but representative number of flaring stars.

- **Studies of the solar atmosphere**

During the total solar eclipse at Akademgorodok, Siberia, Russia, on 1 August 2008, we imaged the flash spectrum with a slitless spectrograph. We have spectroscopically determined the duration of totality, the epoch of the 2nd and 3rd contacts and the duration of the flash spectrum. Here we compare the 2008 flash spectra with those that we similarly obtained from the total solar eclipse of 29 March 2006, at Kastellorizo, Greece. Any changes of the intensity of the coronal emission lines, in particularly those of [Fe X] and [Fe XIV], could give us valuable information about the temperature of the corona. The results show that the ionization state of the corona, as manifested especially by the [Fe XIV] emission line, was much weaker during the 2008 eclipse, indicating that following the long, inactive period during the solar minimum, there was a drop in the overall temperature of the solar corona.

- **Extrasolar Planets**

Searches for extrasolar planets using the "transient" method. Studies of the characteristics of the orbits of these planets with multi-telescope campaigns.

References

Hidas, M. G., Tsapras, Y., Mislis, D., Ramaprakash, A. N., Barros, S. C. C.; Street, R. A., Schmitt, J. H. M. M.; Steele, I.; Pollacco, D., Ayiomamitis, A., Antoniadis, J., Nitsos, A., Seiradakis, J. H., Urakawa, S. "*An ingress and a complete transit of HD80606 b*" Mon. Not. R. Astron. Soc. (2010)

Kalfountzou, E., Trichas, M., Rowan-Robinson, M., Babbedge, T., Clements, D., Seiradakis, J. "EFOSC2 Spectroscopy of SWIRE-CDFS" submitted for publication to Mon. Not. R. Astron. Soc. (2010)

Konstantinova-Antova, R. K., Antov, A. P., Zhilyaev, B. E., Verlyuk, I. A., Romaniuk, Ya. O., Svyatogorov, O. A., Avgoloupis, S., Seiradakis, J. H., Contadakis, M. E. "*The flare activity of V390 Aur: First results of an international collaboration*" Astron. Nachr. AN **326**, No. 1, 38–42 (2005)

Pasachoff, J. M.; Babcock, B. A.; Souza, S. P.; Bruck, M. A.; Hess, P. W.; Kimmel, S. B.; Levitt, J. S.; Steele, A. S.; Tsykalova, A. E.; Rust, D. M.; Noble, M. W.; Wittenmyer, R.; Kern, J.; Hawkins, R. L.; Seiradakis, J. H.; Voulgaris, A.; Pistikoudis, G.; Nestoras, J.; Demianski, M. "*Coronal Observations at the 29 March 2006 Total Solar Eclipse*" Bulletin of the American Astronomical Society, Vol. 38, p.216(2006)

Seiradakis, J. H., Wielebinski R. "*Morphology and characteristics of radio pulsars*" The Astronomy and Astrophysics Review, Vol **12**, Issue 4, pp.239-271 (2004)

Voulgaris A., Athanasiadis T., Seiradakis J.H., Parachoff J.M., "*A comparison of the Red and Green Coronal Line Intensities at the 29 March 2006 and the 1 August 2008 Total Solar Eclipses: Considerations of the Temperature of the Solar Corona*" *Solar Physics*, **264**, p.p. 45-55 (2010).

Zhilyaev, B. E., Romanyuk, Ya. O., Svyatogorov, O. A., Verlyuk, I. A., Kaminsky, B., Andreev, M., Sergeev, A. V., Gershberg, R. E., Lovkaya, M. N., Avgoloupis, S. J., Seiradakis, J. H., Contadakis, M. E., Antov, A. P., Konstantinova-Antova, R. K., Bogdanovski, R. "*Fast colorimetry of the flare star EV Lacertae from UBVRI observations in 2004*" A&A 465,235–240 (2007)

5. Early-Greek Astronomical Science and Technology

α) Ancient Ionian Philosophers

This kind of research refers to the astronomical knowledge of the ancient Greeks and to the importance of their contribution to the astronomical-cosmological science and technology.

