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The role of gravitomagnetism in the energy extraction from a Kerr black hole to power the GeV emission of gamma-ray bursts

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We summarize a new model that explains the high-energy (photon energies of gigaelectronvolts – GeV) observed in the energetic long-duration gamma-ray bursts (GRBs). The model shows that the gravitomagnetic interaction of a Kerr black hole (BH) with a surrounding magnetic field generates GeV radiation in the vicinity of the BH event horizon extracting the (rotational) energy of the BH.

Keywords: Gamma-ray bursts: general – black hole physics – pulsars: general – magnetic fields

1 Introduction

GRBs are the most powerful astrophysical sources in the sky, releasing up to a few 10^{54} erg in just a few seconds. The observations from ground and space show that GRBs radiation across the electromagnetic spectrum, including the radio, optical, X-rays, gamma-rays in the megaelectronvolt (MeV), gigaelectronvolt (GeV) and teraelectronvolt (TeV) regimes, and ultrahigh-energy cosmic rays (UHECRs).

The emission of an energetic ($\gtrsim 10^{52}$ erg) GRB is characterized by seven *Episodes* produced by specific physical processes with widely different characteristic evolution

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timescales ranging from 10^{-14} s to 10^{7} s or longer (Ruffini et al., 2021). Although researchers soon identified that BHs should fuel GRBs (see, e.g., Damour & Ruffini, 1975), it is hard to think that a single object can explain all the above complexity and high energetics. Another crucial piece of information is that one of such Episodes is an associated supernova (SN) explosion. How can a single astrophysical object lead to a SN explosion, a BH, and all the observed emissions at the different wavelengths?

An answer to this question arises from the binary-driven hypernova (BdHN) model (see, e.g., Rueda & Ruffini, 2012; Izzo et al., 2012; Fryer et al., 2014, 2015; Becerra et al., 2015, 2016, 2019). In the BdHN scenario, the GRB originates in a binary system composed of a carbon–oxygen (CO) star and a neutron star (NS) companion. The CO star undergoes a core-collapse SN, forming at its center a newborn neutron star (hereafter νNS), while the ejected material causes a massive accretion process onto the NS companion. The entity of the accretion process depends mostly on the orbital period, and only in tight binaries with orbital periods as short as a few minutes the accretion onto the NS companion induces its gravitational collapse, forming a newborn, rotating (i.e., Kerr) BH. Three-dimensional numerical simulations of the above process in BdHNe were presented in (Becerra et al., 2019). The different fates of the binary explains the variety of GRBs, while the different physical components of the binary powered the different emission Episodes. The binaries in which the BH is formed are called BdHN of type I. In a BdHN I, the rotational energy of the fast rotating νNS and its interaction with the ejected material in the SN powers the synchrotron radiation that explains the radio, optical, and X-rays emission of the GRB afterglow (see, e.g., (Rueda et al., 2020)).

Only the observed GeV emission is associated with the *inner engine* of the GRB (Ruffini et al., 2019; Moradi et al., 2021), i.e., the newborn Kerr BH, surrounded by ionized ultralow density matter, and the magnetic field inherited from the collapsed NS. The aim of this article is to summarize the model presented in Rueda et al. (2022) on the origin of the GeV radiation in a process of energy extraction of the BH rotational energy driven by the gravitomagnetic interaction of the Kerr BH and the magnetic field.

2 The need for new physics

BHs were initially conceptualized either as *dead* objects or as sinks of energy. Subsequently, it was realized that BHs can interact with their surroundings exchanging energy (Christodoulou, 1970; Christodoulou & Ruffini, 1971). This result led to one of the most important concepts in BH physics and astrophysics: the Christodoulou–Ruffini–Hawking BH mass–energy formula (Christodoulou, 1970; Christodoulou & Ruffini, 1971; Hawking, 1971). In its most general form, for a rotating charged BH, it relates the BH mass–energy to three independent pieces: the *irreducible mass*, the charge (leading to the electric energy), and the angular momentum (leading to the rotational energy). The BH mass–energy formula leads to a corollary of great relevance in astrophysics: up to 50% of the mass–energy of a charged BH, and up to 29% of the mass–energy of a rotating BH, could be in principle extracted! Consequently, the concept of BH changed: nature could potentially use their extraordinary amount of energy to power astrophysical sources.

