General relativistic electromagnetic and massive vector field effects with gamma-ray burst production

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We propose a new energy extraction mechanism from the rotational energy of a Kerr-Newman black hole by a gravitating massive photon field generated by electromagnetic and gravitational field coupling effects. Numerical studies show that this mechanism that depends on the black hole rotation parameter, a, shows a clear dependence on the black hole mass, M, and charge, Q, and can extract energies up to 10^{54} erg for a black hole of the solar mass size. With this mechanism we can set a lower bound on the coupling $\xi \sim 10^{-38}$ between electromagnetic and gravitational fields that might be used to explain the hypothetical extremely high energy release, $>10^{53}$ erg, suggested by the observations of some gamma-ray bursts in the controversial "energy crisis" problem if and when gamma-ray bursts seem not to show evidence for collimated emission.

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I. INTRODUCTION

The coupling between gravitation and the other fields represents one of the most important issues for the foundations of physics. At very high energies gravitation and the electromagnetic field are believed to couple together [1]. The most powerful sources are found in the sky, when they take their energy from mechanisms that involve accretion onto a compact object. The exact gamma-ray burst (GRB) energy production mechanism is still a matter of debate. While short GRBs are believed to be originated by the merging of neutron stars, the progenitors of long GRBs are thought to be low-metallicity collapsing massive stars where energy can also be extracted thanks to the rotational energy of the forming black hole. In fact, one possible explanation is the energy release during the formation of a rotating black hole (BH) surrounded by the matter of a rapidly collapsing massive star and, to account for the high energy observed, one has to find very efficient energy extraction mechanisms from the BH [2–4]. Other possible mechanisms can be high-energy phenomena of an energy pulse from electron-positron pair production and the photon plasma fluid created by vacuum polarization in a region surrounding the collapsed star, whose geometry depends on the rotation parameter of the BH called "dyadosphere" or "dyadotorus" [5,6]. This region extends from the exterior event horizon r_+ to a given radius $r_{\rm ds}$ that depends on the mass and charge of the BH with the topology dictated by the BH rotation parameter [7–10].

Energy extraction involving vacuum polarization effects around compact objects require strong magnetic fields and differential motion of electric charges that mimic the effects of a charged BH, described by the Reissner-Nordström solution or by the Kerr-Newman solution when the BH is rotating too [11]. These two classes of solutions provide a good mathematical model for the scenarios in which the energy extraction occurs, with the caveat that one has to realize that this is only a temporary and approximate description. In fact, even if typical astrophysical systems show a strong tendency to eliminate any net electric charge, there are astrophysical scenarios involving charged particles, plasma and strong electromagnetic fields here discussed that can be described temporarily in terms of rotating and charged spacetimes.

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An example is the energy extraction mechanisms where a BH "acquires" a temporary fictitious net charge because of vacuum polarization effects and/or generates an electrostatic field that extends towards the neighborhoods of the event horizon through a selective capture of charged particles. This results in a temporary fictitious charge, a short-living pseudocharged BH that is expected to dissipate on time scales $\tau < 10^7$ s, long enough to set up the GRB energy extraction mechanisms occurring on much shorter time scales during the collapse of the star and thus justify the use of Kerr-Newman-based spacetimes [5,6,12]. Different astrophysical scenarios involving short-living pseudocharged BH states can be found in the literature, e.g., Refs. [13,14].

As described in Ref. [1], photons can acquire mass due to a possible gravitational and electromagnetic (EM) field interaction from a coupling term written in the Lagrangian that can give larger gravitating photon masses due to strong field coupling than those claimed in the literature [15,16]. As we will discuss below, the mechanism described here is different from that providing a virtual Proca mass to photons like occurs in a plasma. Exploiting this possibility, we here describe a new mechanism of energy extraction from black-hole rotational energy made possible by vacuum polarization effects occurring in the region of vacuum polarization around a Kerr-Newman BH and a coupling of electromagnetic and gravitational fields that cause photons to acquire a finite and gravitating mass, as discussed in more detail below.

The main motivation for this work is that one can set a bound to the coupling between EM and gravitational fields in very energetic events as those suggested from observations of GRBs that do not show evidence of collimated emission [17–21]. As shown, e.g., by Amati and Della Valle [22], GRBs have a distribution of released energy, in terms of equivalent isotropic radiation peaking at about $E_{\rm iso} \sim 10^{53}$ erg or higher, e.g., GRB 130427A; see [23]. In some cases they seem to be able to have up to $E_{\rm iso} \sim 10^{54}$ erg, corresponding to emitting one Sun rest mass energy in 1–2 minutes.

