COLLISION OF GEODESIC PARTICLES IN SCALAR-TENSOR-VECTOR GRAVITY

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STVGDA GEODEZIK ZARRACHALARNING TO'QNASHUVI

Annotatsiya. *Ushbu maqolada Gravitatsiya nazariyalari doirasida zarralar to‘qnashuvlarini o‘rganish fazo-vaqt va gravitatsion o‘zaro ta’sirlarning asosiy tabiatiga muhim tushunchalar beradi. Skalar-Tenzor-Vektor Gravitatsiya (STVG), shuningdek, Modifikatsiyalangan Gravitatsiya (MOG) deb ham ataladi, Umumiy Nisbiylikni qo‘shimcha skalar va vektor maydonlarini kiritish orqali kengaytiradi. Ushbu maqola STVG doirasida geodezik zarralar to‘qnashuvlarining dinamikasini o‘rganadi, skalar va vektor maydonlari tomonidan kiritilgan qo‘shimcha erkinlik darajalarining ta'siriga e'tibor qaratadi. Biz STVG fazolarida geodezik bo'ylab harakatlanayotgan zarralarning yo‘nalishlarini va to‘qnashuv natijalarini turli dastlabki shartlar va parametrlar qiymatlari bilan tahlil qilamiz. Bizning topilmalarimiz Umumiy Nisbiylikdan muhim farqlarni ko'rsatadi, ayniqsa zarralar orbitasi va to‘qnashuvlar paytidagi energiya taqsimotida Gravitatsiya. Skalar va vektor maydonlarining mavjudligi, zarralar tomonidan his etiladigan samarali potensialni o‘zgartirib, kuchaytirilgan gravitatsion ta'sirlar keltirib chiqaradi.*

Kalit so'zlar: *Shvartsshild-MOG fazoviy vaqt, GEODEZIK zarrachalar, STVG, ISCO*

COLLISION OF GEODESIC PARTICLES IN STVG

Abstract. *The study of particle collisions in alternative theories of gravity provides crucial insights into the fundamental nature of spacetime and gravitational interactions. Scalar-Tensor-Vector Gravity (STVG), also known as Modified Gravity (MOG), extends General Relativity by incorporating additional scalar and vector fields. This paper investigates the dynamics of geodesic particle collisions within the framework of STVG, focusing on the effects of the additional degrees of freedom introduced by the scalar and vector fields. We analyze the trajectories and collision outcomes of particles moving along geodesics in STVG spacetimes, considering various initial conditions and parameter values. Our findings reveal significant deviations from General Relativity, particularly in the behavior of particle orbits and the energy distributions during collisions. The presence of the scalar and vector fields leads to enhanced gravitational effects, which modify the effective potential experienced by the particles.*

Keywords: *Schwarzschild-MOG spacetime, geodesic particles, STVG, ISCO*

СТОЛКНОВЕНИЕ ГЕОДЕЗИЧЕСКИХ ЧАСТИЦ В СТВГ

Аннотация. Изучение столкновений частиц в альтернативных теориях гравитации предоставляет важные сведения о фундаментальной природе пространства-времени и гравитационных взаимодействий. Гравитация с скалярными, тензорными и векторными полями (STVG), также известная как Модифицированная Гравитация (MOG), расширяет Общую Относительность, включая дополнительные скалярные и векторные поля. Эта работа исследует динамику столкновений частиц по геодезическим в рамках STVG, сосредотачиваясь на эффектах дополнительных степеней свободы, вводимых скалярными и векторными полями. Мы анализируем траектории и результаты столкновений частиц, движущихся по геодезическим в пространствах STVG, учитывая различные начальные условия и значения параметров. Наши результаты показывают значительные отклонения от Общей Относительности, особенно в поведении орбит частиц и распределении энергии во время столкновений. Наличие скалярных и векторных полей приводит к усилению гравитационных эффектов, которые изменяют эффективный потенциал, испытываемый частицами.