How much energy do we need to extract from the Kerr BH? Stellar-mass (i.e., of a few solar masses) BHs are involved in the emission of GRBs while AGNs, releasing 10^{46} erg s^{-1} for billion years, must be powered by supermassive BHs of up to a few billion solar masses. However, the specific physical mechanism leading to the emission is up-to-now unknown, and theoretical efforts to find how to extract the BH energy have evanesced by the implausibility of their realization in nature (see, e.g., Penrose & Floyd, 1971). The existing models of AGN explain the observed jetted emission with massive jets powered by accretion disks around BHs, and GRBs models have inherited the same idea. These models have avoided, in practice, solving the problem of energy extraction from a BH. Therefore, finding an astrophysically viable process that extracts the energy from a BH has remained elusive. Because the efficiency of accretion power is low, so very costly for nature, there is a need for new physics in the explanation of GRBs.

3 The concept of effective charge

A much more efficient mechanism for the acceleration of particles should use electromagnetic fields instead of pure gravity. Electric fields are great accelerators of charged particles. The first way that comes to our mind to use the acceleration power of an electric field is to allow the BH to have a stable net charge that produces a stable electric field. This has been a most debated topic in astrophysics because, in principle, a charged BH could be rapidly neutralized by absorbing an electric charge of the opposite sign to its charge.

In classical electromagnetism, Faraday induction implies that a rotating conductor in an external magnetic field generates an electric field. Accounting for this effect, Ruffini and Treves in 1973 calculated the ground state configuration of a conducting rotating sphere endowed with charge and magnetic field (Ruffini & Treves, 1973). They showed that in the ground state the value of the electric charge is set by the mass and size of the object, the angular momentum, and the magnetic field strength. In 1974, R. Wald studied a similar problem by analyzing a Kerr BH in an external magnetic field (Wald, 1974). In this case, Einstein's theory of general relativity predicts a unique effect based on the concept of *gravitomagnetism*: the interaction of the *gravitomagnetic* field of the rotating BH with the magnetic field induces an electric field. This is somehow analogous to the Faraday induction, but here there is no charge generating that electric field! The induced electric is nearly radial and falls-off with distance as $1/r^2$ (see Figure 1). At the BH horizon, $r = r_+ = (1 + \sqrt{1-\alpha^2})GM/c^2$, the radial electric field can be estimated as (see, e.g., Ruffini et al., 2019; Rueda & Ruffini, 2020)

$$E(r_+) \sim \frac{v}{c} B_0 \sim \frac{\Omega_+ r_+}{c} B_0 = \frac{\alpha\, B_0}{2}, \tag{1}$$

where M, J, $\alpha = cJ/(GM^2)$, and $\Omega_+ = c\,\alpha/(2\,r_+)$ are, respectively, the BH mass, angular momentum, dimensionless spin parameter, and angular velocity. If we think of this electric field as produced by some charge, an *effective charge*, $Q_{\rm eff}$, its value turns out to be (Ruffini et al., 2019; Rueda & Ruffini, 2020; Moradi et al., 2021; Rueda et al., 2022)

$$Q_{\rm eff} = r_+^2 E(r_+) \approx \frac{4G^2M^2}{c^4} \frac{\alpha\, B_0}{2} = \frac{G}{c^3} 2JB_0, \tag{2}$$

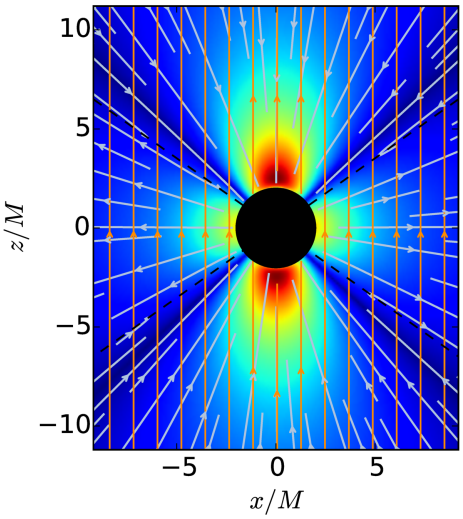


Figure 1 Figure taken from Rueda et al. (2022) with the kind permission of the authors. Electric (light blue) and magnetic (orange) field lines surrounding the Kerr BH. Electrons located in the northern and southern hemisphere cones of semi-aperture angle of $\approx 60^\circ$ are outwardly accelerated leading to GeV radiation.

namely, it is determined only by the BH angular momentum and the magnetic field strength. The generation of electric fields without electric charge has led to the possibility of astrophysical BHs being efficient particle accelerators without being electrically charged objects.

