Testing alternative theories of gravity with the BepiColombo Radio Science Experiment

Candidato: Vincenzo Di Pierri
Relatore: Dott. Giacomo Tommei

General Relativity (GR) is one of the most beautiful and elegant physics theory. It was developed by Albert Einstein at the beginning of '900 with the attempt of unifying gravitation with Special Relativity (SR). SR was another Einstein's intuition, introduced in 1905 with the aim of explaining some results of electromagnetism that seemed to enter in conflict with classical physics. In this theory space and time are not different entities, but live together in the so called space-time. The concept of absolute time was deleted, everything is relative. With GR, Einstein found a very brilliant way to keep together gravitation and electromagnetism by introducing some new concepts: curved space-time and the description of gravity as a geometric property of space and time. In GR, space-time is a manifold equipped with a metric, given by the so called metric tensor. Such tensor is the main character of the theory: everything moves following metric tensor rules, that is bodies move along geodesics of the metric. That is why GR belongs to the class of metric theories of gravity. Just from the beginning, GR succeeded in explaining some effects that classical physics can not explain. These effects are known as the four classical tests of GR: Mercury's perihelion shift, deflection of the light, light-time delay and gravitational redshift.

At the moment, predictions of GR have been confirmed in all the observations and experiments performed (the last confirmation has been the detection of gravitational waves), but the testing of the theory is running yet. Just from the born of GR, many alternatives theories of gravity were introduced in competition to Einstein's theory. Among them, an important class is the one admitting a metric tensor as the GR (usually coupled with other fields). Experiments are the best way to compare different metric theories and then to test the validity of GR. Most of the experiments are performed in the Solar System, using tracking of objects with radio waves. The Solar System region presents a weak gravitational field (the mass of the biggest planet, Jupiter, is about 1/1000 of the mass of Sun and our star has a mass many order of magnitude less than a black hole for example) and the velocities of the objects are small with respect to the velocity of light. Thus, in order to make computations in this regime, an approximation of gravitational theories has been developed: this approximation is called Post-Newtonian (PN) limit. In the second half of 20th century, a global metric theory was developed: the Parameterized Post-Newtonian (PPN) formalism. This theory gives a general form of PN metric tensor depending upon ten parameters and every single metric theory has its own set of values for these ones. The introduction of the PPN Formalism makes possible to compare different metric theories by giving a limitation of the values of the parameters through observations and measurements.

In the '80s some attempts to unify gravitation with quantum mechanics were done and in this contest the so called torsion theories were introduced. Such theories were put apart because there were not experimental evidences. Recently, some papers about testing in the Solar System of metric theories with torsion appear. In this thesis work, following (cit march-bellet), we present torsion theories in their PPN expansion, with the awareness that this is just a toy model. In fact, if torsion is related to the spin of elementary particles and in macroscopic matter it is usually oriented in random way, the effect of torsion generated by massive bodies will be negligible. Following the works of (cit march-bellet),(cit mit) that give an adequate model for the description of torsion effects around macroscopic bodies, we derived PPN equations of motion of a test body in a space-time with torsion. We implemented such equations in the software ORBIT14, that is a software developed by the Celestial Mechanics Group of the University of Pisa in the last nine years. The software is an Orbit Determination (OD) one to use in the context of BepiColombo, a joint mission of the European Space Agency (ESA) and the Japan Aerospace eXploration Agency (JAXA) to the planet Mercury, and Juno, a NASA mission to Jupiter. It enables the generation of the simulated observables and the determination of parameters (not only the orbital ones) by means of a global least squares fit. Our work has been developed for the BepiColombo mission, that will perform a relativity experiment using a radio wave tracking.

Concerning the contents of the thesis, in Chapter 1 we introduce the basic principle of GR, seeing some basis of the so called experimental gravity. Then we see how to find the Post-Newtonian metric, giving just a summary view of the main passages. Then we report the classical method to compute Post-Newtonian limit of any metric theory and we see how to calculate it for GR.

In Chapter 2 we introduce the torsion tensor and we describe a general torsion theory in the Post-Newtonian framework with the help of three torsion parameters t_1, t_2, t_3. In this formulation we compute the equations of motion of a test body in a field generated by a massive body.

Finally, in Chapter 3 we briefly introduce the BepiColombo mission and the software ORBIT14, describing the algorithms implemented in the software. Then we report the results of a full set of simulations of the relativity experiment and in particular the simulations made to give an estimation of the torsion parameters.