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博士学位论文摘要选登

相对论自旋动力学系统的数值研究

韩文标 †

(中国科学院上海天文台 上海 200030)

自旋致密双星是宇宙中的重要研究对象. 其中, 由恒星级致密天体绕转超大质量黑洞构成的极端质量比旋进系统 (EMRIs) 是美国宇航局 LISA 引力波探测计划的首选目标源之一, 对其研究和观测不仅可以直接检验广义相对论的引力波预言, 测量中央黑洞的质量和自旋, 还可以揭示黑洞视界附近的基本物理性质, 具有重要的物理和天体物理意义.

基于现实的天体物理环境中, 极端天体一般都高速自转, 其复杂性远高于无自旋情况, 因此本论文主要用数值方法并辅以一定的分析方法, 研究了相对论极端质量比自旋 (小质量致密天体和中心黑洞均高速自旋) 旋进系统的动力学, 集中讨论自旋对系统动力学性质以及引力波波形的影响.

论文首先考虑了自旋试验粒子绕 Kerr 黑洞的理想模型. 对于赤道轨道, 我们给出了正确的有效势表达式, 分析了圆轨道的稳定性, 发现特别是在试验粒子和黑洞均极端自旋的情况下, 释放的引力结合能远远高于无自旋粒子. 另外, 试验粒子的自旋能大大增加 Kerr 黑洞的拖曳效应. 对于一般的轨道运动, 自旋能够增加试验粒子的轨道倾角, 最大倾角和自旋存在近似的正比关系. 自旋还可能破坏试验粒子轨道关于赤道面的对称性.

自旋最重要的是能够引起轨道混沌, 论文通过对轨道参数和混沌指标的详细研究指出, 强烈自旋试验粒子的混沌行为, 主要集中于近心距较小、偏心率和轨道倾角较大的轨道. 对于探测混沌的数学工具, 强调指出 Poincaré 截面不适合用于自旋粒子的混沌判断. 论文认为, 自旋粒子从有序走向混沌的方式是倍周期分岔.

通过自旋对试验粒子引力波波形的研究发现, 由于自旋能够增加轨道偏心率, 从而使引力波 h_+ 分量更容易被探测器捕捉; 但是对于 $h_\times$ 分量, 由于自旋对轨道倾角的影响非常复杂, 引力波模版的计算变得更加困难.

其次, 为了考虑小质量天体的自引力和辐射反作用, 论文基于标量引力理论构造了一个极端质量比旋进系统的数值相对论模型.

最后, 为了数值研究的需要, 论文发展了一种对于 Hamilton 系统新的线性多步方法. 该方法能有效地保持可分离 Hamilton 系统的各个守恒量. 另外, 对于存在多个首次积分的束缚系统, 发展了一种新的稳定化数值方法, 称为平差稳定化方法. 它能保持系统所有已知的守恒量, 大大提高数值精度, 是目前为止最为完备的稳定化方法.

†2009-07-02 获得博士学位, 导师: 上海天文台廖新浩研究员; wbhan@shao.ac.cn

Numerical Researches on Dynamical Systems with Relativistic Spin

HAN Wen-biao
(*Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030*)

It is well known that spinning compact binaries are one of the most important research objects in the universe. Especially, EMRIs (extreme mass ratio inspirals) involving stellar compact objects which orbit massive black holes, are considered to be primary sources of gravitational radiation (GW) which could be detected by the space-based interferometer LISA. GW signals from EMRIs can be used to test general relativity, measure the masses and spins of central black holes and study essential physics near horizons.

Compared with the situation without spin, the complexity of extreme objects, most of which rotate very fast, is much higher. So the dynamics of EMRI systems are numerically and analytically studied. We focus on how the spin effects on the dynamics of these systems and the produced GW radiations.

Firstly, an ideal model of spinning test particles around Kerr black hole is considered. For equatorial orbits, we present the correct expression of effective potential and analyze the stability of circular orbits. Especially, the gravitational binding energy and frame-dragging effect of extreme Kerr black hole are much bigger than those without spin. For general orbits, spin can monotonically enlarge orbital inclination and destroy the symmetry of orbits about equatorial plane.

It is the most important that extreme spin can produce orbital chaos. By carefully investigating the relations between chaos and orbital parameters, we point out that chaos usually appears for orbits with small pericenter, big eccentricity and orbital inclination. It is emphasized that Poincaré section method is invalid to detect the chaos of spinning particles, and the way of systems toward chaos is the period-doubling bifurcation.

Furthermore, we study how spins effect on GW radiations from spinning test particles orbiting Kerr black holes. It is found that spins can increase orbit eccentricity and then make h_+ component be detected more easily. But for $h_\times$ component, because spins change orbital inclination in a complicated way, it is more difficult to build GW signal templates.

Secondly, based on the scalar gravity theory, a numerical relativistic model of EMRIs is constructed to consider the self-gravity and radiation reaction of low-mass objects.

Finally, we develop a new method with multiple steps for Hamilton systems to meet the needs of numerical researches. This method can effectively maintain each conserved quantity of the separable Hamilton system. In addition, for constrained system with a few first integrals, we present a new numerical stabilization method named as adjustment-stabilization method, which can maintain all known conserved quantities in a given dynamical system and greatly improve the numerical accuracy. Our new method is the most complete stabilization method up to now.