4 The new physical mechanism to power the GeV emission of GRBs

The inner engine uses the general relativistic effect of gravitomagnetism by considering a Kerr BH in an external magnetic field that induces an electric field (see Figure 1). The model exploits this induced electric field to accelerate charged particles (e.g. electrons/protons) in the vicinity of the BH. Along the BH rotation axis, the electrons are accelerated to energies of even thousands of PeV. Hence, stellar-mass BHs in GRBs and supermassive BHs in AGNs might contribute to the observed flux of UHECRs.

At off-axis latitudes, electrons accelerate to energies of hundreds of GeV and emit synchrotron radiation at GeV energies (see Figure 2). This process occurs within 60° around the BH rotation axis (see Figure 1), and due to the equatorial symmetry, it forms a double cone of outgoing radiation.

5 The BH energy extraction

The energy radiated off to infinity by the accelerated electrons is powered by the BH extractable energy

$$E_{\rm extr} \equiv (M - M_{\rm irr})c^2, \tag{3}$$

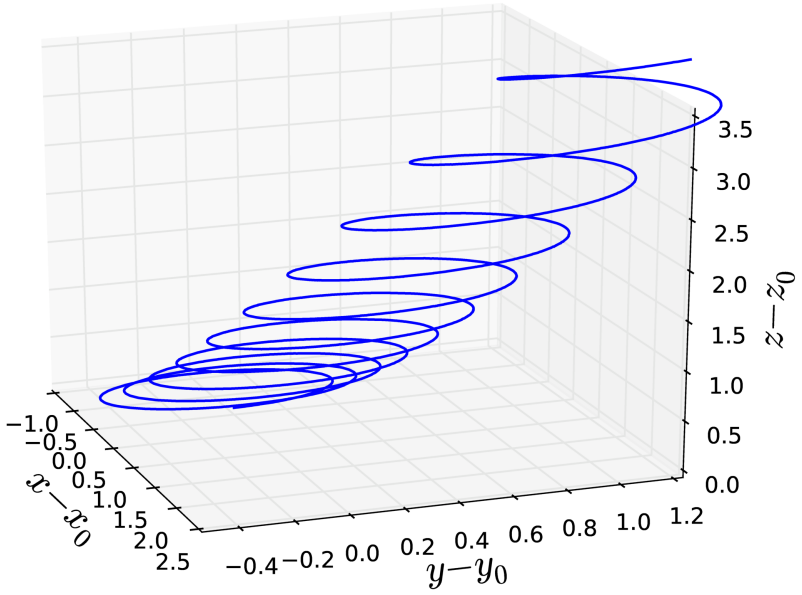


Figure 2 Figure taken from Rueda et al. (2022) with the kind permission of the authors. Helical motion of an electron around the magnetic field lines in the vicinity of the Kerr BH leading to synchrotron radiation at GeV energies.

where $M_{\rm irr}$ is the BH irreducible mass that is related to the BH mass M by the mass–energy formula (Christodoulou, 1970; Christodoulou & Ruffini, 1971; Hawking, 1971)

$$M^2 = \frac{c^2 J^2}{4G^2 M_{\rm irr}^2} + M_{\rm irr}^2. \tag{4}$$

The BH energy extraction process follows from the inner engine operation:

1. The magnetic field and the BH rotation induce an electric field described by the Papapetrou–Wald solution (Wald, 1974). We specialize in the case of aligned and parallel magnetic field and BH spin. The electric field is mostly radial and points inward within the cones of semi-aperture angle of ≈60° from the BH rotation axis (see Figure 1).
2. The induced electric field accelerates electrons from the ultralow density surrounding matter. The number of accelerated electrons is set by the energy stored in the electric field

$$\mathcal{E} \approx \frac{1}{2} E^2(r_+) r_+^3 \approx \frac{G}{c^4} \frac{B_0^2 J^2}{M}. \tag{5}$$

3. Along the polar axis, radiation losses by acceleration are absent because the electric and magnetic fields are parallel (i.e., electrons have zero pitch angle). Hence, electrons on the polar axis accelerate freely outward, gaining the total potential energy difference from the acceleration point to infinity. Such energy

is of the order of the electric potential energy difference from the horizon to infinity

$$\Delta\Phi = \frac{1}{c} e\, a\, B_0. \tag{6}$$

4. Off-polar axis, the electric and magnetic field cross at different angles leading to electrons with non-zero pitch angles. Under these conditions, the electrons lose energy via synchrotron radiation. The observed luminosity, $L_{\rm GeV}$ and the radiation timescale, $t_{\rm rad}$, must fulfill

$$L_{\rm GeV} = \frac{dE_{\rm GeV}}{dt} \leq \frac{dE_{\rm extr}}{dt} \approx \frac{\mathcal{E}}{t_{\rm rad}}, \tag{7}$$

where $\mathcal{E}$ is given by Eq. (5). Here, $E_{\rm GeV}$ is the energy of the observed radiation, i.e.

$$E_{\rm GeV} = \int L_{\rm GeV}\, dt, \tag{8}$$

which necessarily fulfills

$$E_{\rm GeV} \leq E_{\rm extr}, \tag{9}$$

where $E_{\rm extr}$ is given by Eq. (3).

