07/1301 NON-PERTURBATIVE EFFECTS IN COMPLEX GRAVITATIONALLY BOUND SYSTEMS

Type of activity: Medium Study (4 months, 25 KEUR)

Background and Motivation

Introduction

Despite the substantial progress in experimental cosmology within the recent years (such as new data from WMAP, advances in weak gravitational lensing etc.) the dynamics of the Universe is not well understood. According to our present data about 73% of the energy density is expected to be dark energy, 23% dark matter and only the rest normal (baryonic) matter. The nature of dark energy and dark matter is unknown, though there exist several candidates for both of them. Although the dynamics at astrophysical and cosmological scales is dominated by dark matter and dark energy, no major influence thereof on the local dynamics (e.g. the Solar system) has to be expected. Indeed, our current knowledge of the dynamics of the Solar system almost exclusively relies on Newtonian gravity and post-Newtonian corrections from general relativity, whereby any effects from galactic or cosmological scales are discarded.

Nevertheless our understanding of gravitational dynamics on a larger scale should be assessed with respect to possible relevance for the local dynamics, in particular with respect to effects of unknown nature such as the Pioneer anomaly (cf. e.g. ref. [1]). On the one hand, this includes the study of the influence of global effects (such as the cosmological expansion) on the local dynamics, on the other hand, the issue to identify smaller (perhaps even artificial) systems where effects inferred from larger scales could be seen. Some work has been done for the case of cosmological expansion [1-3], this study aims at investigating these two aspects with regard to non-perturbative dynamical effects that can manifest themselves in complex, gravitationally bound systems.

Dark Matter and Dark Energy

Within cosmological and astrophysical models, dark matter and dark energy are ad hoc postulates in order to match observational data. In the latter case it is the need for an accelerated cosmological expansion, the former case originally was inferred from the rotational curves of galaxies and galaxy clusters. Meanwhile there exist independent hints for dark matter, on the one hand from structure formation, on the other hand from (weak) gravitational lensing. Though this results in independent support for dark matter, there remains the unsatisfactory situation to postulate the existence of a new particle solely on the basis of its gravitational interaction. Not surprisingly, alternative explanations avoiding dark matter have been proposed, the most popular claiming that the observational data should be explained by a modification of the gravitational interaction (MOND theory [4] and its general relativistic extension [5] but also f(R) gravity [6,7].)

The Role of Backreaction

More recently, the existence of both, dark energy as well as dark matter, have been questioned on the basis of general relativity calculations [8-11]. In these works the authors claim that there is no need for dark energy and dark matter if the known theories are applied "correctly". The basic idea of all four groups [8-11] was to take into account backreactions (either by a systematic expansion or by an ansatz for an exact solution of Einstein’s equations encompassing the full dynamics) and thereby being able to generate "new" effects within the known theories. The existence of relevant effects due to backreaction does not come as a surprise as neither one is interested in a test-particle moving in a (eventually very complex) background nor does the system just include a few bodies where most of the mass is concentrated. Still, backreactions have been disregarded in the original derivations of dark matter and dark energy, an assumption that is widely assumed to be valid (cf. e.g. [12,13]). Indeed, as the typical velocities of the internal dynamics of the systems in question are small and the typical gravitational forces weak, a systematic expansion starting from the Newtonian law appears to be justified almost everywhere. But then, although it is difficult to derive exact results on the influence of backreaction effects on the local dynamics, any relativistic corrections derived within the perturbative regime should be ignorable due to the tiny expansion parameters.

Despite its intuitive appeal, this way of reasoning might be misleading. Indeed, given the fact that Einstein’s equations are a complicated set of coupled, non-linear differential equations, any attempt to prove the convergence of a post-Newtonian expansion is hopeless even in much simpler systems than considered here. By accounting for the non-convergence of the post-Newtonian expansion as realistic possibility, the wide field of non-perturbative (but purely classical) effects from general relativity comes to the fore. The specific challenge of any research project of this type lies in the fact that a model is needed which (A) can be solved in full general relativity but (B) still is realistic enough to serve as a model of the intended dynamical system (e.g. a galaxy.)