Ключевые слова: Пространство-время Шваришилъда-МОГ, геодезические частицы, *СТВГ*, *ИСКО*

INTRODUCTION

The study of geodesic particles is fundamental in the realm of general relativity and theoretical physics, as it provides insights into the dynamics of objects moving under the influence of gravity alone, without any non-gravitational forces acting upon them. Geodesics represent the paths of free-falling particles in curved spacetime, and their behavior is dictated by the geometry of the spacetime they traverse. In particular, the collision of geodesic particles is of significant interest, especially in the context of black holes and high-energy astrophysical events. Such collisions can lead to a variety of phenomena, including the production of gravitational waves, the emission of high-energy radiation, and the potential formation of exotic states of matter. The dynamics of particle collisions in a curved spacetime framework often involve intricate mathematical descriptions, as particles can interact in ways that reveal the underlying structure of spacetime itself. Studying these collisions not only enhances our understanding of relativistic physics but also informs cosmological models and theories regarding the early universe. This introduction aims to explore the key principles governing the collision of geodesic particles, examining the role of curvature, the conservation laws applicable in such interactions, and the implications of these collisions for our understanding of fundamental physics.

BASIC EQUATIONS

Here we briefly discuss the dynamical motion of a massive particle around the Schwarzschild-MOG black hole in STVG. In the Boyer-Lindquist coordinates $x^\mu=(t,r,\theta,\phi)$, the spacetime metric is expressed as

$$ds^2=-f dt^2+f^{-1}dr^2+r^2\left(d\theta^2+\sin^2\theta d\phi^2\right) \quad (1)$$

where

$$f=1-2(1+\alpha)\frac{M}{r}+\alpha(1+\alpha)\frac{M^2}{r^2}$$

with M being the total mass of the black hole and α the STVG (MOG) parameter. The spacetime metric is associated with the following vector potential

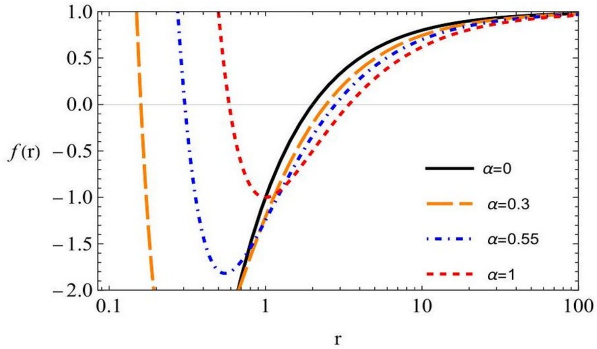

Figure. 1: This graph depicts the function $f(r)$ plotted against r on a logarithmic scale. The different curves represent various values of the parameter α, as indicated in the legend.

$$\Phi^{\mu}=-\delta_t^{\mu}\sqrt{\frac{\alpha M}{r}}$$

which is regarded as the fifth force acting on a massive particle. The horizon of the Schwarzschild-MOG black hole is located at

$$r_H^{+¿=M(1+\alpha+\sqrt{1+\alpha})¿}$$

which is always greater than the Schwarzschild radius for positive values of the α parameter.

According to STVG theory, a massive particle does not follow a geodesic line. Therefore, the equation of motion, or the four-acceleration, of a test particle of mass m in Schwarzschild-MOG spacetime is defined as

$$w^{\mu}=\frac{Du^{\mu}}{ds}=\acute{q}\,m\,B_{\nu}^{\mu}u^{\nu} \qquad (2)$$

where $u^{\mu}=\frac{dx^{\mu}}{ds}$ is the four-velocity of the particle, normalized such that $u^{\mu}u_{\mu}=-1$ and orthogonal to the fouracceleration, i.e., $u^{\mu}w_{\mu}=0$. The term $B_{\nu}^{\mu}=\partial^{\mu}\Phi_{\nu}-\partial_{\nu}\Phi^{\mu}$ is an anti-symmetric tensor, and the coupling constant is defined as $\acute{q}=\kappa m=\sqrt{\alpha}\,m$, which means the MOG parameter α should always be positive, i.e., $\alpha\geq 0$.

From equation (2), we see that massive particles do not follow geodesic lines in this theory[9-10]. Due to the symmetry of the spacetime, there are two constants of motion, namely specific energy and specific angular momentum, i.e.,

$$E=f\,\dot{t} \text{ and } L=r^2\sin^2\theta\dot{\phi}$$

For simplicity, considering circular motion of the massive particle in the equatorial plane (i.e., $¿\frac{\pi}{2}$), and using normalization of the four-velocity, the equation for radial motion in Schwarzschild-MOG spacetime yields