The collimated emission scenario often called for to solve this "energy crisis" implies the detection in the light curves of the afterglow of a sudden "achromatic" change in the slope (break) at the time when the relativistic beaming angle becomes larger than the physical jet opening angle as a consequence of the slowing down of the ejected shells [24]. Based on this method, beaming angles between 4 and 9 degrees can be estimated for a number of GRBs [19,25–27], decreasing their energy budget to below $\sim 5 \times 10^{52}$ erg, including models where angles can actually be much wider [28], where GRBs are supposed to have a wide possibility of collimation angles, from small degrees up to a spherical emission. Simulations of core-collapse peculiar massive stars still permit wide collimation angles; in any case the evidence of no break or a very late break based on the standard model of GRB afterglow shows evidence of low-collimated GRBs [29]. This is comparable to the kinetic energy of so-called hypernovae, a subclass of SNe-Ibc often associated with GRBs [30].

However, in some cases this change in the slope is not observed [18–21], suggesting that some GRBs could be characterized by poorly collimated emission. A quasi-isotropic emission is indeed often observed in low-luminosity GRBs [31], but in this case the energy crisis is avoided by the low amount of energy associated with $E_{\rm iso} \sim 10^{50}$ erg, as shown in Fig. 1. However, the existence of high-luminosity GRBs [31,32] that do not exhibit an achromatic change in the slope of the afterglow light curves poses the question to pinpoint an alternative mechanism of energy production in GRBs other than the ones normally adopted, such as "failed supernovae" [33,34] and magnetars [35–37] that can justify energy production up to $\sim 10^{54}$ erg.

We find that the energy extraction from a Kerr-Newman BH by a massive photon (vector) field can also be larger than $\sim 10^{54}$–10^{55} erg, which is indeed close or beyond the upper limit of the energy budget observed in GRB events [39,40].

The paper is organized as follow. In Sec. II we show that, starting from the Proca-Maxwell Lagrangian, one obtains the Proca-Maxwell equations for a massive vector field. Photons acquire mass in a turbulent and structured plasma through the Anderson-Higgs mechanism [41,42] and only when the EM field is coupled to the gravitational field will the spacetime metrics be affected. In Sec. III we estimate the production of energy for GRBs due to the energy extraction of a vector massive field in the ergosphere of a rotating charged BH and set a lower bound to the coupling constant between the gravitational and electromagnetic fields according to the literature to obtain the observed energy budget.

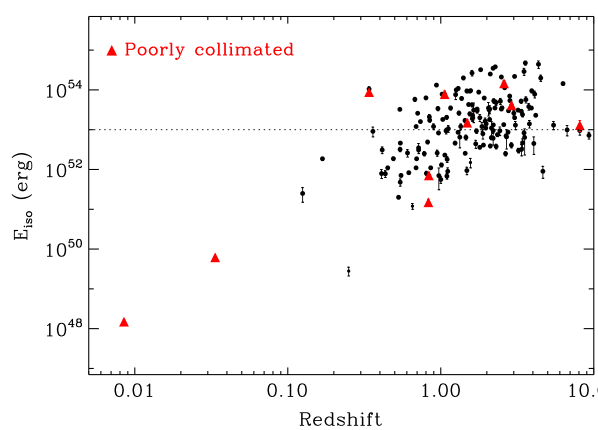

FIG. 1. Isotropic radiated energy distribution of GRBs, $E_{\rm iso}$, with respect to their redshift (see Ref. [22] and references therein). Red triangles indicate those GRBs that exhibit almost spherical emission (subenergetic, e.g., GRB 980425 and GRB 060218 [31]) or those whose optical follow-up provided evidence of no or a late characteristic break (see the compilation by Chandra and Frail [38]) and thus are supposed to have a low degree of collimation (see text). In this case $E_{\rm iso}$ can give the correct order of magnitude of the radiated energy.

II. GENERATION OF A MASSIVE PHOTON FIELD

The presence of an electrostatic charge on the BH unavoidably decreases the efficiency of the BH energy extraction process if charged particles are accreting [43]. For this reason, the charged particles that form the plasma around the BH cannot provide a fully efficient energy extraction in the Penrose process that would generate the energy needed to form a GRB. One way of increasing the energy emission is to include also the contribution of additional resources such as accreting massive neutral vector fields. Massive Proca-Maxwell photons with gravitating mass due to a coupling between electromagnetic and gravitational fields or massive vector field nonminimally coupled to gravitation due to dark energy [44] also represent possibilities for overcoming the 10^{54} erg barrier.

