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Scalar-tensor-vector gravity effects on relativistic jets of AGNs

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Abstract. We investigate the effects predicted by an alternative model of gravity on the shape and trajectory of relativistic plasma ejections from the central region of Active Galactic Nuclei. Specifically, we calculate the effects of gravitational Lorentz-like forces that arise in the context of Moffat's Scalar-Tensor-Vector Gravity (STVG), produced by a supermassive black hole on a relativistic plasma blob.

1. Introduction

The Scalar-Tensor-Vector Gravity (STVG) theory (Moffat, 2006), also referred as MOdified Gravity (MOG) theory, has successfully explained solar system observations (Moffat, 2006), galaxy rotation curves (Brownstein & Moffat, 2006), and the dynamics of galactic clusters (Moffat & Rahvar, 2014). The theory has also been applied with success to describe the growth of structure, the matter power spectrum, and the cosmic microwave background (CMB) acoustical power spectrum data (Moffat & Toth, 2007). It remains as one of the most attractive alternatives to general relativity as a theory of gravitation, with the advantage that it offers a solution to the dark matter and dark energy problems.

Most of the applications published so far are based on vacuum solutions in the weak field limit. Recently, Moffat (2015) has found black hole solutions in this theory. Here, we use the STVG-Kerr solution to study geodetic motion of relativistic ejections in AGNs and compare them with results obtained in the framework of General Relativity (GR).

2. STVG field equations

In STVG, the gravitational coupling constant G is replaced by a scalar field whose numerical value usually exceeds Newton constant G_{N}. This enforces a gravitational attraction that adjusts galactic and cosmological observations without requiring the postulation of dark matter. In order to counterpart the enhanced gravitational constant on Solar System scales, Moffat proposed a gravitational repulsive Yukawa-like vector field ϕ^{μ}, so Newton's gravitational constant can be retrieved and STVG coincides with GR in every Solar System prediction.

The equations of the theory are obtained through the following action for the gravitational field:

$$S = S_{\mathrm{GR}} + S_{\phi} + S_{\mathrm{G}} + S_{\mu} + S_{\mathrm{M}}, \tag{1}$$

where

$$S_{\mathrm{GR}} = \frac{1}{16\pi}\int d^4x \frac{1}{G}\sqrt{-g}R, \tag{2}$$

$$S_{\phi} = \omega \int d^4x \sqrt{-g}\left(\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\mu^2\phi^{\mu}\phi_{\mu}\right), \tag{3}$$

$$S_{\mathrm{G}} = \int d^4x \sqrt{-g}\frac{1}{G^3}\left(\frac{1}{2}g^{\mu\nu}\nabla_{\mu}G\nabla_{\nu}G + V(G)\right), \tag{4}$$

$$S_{\mu} = \int d^4x \sqrt{-g}\frac{1}{G\mu^2}\left(\frac{1}{2}g^{\mu\nu}\nabla_{\mu}\mu\nabla_{\nu}\mu + V(\mu)\right). \tag{5}$$

Here, $g_{\mu\nu}$ denotes the spacetime metric, R is the corresponding Ricci scalar, and ∇_{μ} is the covariant derivative; ϕ^{μ} denotes a Proca-type massive vector field, μ is the mass of the field, $B_{\mu\nu} = \partial_{\mu}\phi_{\nu} - \partial_{\nu}\phi_{\mu}$, and $\omega = 1/\sqrt{12}$; $V(G)$ and $V(\mu)$ denote the potentials of the scalar fields $G(x)$ and $\mu(x)$, respectivly. We adopt the metric signature $\eta_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$, and choose units with $c = 1$. The term S_{M} refers to possible matter sources.

In this work, we neglect the mass of the vector field because its effects manifest on kilo-parsec distances from the supermassive source (see Moffat, 2015). Also, since there is still a lot of freedom on the functional form of the scalar field G, in this first work we consider it as a constant, in accordance with Moffat's previous works on vacuum solutions.