Special attention is given to the contributions of the ancient Ionian Philosophers, as the founders of the current scientific reasoning and to the necessary efforts to restore, at both the national and international levels, the historical truth concerning these contributions.

Fig. 14. The ancient Greek, Ionian philosopher, astronomer and geometer, *Aristarchos of Samos*.

A Few Activities

Spyrou N.K. "*Ionian Philosophers and Early Greek Cosmology*", Invited Open Talk, In Proceedings of the International Conference Multiwavelength Cosmology, 17-20 June, 2003, Astrophysics and Space Science Library, Volume 301, Kluwer Academic Publishers, Dordrecht, 2004.

Spyrou N.K. "*Ionian Philosophers and Cosmological Science*", Invited Talk, In Proceedings of the International Conference Influence of the Olympic Spirit on Human Progress, 5-7 December 2003, Ed. IDISIEEP, Publisher Mathitis-Anatoli, Thessaloniki, 2004.

Spyrou N.K. "*Aristarchos of Samos ATV-4*" Official Suggestion to the *European Space Agency* for naming the European spacecraft ATV-4 as *Aristarchos of Samos*, 2010, Thessaloniki.

b) The Antikythera Mechanism

The Antikythera Mechanism was found by chance, in a shipwreck, close to the small Greek island of Antikythera (between Crete and Peloponnese) in April 1900, by sponge divers. The shipwreck was dated between 86 and 67 B.C. (coins from Pergamon). Later the Mechanism was stylistically dated, by epigraphologists, around the second half of the 2nd century B.C. (100 – 150 B.C.). About this time the great Greek astronomer Hipparchos (190 – 120 B.C.) lived in Rhodes.

Fig. 15. The, under study, fragments of Antikythera Mechanism. The larger piece's (upper left side) dimensions measured to be 15cm × 16cm.

It was a portable (laptop-size), geared artifact which calculated and displayed, with high precision, the movement of the Sun and the Moon on the sky and the phase of the Moon for a given epoch. It could calculate the dates of the four-year cycle of the Olympiad and its associated Crown Panhellenic Games and could predict eclipses. It had one dial on the front and two on the back. Its 30 precisely cut gears were driven by a manifold, with which the user could set a pointer to any particular epoch (at the front dial). While doing so, several pointers were synchronously driven by the gears, to show the above mentioned celestial phenomena on three accurately marked annuli. It contained an extensive user's manual. The exact function of the gears has finally been decoded and a large portion of the manual has been read after 2000 years by a major new investigation, using state of the art equipment.

Based on new surface photography and high resolution tomography data, a new model has been built at the Aristotle University, revealing the technological abilities of ancient greeks.

No complicated geared instruments are known before the Antikythera Mechanism and for several centuries after. Therefore, this astronomical device, which stands out as an extraordinary proof of high tech in ancient times, imposes a compelling need to re-write the books of the history and evolution of early Technology.

References

Freeth T., Bitsakis Y., Moussas X., Seiradakis J. H., Tselikas A., Mangou H., Zafeiropoulou M., Hadland R., Bate D., Ramsey A., Allen M., Crawley A., Hockley P., Malzbender T., Gelb D., Ambrisco, W., Edmunds M. G., *"Decoding the ancient Greek astronomical calculator known as the Antikythera Mechanism"* Nature, 444, pp. 587-591 (2006).

Moussas X., Seiradakis J. H., Freeth T., Bitsakis Y., Tselikas A., Magkou E., Zafeiropoulou M., Hadland R., Ramsey A., Allen M., Malzbender T., Edmunds M. G., Dumas G., *"The Antikythera Mechanism, the Oldest Known Astronomical Computer"* Romanian Astronomical Journal, Vol. 18, 281-282 (2008).