Because of the scenario involved in regions surrounding the BH as described by the dyadosphere model [5,6], the vacuum is polarized and processes of pair production, annihilation and oscillation lead to the formation of a high-energetic and dense plasma of electrons, positrons and photons. Because of number equipartition, electron-positron pairs' number densities are asymptotically comparable to that of photons that obey Proca-Maxwell vector fields. A massive photon Proca-Maxwell field has no electric charge and nonzero rest mass under the particular conditions described below. Being neutral particles, their extraction energy efficiency from the BH is not affected by the temporary Kerr-Newman electrostatic charge. The electromagnetic potential enters actively into the energy budget of the Penrose process, and the finite rest mass of the photon plays a crucial role, changing the spacetime metrics and increasing the total energy extraction.

The generation of a massive photon field requires a spacetime symmetry breaking of Maxwell's equations and a coupling between the electromagnetic and gravitational field to modify spacetime curvature and the energy extraction. This is a different mechanism from the one that usually provides a virtual photon Proca mass in a plasma. This can happen in this scenario: the core of the collapsing star is thought to be surrounded by a plasma during the BH formation, and photons acquire a virtual mass through the Anderson-Higgs mechanism [45,46] as a hidden gauge invariance of the Proca-Maxwell equations preserving the Lorentz invariance [47]. The Proca-Maxwell Lagrangian density $\mathcal{L}$ describing a massive EM field contains a mass term $\mu_\gamma^2 A_\mu A^\mu/2$ because of the gauge invariance [see Ref. [48] Eq. (3)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - j_\mu A^\mu + \frac{1}{2}\mu_\gamma^2 A_\mu A^\mu, \tag{1}$$

where μ_γ^{-1} is the reduced Compton wavelength associated with the photon rest mass and $j_\mu = (\rho, -\mathbf{j})$ is the 4-current. $F^{\mu\nu}$ is the electromagnetic field tensor and A_μ the 4-vector potential. From the Lagrangian density, one obtains the covariant form of the Proca-Maxwell equations

$$\frac{\partial F_{\mu\nu}}{\partial x_\nu} + \mu_\gamma^2 A_\mu = 4\pi j_\mu, \tag{2}$$

that lead to the Proca wave equation for the 4-potential A_μ

$$(\Box - \mu_\gamma^2)A_\mu = -4\pi j_\mu, \tag{3}$$

with the constraint derived from the massive photon in a medium ($\partial^\mu A_\mu = 0$). Proca-Maxwell equations include a masslike term for the photon due to light-matter interaction, viz., a term encompassing the photon's interaction with the plasma (photon-plasmon interactions). This is a virtual photon mass from the coupling between photons and plasma that does not gravitate. Photons and plasmas themselves gravitate, but not their coupling. In the presence of strong fields, one can assume that the two fields may couple together.

The only way of producing a massive photon vector field is when a nonminimal coupling of the EM vector potential to gravity is present in the Lagrangian, namely, $\mathcal{L}_R = \xi R A^\nu A_\nu$, where R is the curvature scalar of the gravitational field, A_ν the 4-vector potential of the EM field and ξ the coupling constant between the gravitational and EM fields. Because of this coupling term, photons can carry a finite rest mass together with the virtual Proca mass due to the plasma, and an additional new gravitating term appears in Einstein's equations. This coupling is thought to occur, e.g., in the presence of a charge asymmetry [1] as is supposed to happen in regions near the forming BH of a GRB. The mass acquired because of this field coupling is not to be intended as that provided from the particle data group.

We now calculate the energy extracted from a rotating BH by the classical Penrose process [49,50] of the massive vector field of photons so far produced, which is different from superradiance [51,52]. An exhaustive theoretical description of this coupling is beyond the scope of this paper and would need a deep understanding of a possible unification between electromagnetism and gravitation. The additional coupling term in the Lagrangian of the system mimics with good approximation the coupling between EM and gravitational fields expected at such high energies. This obviously may provide different and large mass values to those expected for photons in vacuum, that are on the order of 10^{-59} g [15], because it is a different scenario.