Varying the action with respect to $g^{\mu\nu}$ and taking previous simplifications into account, we obtain the metric field equations:

$$G_{\mu\nu} = 8\pi G\left(T^{\mathrm{M}}_{\mu\nu} + T^{\phi}_{\mu\nu}\right), \tag{6}$$

where $G_{\mu\nu}$ denotes the Einstein tensor, and $T^{\mathrm{M}}_{\mu\nu}$, $T^{\phi}_{\mu\nu}$ are the matter and vector field energy-momentum tensors, respectively. We adopt for the enhanced gravitational coupling constant the same prescription as Moffat (2006):

$$G = G_{\mathrm{N}}(1 + \alpha), \tag{7}$$

where G_{N} denotes Newton gravitational constant, and α is a free parameter. Within these approximations, STVG coincides with GR for $\alpha = 0$.

Variation of the simplified action with respect to ϕ_{μ} yields:

$$\nabla_{\nu}B^{\nu\mu} = \frac{\sqrt{\alpha G_{\mathrm{N}}}}{\omega}J^{\mu}, \tag{8}$$

where J^{μ} denotes the four-current matter density, and the constant $\sqrt{\alpha G_{\mathrm{N}}}$ is determined to adjust the known phenomenology.

Finally, variation with respect to particle coordinates δx^{μ} yields the modified equation of motion:

$$m\left(\frac{d^2x^{\mu}}{d\tau^2}+\Gamma^{\mu}_{\alpha\beta}\frac{dx^{\alpha}}{d\tau}\frac{dx^{\beta}}{d\tau}\right)=\kappa m\omega B^{\mu}{}_{\nu}\frac{dx^{\nu}}{d\tau}. \tag{9}$$

With the mentioned approximations, STVG equations 6, 8 and 9, are similar to Einstein-Maxwell equations. In the following, we make use of the equivalence between these formalisms and integrate Eq. 9 for a relativistic jet ejected by STVG-Kerr black hole.

3. STVG-Kerr spacetime

The vacuum axially symmetric solution that represents a rotating black hole in STVG theory is (Moffat 2015):

$$ds^2=\frac{\Delta}{\rho^2}(dt-a\sin^2\theta d\phi)^2-\frac{\sin^2\theta}{\rho^2}\Big[(r^2+a^2)d\phi-adt\Big]^2-\frac{\rho^2}{\Delta}dr^2-\rho^2d\theta^2, \tag{10}$$

where we have taken units such that $c=1$, and:

$$\Delta=r^2-2GMr+a^2+\alpha G_{\rm N}GM^2,\quad \rho^2=r^2+a^2\cos^2\theta. \tag{11}$$

Here, a denotes the black hole angular momentum per unit mass and G the effective gravitational constant (see Eq. 7). A Kerr black hole is recovered for $\alpha=0$. The STVG-Kerr black hole has two event horizons and an ergosphere, just like the classical Kerr geometry. It resembles Kerr-Newman black hole, where the electric charge is replaced by $Q=\sqrt{\alpha G_{\rm N}}M$, with M the mass of the black hole.

Field equations 6, 8, and geodetic equation 9 for a test particle in the Kerr-Newman black hole geometry have been studied by Carter (1968) and Misner, et al (1973). Replacing the electric charge in Kerr-Newman formalism by $Q=\sqrt{\alpha G_{\rm N}}M$, leads us to STVG-Kerr geometry results. In this way, the equations of motion for a test particle in the STVG-Kerr geometry are:

$$\rho^2\frac{dr}{d\lambda}=\frac{\sqrt{R(r)}}{c^2}, \tag{12}$$

$$\rho^2\frac{d\theta}{d\lambda}=\sqrt{\Theta(\theta)}, \tag{13}$$

$$\rho^2\frac{d\phi}{d\lambda}=-\left(\frac{aE}{c^2}-\frac{L}{\sin^2\theta}\right)+\frac{aP(r)}{\Delta(r)c^2}, \tag{14}$$

