B.1 Concept and scientific/technical objectives

B.1.1 Concept and scientific/technical objectives of the project

Recent developments in fundamental sciences as Theoretical Physics, Gravitation, Cosmology and Astrophysics provide a series of new computational methods (numerical, symbolic and graphical simulations) which can be applied in wide areas of space technologies, mainly designing new experiments and measurements in space. On the other hand, the recent announce of direct detection of gravitational waves together with other Astrophysical achievements (accelerated expansion of the Universe, dark matter and dark energy hypothesis, Gamma-ray bursts, galactic black-holes nuclei, etc.) impose validation of different theories and models through future experiments and space missions.

Along these lines, during the last three years the consortium proposed in the present project has implemented a research project (COMISIS – Computational Methods in Scientific Investigation of Space) within the STAR program focused on new computational methods and techniques to be applied in different parts of the space technology.

Although the main objectives of previous COMISIS project where completely accomplished, certain directions of research proved to be richer in consequences than we initially appreciated and certain results obtained in that project can be continued and developed.

Thus, this project proposes a joint research program which extends the research done in COMISIS and which has as main objective to develop fundamental research and to design new methods and software products useful in Space Science. Three main domains will be considered: (i) Astrophysics, Cosmology and General Relativity; (ii) Nonlinear phenomena and spatial dynamics; (iii) Solar winds and plasmas. Correspondingly, our research will focus on the following three directions described below.

The **first research direction** (mainly contained in the Work Package no. 1) is dedicated to our computational investigations with space science applications. Its title is:

- ***New libraries devoted to numerical, symbolic computation and algebraic programming methods in space science areas and applications.***

Within this research direction we will investigate the possibility of application and use of the new computational methods provided by different areas of fundamental research in gravitation, numerical relativity and cosmology for space sciences investigations.
Taking into account the difficulties encountered in solving specific models for describing astrophysical processes such as dynamics of black-holes, supernovae explosions, emission of gravitational waves, etc. it is necessary to develop new computational methods in all aspects i.e. numerical, symbolic and graphical computations.
Also theoretical cosmology is in a continue search for new models capable to describe the recent discovered cosmic acceleration of the universe and other phenomena based on alternative theories of gravity.
Based on the results obtained in the previous COMISIS project we will continue to investigate new computer techniques in certain areas where the previous reported results opened new possibilities and applications.
A series of results our team obtained (both in previous COMISIS project and independently) opened the possibility of further investigations in numerical relativity within alternative theories of gravity and cosmology such as simulations in exact solutions in accelerated universe, gravitational waves emerged in astrophysical processes. In this project we will concentrate on the possible effects of free falling of particles in gravitational field (geodesic motion) in different theories of gravity – such as in Schwarzschild,