The Penrose energy extraction mechanism becomes more efficient due to the finite effective photon mass stress-energy tensor of Proca-Maxwell equations that would not be traceless like the one of Maxwell's equations in vacuum. Because of this symmetry breaking and the coupling between EM and gravitational fields, the total photon "Proca mass" introduces an additional mass term, which is an intrinsically gravitating term that can be included as a source in Einstein's equations. When photons acquire such an additional mass term, the spacetime curvature is unavoidably modified and the environment around the BH is endowed with a massive vector field described by the Proca-Maxwell equations of the EM field. See, e.g., Refs. [53–56] for more details. This is a more general mechanism to photon Proca mass acquisition that adds to the virtual mass acquired in the plasma, a finite gravitating mass to photons due to the coupling between EM and gravitational fields.

If the plasma is turbulent, then one has to consider an additional effect due to the spatial structure of the plasma itself at the plasma resonance frequencies. In fact, unlike the mathematical structure of the spacetime manifold described by the Lorentz group in which space is homogeneous and isotropic and time homogeneous, a plasma may exhibit peculiar spatial/temporal structures that break the spacetime symmetry and cause the conversion of a fraction of the Proca mass into photon orbital angular momentum (OAM) that acts as a mass reducing term in the photon Proca mass [46,48,57]. In this case the OAM term changes the mass in the Proca-Maxwell equations and the Yukawa potential of the spacetime curvature [58,59], preserving, in any case, the sign of the norm of the metric tensor, $\|g\|$, as the acquired mass never becomes negative [57].

III. ENERGY EXTRACTION FROM A MASSIVE PHOTON VECTOR FIELD

Accretion of a massive neutral field in the vacuum polarization region is much more efficient than accretion involving charged particles and can supply or even replace the electromagnetic pulse that is expected to occur to generate the GRB. Moreover, the presence of these massive photons modifies the original Kerr-Newman metric by introducing a Yukawa potential that depends on the electrostatic charge Q of the BH, via the term $\Xi(Q)$ describing the charge asymmetry. For the simplest model of charged BH, one obtains $\Xi(Q) = Q^2/4\pi$.

The modified Kerr-Newman metric in natural units where $e = G = c = 1$, and in the Boyer-Lindquist coordinates (t, r, θ, φ), with the presence of the massive photon field also carrying OAM, becomes

$$
\begin{aligned}
ds^2 = &-\left(1 - \frac{2Mr + \Xi(Q)\mathrm{e}^{-\mu_{\gamma T} r}}{\rho^2} + \mu_{\gamma T} I_\Xi\right) dt^2 + \left(\frac{r^2 + a^2}{\rho^2} - \frac{2Mr + \Xi(Q)\mathrm{e}^{-\mu_{\gamma T} r}}{\rho^2} + \mu_{\gamma T} I_\Xi\right)^{-1} dr^2 \\
&+ \rho^2 d\theta^2 + \left[\rho^2 \sin^2\theta + \left(\frac{2Mr + \Xi(Q)\mathrm{e}^{-\mu_{\gamma T} r}}{\rho^2} \mu_\gamma I_\Xi\right) a^2 \sin^2\theta\right] d\varphi^2 \\
&+ 2a\sin^2\theta \left(\frac{2Mr + \Xi(Q)\mathrm{e}^{-\mu_{\gamma T} r}}{\rho^2} - \mu_{\gamma T} I_\Xi\right) d\varphi dt, \qquad (4)
\end{aligned}
$$

where $\rho^2 = r^2 + a^2 \cos^2\theta$ and $I_\Xi = \int_r^\infty \Xi(Q) \times (\mathrm{e}^{-\mu_{\gamma T} r}/\rho^2) dr$.

To the first order, when $h = 1$, the metric shows a dependence on the absolute value of the OAM acquired by photons [48], viz.,

$$\mu_{\gamma T} \sim 2\pi \left(P_\mu - \ell \frac{D_\mu \tilde{n} \sin(qr)}{2P_\mu}\right), \qquad (5)$$

and the parameters characterizing the Proca mass are

$$P_\mu = \mu_G + \sqrt{B_\mu + C_\mu - D_\mu \cos(qr)}, \qquad (6)$$

where

$$B_\mu = E\omega_{p0}^2 \frac{1 + \varepsilon}{E + \hat{\mathbf{v}} \cdot \nabla\phi} \qquad (7a)$$

$$C_\mu = \frac{4\pi\delta\dot{v} n_0 - 4\pi\hat{\mathbf{v}} \cdot \Box\nabla\phi}{E + \hat{\mathbf{v}} \cdot \nabla\phi} \qquad (7b)$$

$$D_\mu = \frac{4\pi\varphi^* \delta\dot{v}}{E + \hat{\mathbf{v}} \cdot \nabla\phi}. \qquad (7c)$$

If the EM field and the plasma density tend to zero, together with ℓ, the virtual and actual photon mass, μ and μ_T, go to zero, thus recovering the Kerr-Newman spacetime.