6. Near-Earth Space Environment

The purpose of this kind of research is to reveal a new form of environment, the so-called “Near-Earth Space Environment”, and to present evidence in favor of Astronomy as a typical environmental science. Furthermore, the inevitable, mutual interaction of man and Near-Earth Space Environment and its consequences are examined. The necessary actions are described for the protection of the Near-Earth Space Environment, in order to preserve it and our planet Earth for the benefit of Astronomy and future generations. Finally, the adverse environmental risks for mankind, due to man himself, are exposed, the consequent risks due to the acceptance of science, its role, and its importance are briefly exposed, and, finally, actions are suggested for the long range confrontation of these risks.

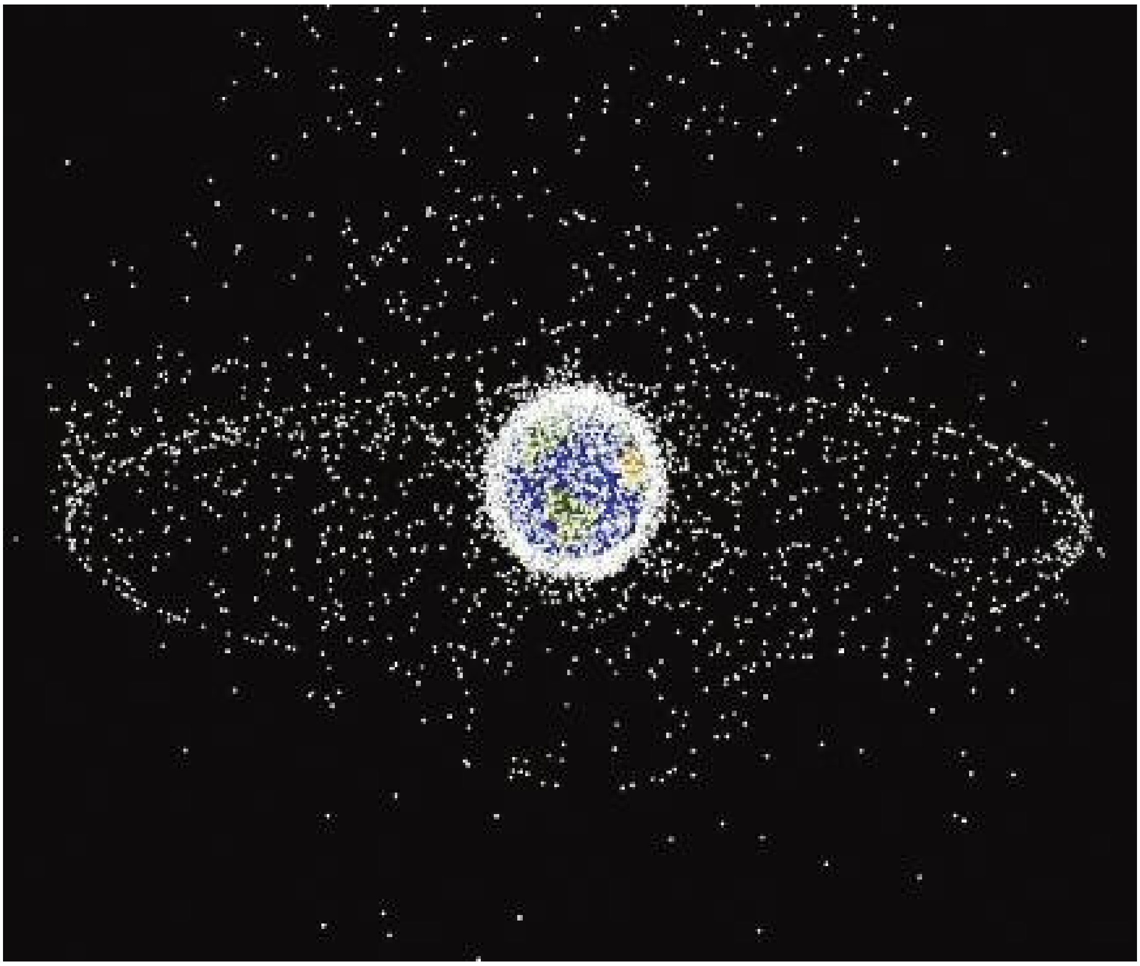


Fig. 16. A schematic showing the locations of known debris in Earth orbit with heavy concentrations in low-Earth orbit and geostationary orbit