5. The release of the energy amount $\mathcal{E}$ reduces the BH mass and angular momentum by amounts dM and dJ, respectively. The change in the BH mass is

$$c^2 dM = dE_{\rm extr} \approx dE_{\rm GeV} \approx \mathcal{E}, \tag{10}$$

and for a reversible process, i.e. for an irreducible mass that holds constant during the process of energy extraction, the change in the BH angular momentum is

$$dJ = \frac{c^2 dM}{\Omega_+}. \tag{11}$$

6. The entire above procedure repeats with the same efficiency while the density of the surrounding matter provides the number of particles to use the entire new electric energy.
7. Assuming that the surrounding medium feeds the BH, the repetition of the above process leads to a maximum fractional change of BH mass and angular momentum

$$\frac{\Delta M}{M} = 1 - \frac{M_{\rm irr}}{M}, \quad \frac{\Delta J}{J} = \left(1 + \frac{M_{\rm irr}}{M}\right)^{-1}, \tag{12}$$

where we have used Eqs. (4), (10), (11), and the relation between the BH irreducible mass and the horizon, $r_+ = 2GM_{\rm irr}^2/(Mc^2)$.

Having set the entire radiation and energy extraction process, we turn to a quantitative example using the numbers of the analysis of GRB 190114C presented in Moradi et al. (2021). For a magnetic field strength $B_0 = 10^{11}$ G, BH mass $M = 4.4 M_\odot$ and spin $\alpha = 0.3$, the stored electric energy is $\mathcal{E} \approx 2.04 \times 10^{37}$ erg. The electrons reach a Lorentz factor $\gamma \approx 3 \times 10^4$ (Moradi et al., 2021; Rueda et al., 2022), so an energy

of nearly $\epsilon_e = \gamma m_e c^2 \approx 10^{11}\,\mathrm{eV} \approx 10^{-1}$ erg, which implies a synchrotron radiation power per electron of $\mathcal{P}_\infty \approx 10^{13}$ erg s^{-1}, leading to a radiation timescale

$$t_{\rm rad} = -\frac{p_\mu \eta^\mu}{\mathcal{P}_\infty} \approx 10^{-14}\,\mathrm{s}, \tag{13}$$

where p_μ is the electron's four-momentum measured by an observer at rest at infinity and η^μ is the time-like Killing vector (see Rueda et al., 2022, for details). The above figures imply that the inner engine radiates synchrotron radiation at GeV energies with a power $\mathcal{E}/t_{\rm rad} \approx 10^{51}$ erg s^{-1}. For these parameters, in each elementary emission, the fractional changes of mass and angular momentum of the BH are, respectively, $dM/M \approx 2.59 \times 10^{-18}$ and $dJ/J \approx 1.12 \times 10^{-16}$. Assuming constant the BH irreducible mass, $M_{\rm irr} \approx 4.35\,M_\odot$, the total radiated energy equals the extractable energy, i.e., $\Delta E = \Delta M c^2 = \Omega_+ \Delta J = E_{\rm extr} = (M - M_{\rm irr})c^2 \approx 8.95 \times 10^{52}$ erg. The total fractional changes in the BH mass and angular momentum are, respectively, $\Delta M/M \approx 0.0114$ and $\Delta J/J \approx 0.503$.

6 Conclusions

The rotational energy of a Kerr BH can be efficiently extracted to power the high-energy (GeV) emission of GRBs. The emission occurs within a double-cone with a semi-aperture angle around $\approx 60^\circ$ from the BH rotation axis. Such *jetted* emission does not originate from an ultra-relativistic acceleration of matter in bulk, like massive jets powered by accretion disks. The emission is produced by a general relativistic, electrodynamical process. The emission is driven by a mechanism that uses the general relativistic gravitomagnetic interaction of the Kerr BH with the surrounding magnetic field, and the electrodynamics of accelerated charged electrons from the ionized low density matter around the Kerr BH. The mechanism also works for the supermassive BHs in AGNs (see, e.g., Moradi et al., 2021; Rueda et al., 2022). We refer the interested reader to Rueda et al. (2022) for further details and a full general relativistic formulation of the theoretical treatment summarized in this article.

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