For a BH with mass in the range of 3–5 $M_\odot$, electric charge $Q/M \sim 7 \times 10^{-3}$–$7 \times 10^{-2}$ and rotation parameter $a \leq 1$, we find that the Yukawa potential is always confined between the radii $r_1 = 2.95 \times 10^6$ cm and $r_2 = 2.81 \times 10^7$ cm. Much higher energies, up to 10^{55} erg, can be obtained with a progenitor of 10 solar masses. The numerical results indicate that energy produced by the Penrose extraction process of the massive photon field provides the missing energy budget required to reach the 10^{54} erg needed for isotropic emission, having the same order of magnitude as in the GRB process, 10^{47}–10^{54} erg, as reported in Table I. The lower bounds on photon mass values obtained by

TABLE I. Samples of the contribution of a massive photon field to the energy produced by the Penrose extraction process from a rotating charged black hole.

μ_γ (g)	$M_\odot(g)$	a	Q/M	Energy
1.78×10^{-51}	3	0.1	7×10^{-3}	2.88×10^{51}
1.78×10^{-53}	5	0.5	7×10^{-3}	5.77×10^{52}
1.78×10^{-53}	3	0.9	7×10^{-2}	2.88×10^{53}
1×10^{-51}	10	0.9	7×10^{-2}	2.88×10^{55}
1×10^{-51}	10	0.4	0.9	7×10^{55}
1×10^{-51}	10	0.9	0.4	7×10^{55}

varying ℓ as a free integer parameter are those derived from massive vector fields, according to Refs. [55,56] in the range of $\mu_\gamma \sim 10^{-53} - 10^{-51}$ g.

IV. CONCLUSIONS

Accretion onto a Kerr-Newman-like black hole of massive neutral vector fields can explain the energy crisis problem of GRBs. Photons propagating in a structured plasma and in a strong gravitational field are thought to acquire mass and orbital angular momentum because of the hidden gauge invariance due to the Anderson-Higgs mechanism in Proca-Maxwell equations and only when there is an effective coupling between the gravitational and electromagnetic fields in the Lagrangian at high energies.

The interplay between BH mass, charge, and rotation for the energy extraction from the neutrally charged massive photon field gives the correct order of magnitude of the energy expected for a GRB, showing a strong dependence on the charge Q, with the result of diminishing the importance of the rotation parameter in the energy extraction from the BH. This effect, similar to that provided by charged particles falling into the BH [43], could flatten the possible differences in the energy distribution due to differently rotating BHs. We observe in fact a strong dependence on the BH mass M, rotation parameter a and charge Q, with an interesting interplay between angular momentum and charge: highly charged and maximally rotating BH are similar to slowly rotating but hardly charged BHs. With the assumptions made so far, these values allow us to set the lower bound for the coupling constant between the EM and gravitational field to the $\xi \sim 10^{-38}$ value that is expected at very high energies.

Superradiant instabilities because of the small mass of the BH in the GRB precursor considered in our calculations do not play a crucial role in the too rapid formation of the GRB. The energy extraction obtained here, up to 10^{55} erg, comes from the Penrose mechanism applied to a massive photon field where vacuum polarization and coupling between the electromagnetic and gravitational field can occur.

The effects induced by the plasma turbulence on the photon mass, effective at the frequencies where the plasma is resonant, seem not to play a significant role in the energy extraction. Moreover, this study could also be used in the energy budget in massive neutrino-antineutrino fireball models if the couples so generated experience both a Penrose process and viscous dissipation [60] or in the accretion of dark matter vector fields.

From our results we can set a lower bound for the coupling constant between the EM and gravitational field to $\xi \sim 10^{-38}$, a coupling that might contribute to electromagnetic emission also in those strong energy scenarios where EM waves are not expected, such as in BH-BH collisions, as hypothesized for the recent LIGO GW150914 gravitational wave detection and possible Fermi event coincidence observed after 0.4 s in the electromagnetic spectrum [61–63].

The effect of this field coupling might also be accompanied by other nonlinear gravitational wave interactions with plasmas [64]. No direct transfer of OAM from Kerr metric lensing to photons [65] has been considered because of the physical properties inside the dyadosphere.

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