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利用 Laniakea 超星系团引力势检验爱因斯坦弱等效原理

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Testing Einstein's Weak Equivalence Principle with Supercluster Laniakea's Gravitational Field

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摘　要

爱因斯坦等效原理作为广义相对论的重要假设之一，不仅是广义相对论的理论基石，还是许多其他的引力理论的基础。根据爱因斯坦等效原理，真空中不带电粒子的运行路径与粒子的内部结构和成分无关。所有将爱因斯坦等效原理作为假设的度规理论都假设一个后牛顿参数$\gamma_1 = \gamma_2 = \gamma$，其中1和2代表不同的实验粒子（例如光子和中微子）。因此，爱因斯坦等效原理的检验可以通过比较不同粒子或者具有不同能量的相同粒子的后牛顿参数的值。爱因斯坦等效原理任何可能的破缺都会导致人们对自然界的认识产生重大影响，所以不断提高检验精度具有十分重要的意义。

第一章介绍了等效原理和后牛顿参数。等效原理由强等效原理和弱等效原理两个部分组成。爱因斯坦从弱等效原理出发，推广到强等效原理, 作为广义相对论的基础。弱等效原理是说, 引力场和惯性场的力学效应是局域不可分辨的。强等效原理是说,引力场和惯性场的一切物理效应都是局域不可分辨的。爱因斯坦等效原理的准确性可以很方便地用后牛顿参数来描述。对于所有满足爱因斯坦等效原理的引力度规理论，都有着不同于牛顿万有引力的后牛顿参数形式。每一个理论都有一组确定的后牛顿参数值。

第二章介绍了几种宇宙暂现源－伽玛暴、快速射电暴、耀变体。伽玛暴是指天空中某一方向的伽玛射线强度在短时间内突然增强，随后又迅速减弱的现象，其持续时间一般在0.1-1000秒，辐射主要集中在0.1-100 MeV的能段。快速射电暴是指遥远宇宙中突然出现的短暂而猛烈的无线电波爆发，持续时间极短，通常只有几毫秒，却能够释放出相当于太阳在一天内释放的能量。耀变体是活动星系核中极端的一类。耀变体辐射能谱的特点是从射电一直延伸到伽玛射线，甚至达到了极高能伽玛射线，其剧烈变化的持续时间可以从几分钟到几年。

第三章介绍了在银河系和超星系团Laniakea引力势下检验爱因斯坦等效原理。在银河系引力势下，检验精度可以达到$|\gamma_1 - \gamma_2| < 10^{-8}$。由于超星系团Laniakea的引力势比银河系引力势大，可以使得检验结果提升了4到5个量级。

Abstract

The Einstein Equivalence Principle (EEP), which is one of the major pillars of general relativity and other metric theories of gravity, says that the trajectories of freely falling uncharged test bodies are independent of their internal compositions and structures. As long as the EEP is valid, all metric theories predict$\gamma_1 = \gamma_2 = \gamma$, where 1 and 2 represent two different test particles. In this case, the accuracy of the EEP can be characterized by limits on the differences of γ value for different species of particles, or the same species of particle with varying energies. The possible violations of EEP would have significant impact on our understanding of the nature, it is therefore important to steadily improve the accuracy of the tests.

The first chapter introduces the equivalence principle and Post Newtonian parameters. The equivalence principle is composed of two parts: the strong equivalence principle and the weak equivalence principle. Einstein extended the weak equivalence principle to the strong equivalence principle, which is the basis of the general theory of relativity. The weak equivalence principle shows that the trajectory of a freely falling uncharged "test" body is independent of its internal structure and composition. The strong equivalence principle shows that all the physical effects of the gravitational field and the inertial field are local and can not be distinguished. Testing the accuracy of the EEP can be conveniently described by the parameterized post-Newtonian (PPN) formalism. For all metric theories of gravitation in which all bodies satisfy the EEP, the PPN formalism explicitly details the parameters in which a general theory of gravity can differ from Newtonian gravity. Each theory is specified by a set of numerical coefficients.

The second chapter introduces several transient sources - cosmic gamma ray bursts (GRBs), fast radio bursts (FRBs), blazars. GRBs are the most extreme explosive events in the Universe. They are initially observed as short, intense, and non- repeating flashes of γ-rays. The duration of the prompt emission of a GRB is relatively short, typically from 0.1 to 1000s. FRBs are short and violent bursts of radio waves from the distant universe. Its duration is very short, which is only a few milliseconds. Blazars are an extreme subclass of active galactic nuclei, which are characterized by broadband non-thermal emission extending from radio up to high-energy and very-high-energy (VHE) gamma-rays, and display of violent variability on different timescales from minutes to years.

The third chapter introduces the tests of the Einstein weak equivalence principle in the gravitational potential of the Milky Way and the supercluster Laniakea. In the gravitational potential of the Milky Way, the testing result can reach about $|\gamma_1 - \gamma_2| < 10^{-8}$. Comparing with the Milky Way's gravitational potential, the testing result of considering the gravitational potential of the supercluster Laniakea can be improved by 4 - 5 orders of magnitudes.

Keywords: Equivalence Principle, Post Newtonian Parametrization, Laniakea supercluster of galaxies, gamma-ray bursts, fast radio bursts, blazars

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