$$\dot{r}^2=E-\frac{\alpha M}{r^2}-f\left(1+\frac{L^2}{r^2}\right)=¿$$
$$¿$$

where the effective potential $V^{\pm}(r)$ is defined as

$$V^{\pm}(r)=\frac{\alpha M}{r}\pm f\left(1+\frac{L^2}{r^2}\right)$$

The concept of the effective potential serves as an invaluable tool for gaining insights into the trajectories of test particles in the vicinity of black holes. It is well-known that a stationary point of the effective potential corresponds to the position of the so-called innermost stable circular orbit (ISCO). Here, we focus on determining the ISCO radius for massive particles around the Schwarzschild-MOG black hole and briefly examining its dependence on the MOG parameter α. By applying the conditions $V^{+}(r)=E, V'_{+}(r)=0$, and $V''_{+}(r)\leq 0$, one can readily pinpoint the ISCO radius. The dependence of the ISCO position on the MOG parameter is determined through numerical analysis, as shown in Figure 1. It indicates that the ISCO position for massive particles increases due to MOG.

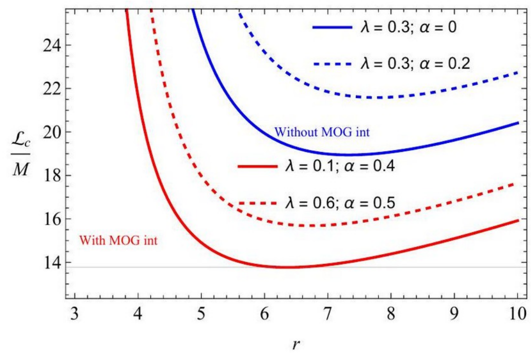

Figure.2 : Radial dependence of the critical angular momentum with and without MOG interaction.

COLLISION OF GEODESIC PARTICLES

Explicit explanation of physical mechanisms, energy extraction processes, and the role of gravity in processes is an important task in theoretical astrophysics. The classical Penrose process suggested by R. Penrose is an accepted mechanism. Later, the electric Penrose process is an advanced method of extracting energy from electrically charged black holes. This process involves a particle splitting near the event horizon of a charged black hole, where one fragment is absorbed by the black hole and the other, carrying more energy, escapes to infinity. The black hole's electric charge enhances this energy extraction by affecting particle behavior. Even a small charge can significantly improve energy extraction compared to an uncharged black hole. These findings enhance our understanding of BH thermodynamics and astrophysical jets, highlighting the complex relationship between electric charge and energy dynamics in intense gravitational fields. Various Penrose processes, including magnetic and electric versions, have been developed for different BH models. In this scenario, the study by Banados (in 2009) was the first to investigate the acceleration of particles colliding near rotating Kerr black holes, showing that the center of mass energy of colliding particles can become infinite in an extremely fast-spinning Kerr black hole. Subsequent research has explored the impact of external magnetic fields on the acceleration of charged particles near black holes in various gravity models and scenarios. These studies indicate that energy extraction is more efficient during head-on collisions.

The CME is essential for generating new particles that arise from the collision of particles in the center-of-mass frame. This energy is acquired by adding the masses and kinetic energies of the collide particles. Black holes can be effective particle accelerators, accelerating particle collisions to an infinite CME. This creates favorable circumstances for high-energy physics events that are otherwise difficult to reproduce. In this section, we examine the collision between two particles within the framework of a regular black hole in MOG, especially on an equatorial plane. This configuration is critical because it provides valuable knowledge of the mechanics and interplay in intense gravitational conditions. Such insights are critical for understanding basic physics and the properties of matter near black holes[14].

Before analyzing the CME plots, it is important to note a fascinating phenomenon related to angular momentum, referred to as a "critical value"essential for approaching a black hole. The critical value of angular momentum may be calculated by satisfying two conditions: (a) $\dot{r}=0$ and (b) $d\dot{r}/dr=0$. This is shown in Figure 2. An increase in the angular momentum results in a negative value for the square of the radial velocity, indicating that the particles cannot approach the center object from that particular value. Consequently, we examined the permissible values of the angular momentum and identified the critical values. Figure 3 illustrates the radial dependence of the critical angular momentum with and without MOG interaction. The graph demonstrates that the critical angular momentum range is broader in the presence of MOG interaction than when there is no MOG interaction. Additionally, the plot indicates that the Schw. BH case allows for the maximum range of angular momentum.