A Few Activities

Spyrou N.K., “*Mutual Interaction of Man and the Near-Earth Space Environment*” Invited Lecture, University of Aegean, Mytilene, 20 May 2009

7. Greece and the European Space Agency (ESA)

This kind of activities aim to promoting the importance of the peaceful and interdisciplinary co-operation in space for the benefit of man and life on Earth, and also for advertizing the ideas of the *European Space Agency* (*ESA),* the *International Space Station*, and the European Space Laboratory *Columbus*, thus contributing to the success of the official joining of Greece to ESA (For details see www.astro.auth.gr Link: ESA Activities)

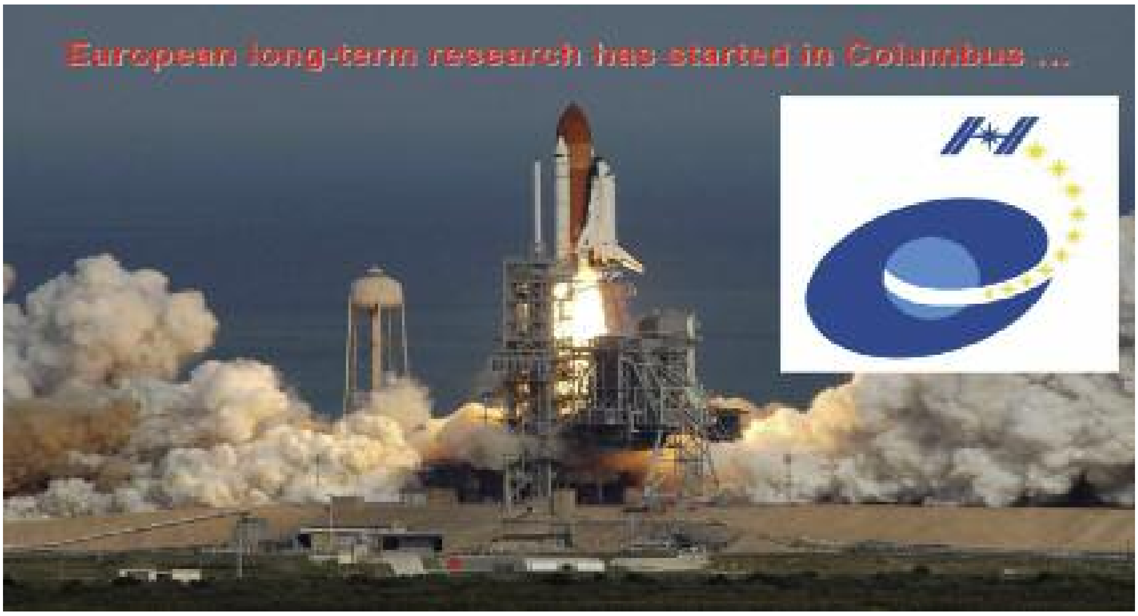


Fig. 17. The European long-term research has started with the European space laboratory "Columbus", already docked permanently to the International Space Station.