Ressner-Nordstrom or Kerr spacetimes with or without cosmological constant. Possible deviations from the standard Einstein theory will be pointed out and measurements in space observatories (as HUBBLE, PLANCK, WMAP, etc.). The recent announced detection of gravitational waves from a process of black hole colliding gives the hope to investigate other processes even in order to point out the mentioned deviation from standard Einstein theory. We will use our routines and programs already developed previously (and of course compose new ones if necessary) in order to compute gravitational waves produced in some simple cases, possible to simulate on single processor computers. Some of the simulations will be done on more high performance computer systems. All these researches are included in the below described Task1.1 of the first main objective of the project.
Considering the results obtained in our previous project (COMISIS) regarding the scattering of fermions on Schwarzschild black holes, in this new project we will extend the results, thus completing them with a numerical and graphical analysis for the cross section and degree of polarization in terms of the mass of the black hole and mass, energy and momenta of the scattered fermion. This study could improve the analytical results since it can give us an indication about the range of validity of these results by considering the cases when the incident particles have large/small speeds and given angular momenta.
An interesting fact is that we can draw some conclusions about the quantum fields interactions in strong gravitational fields if we work in the de Sitter metric which describes the conditions from the early Universe, when the expansion was large (i.e. strong gravitational fields). A fundamental problem is related to the interaction between the electromagnetic field and the scalar field in the conditions of large expansion. Then the problem of pair production in magnetic fields will be studied in de Sitter geometry. As it is well known in the vicinity of a black hole the magnetic fields are also strong and for that reason it is important to understand what happens with the interactions between quantum fields when we have a strong gravitational field and in addition there is a magnetic field. For that we propose to study the production of scalar particles in the dipolar magnetic field in the conditions from early universe (when the gravitational field was strong).
For the beginning we will establish the form of the magnetic fields, with the help of the potential vector which is time-dependent in de Sitter geometry. The de Sitter metric is conformal with the Minkowski metric, and by taking into account the conformal invariance, the form of the four vector potential in de Sitter space can be established easily. First we will calculate the scalar pair production from vacuum in the presence of a dipolar magnetic field in de Sitter background. This kind of magnetic field does not produce pairs of particles in Minkowski theory, but for large expansion factor (strong gravitational field), this phenomenon cannot be excluded.
The solutions of the Klein-Gordon equation (describing the scalar field) with a defined momentum, written in Cartesian gauge will be used. All these will correspond to the first order of perturbation theory in de Sitter scalar QED. The temporal integrals will contain the influence of space expansion upon the process of particle production. We can adopt two strategies to follow taking into account that the integrals involved contain the product of two Hankel functions and a power. After completing the calculations, the physical consequences will be discussed with a special attention to the problem of momentum non-conservation due to the presence of an external field. The amplitude/probability will depend only on the ratio mass of the electron to the expansion factor and on the momenta of the particles. A graphical representation of the probability as a function of this ratio, for given values of the momenta, will be done. The Minkowski limit of our amplitude will be taken and the limit of a large expansion of the space will be discussed, both limits will be studied analytically and then and the results will be compared with the graphical ones. We can also study the directions in which the particles are emitted relatively to the direction of the magnetic field. This study will help us to address the mechanism of separation in the early Universe between particles and antiparticles. The total number of produced particles can be obtained if one integrates over the final particle-antiparticle momenta, by using numerical and graphical methods. All these results will be oriented to point out measurable effects in the astrophysical observatories (both terrestrial and in outer space). Some of these will be proposed to be integrated in future ROSA/ESA/NASA missions.

In a recent published article was reported the first analytical study of greybody factors for fermions (electrons, miuons etc.) emitted by a Schwarzschild-de Sitter Black Hole (SdS) where it was showed that at low energies the SdS greybody factors take constant values. In the present project we will continue this line of research in order to obtain the dependence of the SdS greybody factors on the velocity of the emitted (fermionic) Hawking radiation. It is believed that if micro black holes exist in nature, where by micro we understand black holes that have a small mass, then the Hawking radiation could be detected in the near future with the help of satellite observations (performed by ESA or other agencies).
The main goal is to identify those terms and factors introduced by these new theories and models which can be measured in new type of space science experiments or even contained in data from existing experiments and missions.
Thus in this research direction the present project will concentrate on the next main objectives and tasks:

Task 1.1: Investigations on measurable effects of alternative gravity theories for non-standard cosmologies. We will study (using new computer routines) the possible effects of modified gravity on different processes as light deflection or free fall of particles around massive objects as black-holes or clusters of stars or gravitational waves generation in astrophysical processes pointing out possible measurable effects in space missions.
Task 1.2: Investigating scattering processes on different types of black holes using computational methods. Study of velocity dependence of the greybody factors for fermions emitted as Hawking radiation by a Schwarzschild-de Sitter black hole. Properties of the scattered radiation on black holes will be also studied. Measurable effects in astrophysical experiments included in space missions will be pointed out.

The **second research direction** (mainly contained in **Work Package no. 2**) is dedicated to research in the field of spatial dynamics, more precisely on turbulences and nonlinear phenomena which can appear in the motion of spatial objects, planets and of satellites. The title of this research direction is:

- **Modeling of nonlinear phenomena and estimations in spatial dynamics.**

The research will extend the previous results obtained by the team from University of Craiova (UCV) in COMISIS and will bring new original contributions related to:

- Development of new mathematical tools for investigating spatial nonlinear phenomena
- Design of new reduced-order multiple observers with applications to the flight of spacecraft.