$$\rho^2\frac{dt}{d\lambda}=-\frac{a}{c}\left(\frac{aE\sin^2\theta}{c^4}-\frac{L}{c^2}\right)+\left(r^2+\frac{a^2}{c^2}\right)\frac{P(r)}{\Delta(r)c^2}, \tag{15}$$

where

$$R(r)=P^2(r)-\Delta(r)\left(m^2r^2c^4+c^2\mathcal{K}\right), \tag{16}$$

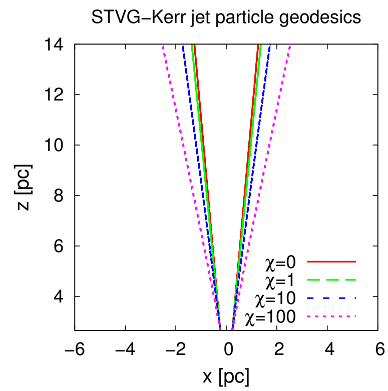

Figure 1. xz-plane trajectories of a test particle ejected by a STVG-Kerr supermassive black hole. The parameter χ quantifies the action of vectorial forces of STVG and corresponding deviations from GR. We model the STVG-Kerr black hole with mass $M = 10^9\ M_\odot$ and normalized spin $a = 0.99$. We study a test particle with $m = 1$ g, initial radial velocity $v = 0.97c$, and initial position $r_{\rm ini} = 1 \times 10^{19}$cm, $\theta_{\rm ini} = 0.1$, $\phi_{\rm ini} = 0$, $p_{\theta,{\rm ini}} = 0$.

$$\Theta(\theta) = \mathcal{Q} - \cos^2\theta \left[\frac{a^2}{c^2}\left(m^2 - \frac{E^2}{c^2}\right) + \frac{L^2}{\sin^2\theta}\right], \tag{17}$$

$$P(r) = E\left(r^2 + \frac{a^2}{c^2}\right) - La + \frac{mQr}{\sqrt{12}}. \tag{18}$$

Here, we have reinstall the speed of light c, λ denotes a time parameter, (t, r, θ, ϕ) are the particle Boyer-Lindquist coordinates, E stands for the test particle energy, L its angular momentum around the symmetry axis, and m its mass. Further, we have defined the constants of motion:

$$\mathcal{K} = p_\theta^2 + \cos^2\theta \left[a^2\left(m^2 - \frac{E^2}{c^2}\right) + \frac{L^2}{\sin^2\theta}\right], \tag{19}$$

$$\mathcal{Q} = \mathcal{K} - \left(L - \frac{aE}{c^2}\right). \tag{20}$$

In the next section, we integrate equations 12, 13, 14, 15 for a relativistic jet, and show preliminary results of the xz-plane trajectories.

4. Preliminary results

As a first step, we have calculated the geodetic motion of a particle ejected close to the rotational axis of a STVG-Kerr supermassive black hole. We take for the parameter α the same prescription as Brownstein & Moffat (2007):

$$\alpha^2 = \chi\,(60.4 \pm 4.1) \times 10^{14} M_\odot \left(\frac{M}{10^{14} M_\odot}\right)^{0.39\pm0.1} M, \tag{21}$$

and we sample different values of the χ parameter.

We use a fourth order Runge-Kutta method to integrate equations 12, 13, 14, 15. The resulting xz-plane trajectory is plotted in Figure 1. As can be seen from the graphic, the effect of the gravitational Lorentz force that appears in STVG results in a lateral deviation of the trajectories from what is expected in GR.

5. Conclusions

We conclude that STVG theory can be tested in a context not explored before: the environments of a rotating supermassive black hole. Deep, multi-epoch radio interferometric observations are ideal to test the theory, since blobs are expected to produce synchrotron radiation. Best targets are nearby AGNs such as Cen A or systems harbouring more massive black holes as 3C273 or 3C279.

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