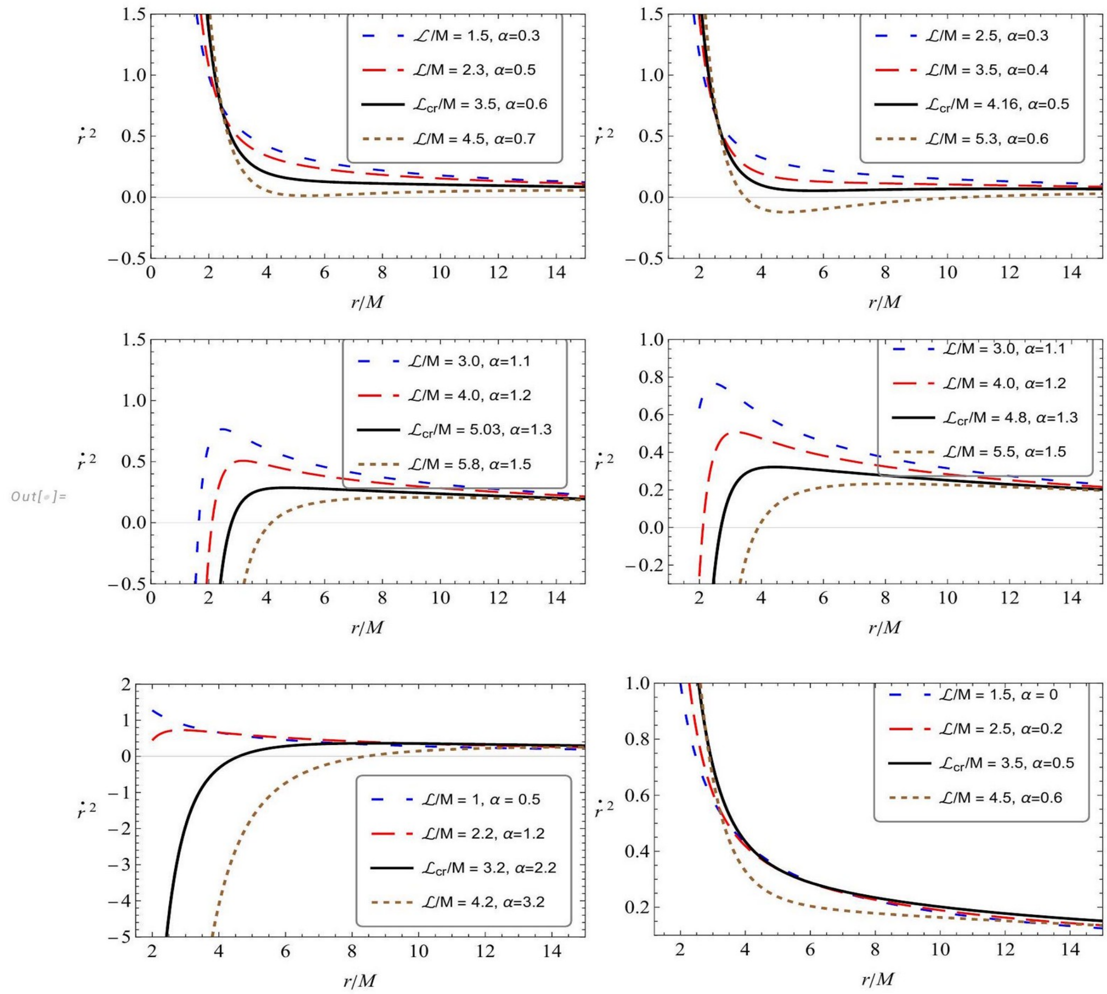

Figure. 3: Radial dependence of the square of radial velocity for different values of angular momentum of the particle.

CONCLUSIONS

The STVG theory provides a framework that extends traditional general relativity by incorporating additional forces and gravitational interactions. The collision of geodesic particles within this context allows for the exploration of intriguing phenomena surrounding black holes and other gravitational sources. These collision processes adhere to the conservation laws of energy and momentum, potentially leading to the generation of gravitational waves and high-energy radiation. Furthermore, the interactions of geodesic particles reveal insights into the curvature of spacetime and the influence of these forces, enhancing our understanding of cosmic dynamics. Studying collisions of geodesic particles in STVG is essential not only for grasping the structure of spacetime but also for addressing astrophysical processes, particularly related to black holes. Research in this area opens new avenues for expanding our knowledge of the universe and testing the fundamental laws of physics.

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