A Few Activities

Spyrou N.K., "*The Selection of the New European Astronauts and the Greek Participation*" press conference in the occasion of selection of the new European Astronauts, Thessaloniki, 16 June 2009

Spyrou N.K., "*Man and the Near-Earth Space Environment – The Astronomical Perception*" Invited Talk in Proceedings of the 3rd Conference of the Environmental Council of Aristotle University of Thessaloniki, pp. 45-53 (Ed. Ziti, Thessaloniki 2009)

Spyrou N.K., Spyrou K.N., "*SPACE Base Europe*" Book, cited in *ESA Bulletin*, Issue 141 (February 2010, p.80 www.esa.int)

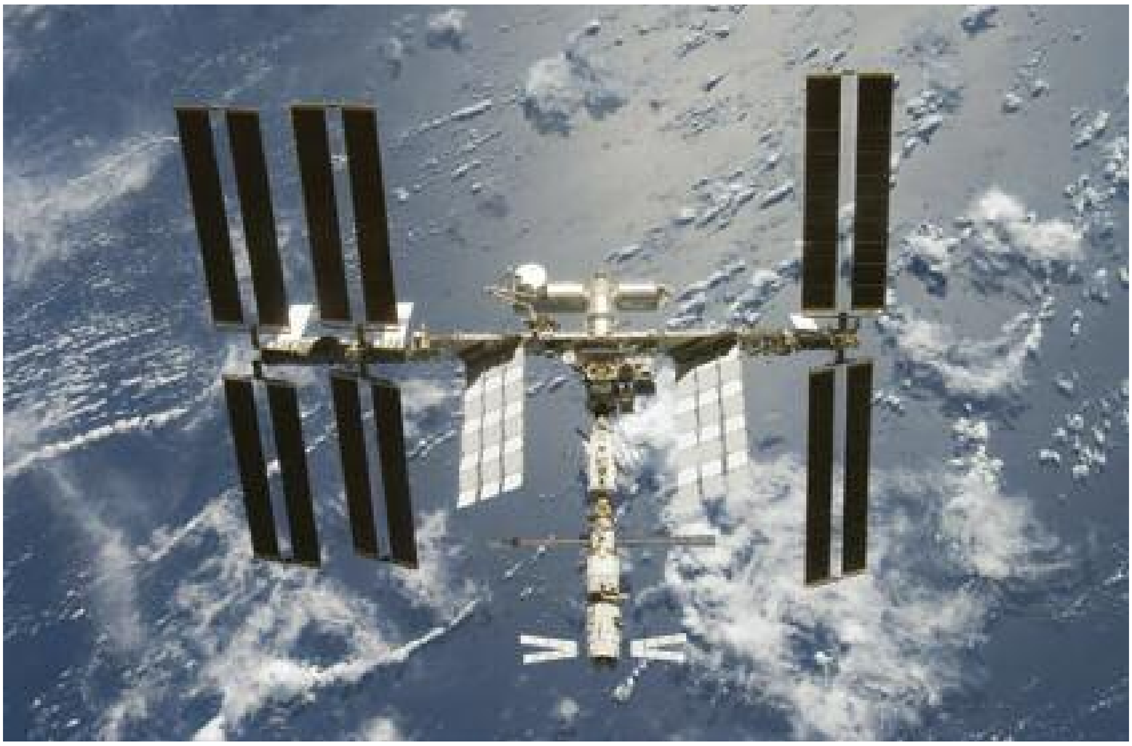
A new UNESCO Chair on "Near-Earth Space Environment/European Space Agency" at the University of Thessaloniki (to be announced shortly

8. The Laboratory of Astronomy and the Public

Once a month (to be exact, every 29.53 days!), when the Moon is between 4 and 8 days old, the Observatory of the University of Thessaloniki opens its gates to the public. If the sky is clear, a series of observations of the Moon, the bright planets and several other astronomical objects, e.g. galaxies, stellar clusters e.t.c., can be marveled through the 20-cm refractor of the Observatory. The staff and post-graduate students will guide the visitors to the splendors of the sky. Slide shows, movies and lectures often accompany the observations.

References

The potentially interested visitors can find further details on the above and the various activities of the staff of the Laboratory of Astronomy in the website: http://www.astro.auth.gr



Source NASA

The International Space Station with the European Space Laboratory “Columbus” on the far right.