The specific tasks which are assumed and the associated objectives are:

Task 2.1: Nonlinear dynamics generated by gravitational models. Important models arising from Gravitation can be analyzed following the specific procedure of nonlinear dynamics. The Ricci flow equation is a good example. The equation arising from gravity can be transformed in a partial differential equation, which can be studied from different specific approaches, as extended symmetries, class of solutions, stability of the solutions, regular and chaotic behavior. Other known models as Calabi-Yau manifold, but new models also will be studied.

Task 2.2: Analytical and computational investigation of nonlinear equations describing turbulent phenomena (including solar wind). This task mainly supposes the description of nonlinear phenomena which appear in spatial dynamics. The research will focus on phenomena related to the motion of spatial objects and to the propagation of cosmic radiations. Despite the complexity of these phenomena, it was proved that they can be modeled through nonlinear wave type equations. Important results are already obtained through this approach on the description of solar wind and plasma, and of other interesting topics related to the space science. We shall concentrate our attention to the Lie group method. It is well-known that this method is a powerful and direct approach to construct many types of exact solutions of nonlinear differential equations, such as soliton solutions, power series solutions, fundamental solutions, and so on.

The existence of the operators associated with the Lie group of infinitesimal transformations allows the reduction of equations to simpler ones. The similarity reduction method for example is an important way of transforming a (1+1) - dimensional partial differential equation into an ordinary differential one.

Task 2.3: Design, software implementation and validation of reduced-order multiple observers for Takagi-Sugeno nonlinear systems with/without unknown inputs. Because during the flight of spacecraft or satellites, their constrained and turbulent dynamics is characterized by different disturbances, the estimation of the states and/or unknown inputs is an important challenge; to reduce the number of sensors and measurements systems, we will design reduced-order multiple observers for Takagi-Sugeno nonlinear systems to estimate some of the dynamics' variables using intelligent algorithms and software. The work will start from the nonlinear dynamics of spacecraft/satellites – enriched with different perturbing forces (work already done in COMISIS project by UCV and CS Romania S.A. through the extension of the OREKIT low level space dynamics). There will be designed different types of multiple observers in order to achieve finite-time reconstruction of the state vector for a class of nonlinear systems (Takagi-Sugeno type) with or without unknown inputs; due to the appearance of the faults, calculation errors, modeling errors or small variance of the system in the linearization process, robustness improvement activities will be also achieved. In the literature, there are several multiple observers for Takagi-Sugeno systems affected or not by unknown inputs, but all of them are full-order multiple observers; the main advantage and innovative element of the new reduced-order multiple observer is related to the decrease of the system sensors' number: some of the state variables are measured, while the other are estimated. Beside the new architectures to be obtained, the software packages are other novelties of the UCV team, as well as the expected results and end products.

A **third research direction** on which the project will focus (in the **Work Package no. 3**) consists in constructing a theoretical tool to predict the occurrence of unstable Kelvin-Helmholtz instabilities (dissipative instabilities or negative energy waves) in solar plasma with lower flow rates, and to study the manner in which the Kelvin-Helmholtz instabilities are influenced by the ion and neutral frequency collisions. The title of this research direction is:

- **The relevance of Kelvin-Helmholtz instability in the solar partially ionized plasma structures**

This is again a prolongation of the objectives of the former COMISIS project. The main tasks assumed on this research direction are:

Task 3.1. The theoretical tool to predict the occurrence of unstable Kelvin-Helmholtz instabilities (dissipative instabilities or negative energy waves) in solar plasma with lower flow rates, and the manner in which the Kelvin-Helmholtz instabilities are influenced by the ion and neutral frequency collisions.

Task 3.2. Obtaining bulk transport properties of plasma through a statistical approach based on solving the stochastic differential equations associated to the motion of each particle, charged or neutral.

Task 3.3. Numerical simulations by implementation of the proposed algorithm and the identification of the space of parameters that characterizes the output of the simulation.

B.1.2 State of the art

Here are some notes on the state of the art in the three main research directions.

- ***New libraries devoted to numerical, symbolic computation and algebraic programming methods in space science areas and applications.***

Recent developments in fundamental sciences as Theoretical Physics, Gravitation, Cosmology and Astrophysics provide a series of new computational methods (numerical, symbolic and graphical simulations) which can be applied in wide areas of space technologies, mainly designing new