Exactly this task has been addressed in ref. [8] for the case of a galaxy and the result suggests large deviations in gravitationally bound systems from Newtonian dynamics even if the gravitational field is weak. In the interpretation of the authors, the theoretical prediction of the rotation curves of the galaxies can be inferred neither from Newtonian physics nor from any systematic expansion that starts from the Newtonian potential, but essentially needs a treatment in full general relativity. As a consequence the authors claim that dark matter is not needed to explain the rotation curves of galaxies. If such a non-perturbative effect exists, our intuition about the dynamics of the Universe based on Newtonian physics plus small corrections from general relativity could turn out to be wrong. The model by Cooperstock and Tieu has been criticised in several works (see e.g. [14-17]), the main objection raised considers a discontinuity in the galactic plain which induces matter fluxes and therefore an infinite disk of exotic matter in the model. It should be mentioned that the authors of ref. [8] in their replies [18,19] insisted on the correctness of their approach. Unfortunately, most of the works initiated by ref. [8] did not pursue the basic strategy formulated therein, but restricted to pointing out apparent weak points in the specific model. However, in ref. [20] an alternative model has been presented, which circumvents the critical point of the mentioned discontinuity in ref. [8] but still shows a large non-perturbative effect. Though these authors conclude that dark matter cannot be circumvented altogether, the result shows that the original intention of ref. [8] is correct and that the role of large non-perturbative effects in the weak gravity regime of complex, gravitationally bound systems should be investigated in detail.

Research and Study Objectives

Considering the dynamics of the Solar system and its surrounding in general and space flight in particular, a direct influence of the suggested effects appears to be unlikely. As far as a spacecraft can be seen as a test particle moving in the background of a given gravitational field, it won't be directly affected by dynamical effects. However, the potential misinterpretation in a systematic way of the dynamics of the gravitational background could result in a net effect even at solar system and spacecraft level as we might misinterpret the nature of the background space-time (as an example the postulation of dark matter relevantly changes the metric of space-time which affects the dynamics independently of the discussion of backreactions). The purpose of this study is therefore to assess this potential net effect. The steps in particular include:

1. Review the galaxy models used until now and find more refined models of systems with large non-perturbative effects (complex, gravitationally bound systems such as galaxies). In this main part of the study the following question are proposed to be addressed:
   - It is desirable to proceed along the lines of research as worked out in refs. [8,18-20], whereby the models used should be refined and more detailed answers about the expected effect should be given. (The study however should not concentrate on this question alone.)
   - Though the specific question raised by Cooperstock and Tieu (namely the rotation curves of galaxies) should serve as a guiding principle (also thanks to the established experimental observations), the topics covered can be more general. In particular, refs. [8,18-20] used a top-down approach, where parameters of the solution were fitted to reproduce the velocity profiles of the galaxies and therefore the necessary density distribution emerged. Since this study is not interested in fitting observed galaxies exclusively, a bottom-up approach starting from given rotating dust solutions (as e.g. in [21-24]) is possible as well. Here, special emphasis should be put on the nature of the non-linear effects and on conditions found in order that they emerge.
   - Apart from rotating dust solutions and their generalisations, different dynamical models, where large non-linear effects within the weak gravity regime are seen, can be proposed and analysed as far as a realisation (artificial or as astrophysical object) is conceivable.
   - This main part of the study can but need not include numerical analysis and computer simulations. Of course, given the computational difficulties in complex, generally relativistic systems, the numerical approach cannot avoid making simplifying assumptions. However, it can be expected that a numerical integration within the dust approximation helps to obtain more realistic results than the purely analytical approach.
2. The influence of the results from point 1 on our view of the dynamics of the Universe or a subsystem thereof shall be assessed (reduction of necessary dark matter, dark energy etc.) and these results--if possible--shall be confronted with independent measurements (e.g. weak lensing, structure formation).
3. If relevant non-linear effects exist at galactic or even larger scales, how could similar dynamics be seen at smaller scales? This part of the study in particular includes the investigation of
   - the scalability of the effect in terms of size (or mass to size ratio) of the system and the size (or mass to size ratio) of its constituents,

- the identification of gravitationally bound systems where non-linear effects could become relevant or at least detectable (e.g. the simulation of complicated, gravitationally bound clouds in asteroid dynamics [25,26].)

References

[1] C. Lammerzahl, O. Preuss and H. Dittus, "Is the physics within the Solar system really understood?," arXiv:gr-qc/0604052.

[2] V. Kagramanova, J. Kunz and C. Lammerzahl, "Solar system effects in Schwarzschild--de Sitter spacetime," Phys. Lett. B 634 (2006) 465, arXiv:gr-qc/0602002.

[3] Giulini D., Carrera M., "On the effect of the global cosmological expansion on the local dynamics in the Solar System," European Space Agency, the Advanced Concepts Team, Ariadna Final Report 04-1302, 2005, arXiv:gr-qc/0602098.

