

高精度天体测量资料处理的相对论模型和 引力理论的检验

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随着科学技术的迅猛发展, 现今的天体力学和天体测量已经发生了日新月异的变化. 人类已经能够近距离探测太阳系内的一些天体, 精度也达到了前所未有的程度. 例如, 激光测月 (LLR) 的精度已经达到了 3 mm, 正在向 1 mm 迈进; 激光测卫 (SLR), 如激光地球动力学卫星 (LAGEOS) 的测轨精度已经达到了 0.5 mas; 甚长基线干涉测量 (VLBI) 的精度已经好于 0.1 mas; 对于未来的两个空间探测计划, 全天天体测量干涉仪 (GAIA) 和空间干涉测量任务 (SIM) 都有望达到 μas 的精度.

面对当前和未来如此高的精度要求, 一方面已经认识到牛顿力学体系已经无法适用于高精度的天文观测, 取而代之的是相对论框架的建立. 另一方面, 人类的一些未解之谜 (4 种基本作用力的统一、暗物质以及暗能量等问题) 使得爱因斯坦的广义相对论并不是最终的赢家. 为此, 高精度天体测量的资料处理模型不仅需要相对论框架的引入, 而且还需要将相对论引力理论进行参数化, 参数化的意义就在于通过参数的引入将各种引力理论合而为一, 进而使得不同的参数值对应不同的引力理论. 如此, 通过实验测量到的参数值来检验并裁决引力理论.

论文首先通过对 Moffat 的 STVG 理论进行一阶后牛顿展开, 得到了该理论的 PPN 参数 γ 不等于 1, 进而在太阳系实验下排除了这个理论. 为了让该理论满足太阳系的实验检验, 对该理论进行了修正并提出了修正的标量 - 张量 - 矢量引力理论 (MSTVG). 最后, 用脉冲双星来限制理论中的两个参数.

其次, 鉴于光传播在深空探测中的重要地位, 在前人工作基础之上, 在 BCRS 中建立了用于光传播的参数化 2PN 相对论模型. 通过考虑非静态的引力场, 讨论了在 $1 \mu\text{as}$ 精度下不同物理本源的各种相对论效应对光传播的影响. 其中包括了引力天体单极矩、四极矩以及引力磁的影响. 此外, 还导出了用 2 阶球谐系数 J_2 代替四极矩的更适合于实践应用的公式, 以及在此参数化 2PN 精度下用于时间延迟和测距的光行时公式, 并进行了一些量级估算. 进一步导出了固有时和坐标时之间的关系; 详细推导出用于较差测量的光线偏折角, 其中包括了光行差、引力天体单极矩、四极矩以及引力磁效应产生的光偏折角, 并用于相对论的激光天体测量检验 (LATOR) 的实例分析.

最后, 拓展了已建立的光传播相对论模型. 首先, 讨论了在光传播中天体轨道运动对于四极矩 (包括了 J_2) 以及引力磁效应的影响. 其次, 将光传播模型从无穷远到有限推广到从有限到有限. 最后, 给出了在此参数化 2PN 精度下的频移公式并给出相关的量级估算.

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A Relativistic Model for Data Processing of High-precision Astrometry and a Test of Alternative Gravity Theories

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With the development of the unprecedented techniques for observation and the improvement of the advanced methods for measurement, it is time for astrometry to unfold a new era indubitably. Presently, the satellite laser ranging like LAser GEODynamics Satellite (LAGEOS) has achieved a precision of 0.5 mas for orbit determination, the precision of Lunar Laser Ranging (LLR) has approached one millimeter, and Very Long Baseline Interferometry (VLBI) has attained the precision of 0.1 mas or even better. Beyond the current thresholds, astrometric observation will be able to attain the precision of a few μas or higher for some astrometric missions in the near future, such as Global Astrometric Interferometer for Astrophysics (GAIA) and Space Interferometry Mission (SIM).

With the modern continuous improvement of the observational accuracy, we realize that Newtonian mechanics has already deviated from the high-precision astronomical observation. A relativistic model for data processing of high-precision astrometry needs to be established. On the other hand, the continued failure in merging gravity with quantum mechanics and recent cosmological observations indicate that Einstein's general relativity needs some modifications. Thus, we are motivated by testing alternative gravity theories and parameterizing relativistic model. We mainly try to research these deeply.

Firstly, it is shown that the parameterized post-Newtonian parameter $\gamma \neq 1$ for Moffat's STVG by using Chandrasekhar's approach, and the theory is then ruled out by the experiments in the solar system. Then we propose a modified theory, MSTVG, to solve this problem. Besides, we use binary pulsar data to constrain two parameters in MSTVG.

Secondly, a parameterized 2PN framework for light propagation is developed based on the previous works in our research. By considering the non-static gravitational field of the solar system, the influences of all kinds of relativistic terms with different physical origins on light propagation are taken into account in this framework, which include the effects of the monopole and quadrupole moments of the gravitating bodies in the solar system and their gravitomagnetic fields. Besides, the expression for the influence of the second-order zonal harmonic coefficient on light propagation is presented. At last, a gauge-invariant angle between the directions of two incoming photons for the differential measurements in astrometric observation is derived in detail.

Finally, we expand the 2PN framework for light propagation proposed in the previous works. We consider the influences on the translational motion of bodies in the 1PN terms, the quadrupole and gravitomagnetic effects for light propagation. Afterwards, we derive the model of light propagation from finite to finite instead of the previous one from infinite to finite. It could be applied to the current and future space missions.