[4] M. Milgrom, "A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis," Astrophys. J. 270 (1983) 365-370; "A modification of the Newtonian dynamics: Implications for galaxies," Astrophys. J. 270 (1983) 371-383; "A modification of the Newtonian dynamics: Implications for galaxy systems," Astrophys. J. 270 (1983) 384-389.

[5] J. D. Bekenstein, "Modified gravity vs dark matter: relativistic theory for MOND," PoS JHW2004 (2005) 012, arXiv:astro-ph/0412652.

[6] S. Capozziello, V. F. Cardone and A. Troisi, "Dark energy and dark matter as curvature effects," JCAP 0608 (2006) 001, arXiv:astro-ph/0602349; "Low surface brightness galaxies rotation curves in the low energy limit of R^n gravity: No need for dark matter?," Mon. Not. Roy. Astron. Soc. 375 (2007) 1423, arXiv:astro-ph/0603522.

[7] C. F. Martins and P. Salucci, "Analysis of rotation curves in the framework of R^n gravity," arXiv:astro-ph/0703243.

[8] F. I. Cooperstock and S. Tieu, “General relativity resolves galactic rotation without exotic dark matter,” arXiv:astro-ph/0507619.

[9] E. W. Kolb, S. Matarrese, and A. Riotto, “On cosmic acceleration without dark energy,” New J. Phys. 8 (2006) 322, arXiv:astro-ph/0506534.

[10] T. Buchert, "Backreaction issues in relativistic cosmology and the dark energy debate," arXiv:gr-qc/0612166.

[11] M. Ishak, J. Richardson, D. Whittington and D. Garred, "Dark Energy or Apparent Acceleration Due to a Relativistic Cosmological Model More Complex than FLRW?," arXiv:0708.2943 [astro-ph].

[12] K. A. Olive, "TASI lectures on dark matter," arXiv:astro-ph/0301505.

[13] P. J. E. Peebles and B. Ratra, "The cosmological constant and dark energy," Rev. Mod. Phys. 75 (2003) 559, arXiv:astro-ph/0207347.

[14] M. Korzynski, “Singular disk of matter in the Cooperstock and Tieu galaxy model,” arXiv:astro-ph/0508377.

[15] D. Vogt and P. S. Letelier, “Presence of exotic matter in the Cooperstock and Tieu galaxy model,” arXiv:astro-ph/0510750.

[16] T. Zingg, A. Aste, and D. Trautmann, “Just dust : About the (in)applicability of rotating dust solutions as realistic galaxy models,” arXiv:astro-ph/0608299.

[17] D. Vogt and P. S. Letelier, "Exact General Relativistic Rotating Disks Immersed in Rotating Dust Generated from van Stockum Solutions," to appiear in IJMPD, arXiv:astro-ph/0611428.

[18] F. I. Cooperstock and S. Tieu, “Perspectives on galactic dynamics via general relativity,” arXiv:astro-ph/0512048.

[19] F. I. Cooperstock and S. Tieu, “Galactic dynamics via general relativity: A compilation and new developments,” arXiv:astro-ph/0610370.

[20] H. Balasin and D. Grumiller, “Significant reduction of galactic dark matter by general relativity,” arXiv:astro-ph/0602519.

[21] J. Bicak and T. Ledvinka, "Relativistic disks as sources of the Kerr metric," Phys. Rev. Lett. 71 (1993) 1669.

[22] J. Bicak, "Selected solutions of Einsteins field equations," Lect. Notes Phys. 540 (2000), arXiv:gr-qc/0004016.

[23] G. Neugebauer and R. Meinel, "General relativistic gravitational field of a rigidly rotating disk of dust: Solution in terms of ultraelliptic functions," Phys. Rev. Lett. 75 (1995) 3046, arXiv:gr-qc/0302060.

[24] G. Neugebauer, A. Kleinwachter and R. Meinel, "Relativistically rotating dust," Helv. Phys. Acta 69 (1996) 472 arXiv:gr-qc/0301107.

[25] P. Michel, W. Benz, P. Tanga, D.C. Richardson, "Collisions and gravitational reaccumulation: forming asteroid families and satellites," Science 294 (2001) 1696-1700.

[26] P. Michel, W. Benz, D.C. Richardson, "Fragmented parent bodies at the origin of asteroid families," Nature 421 (2003) 608-611.