

Gravitomagnetic interaction of a Kerr black hole with a magnetic field as the source of the jetted GeV radiation of gamma-ray bursts

Press release

A new theory explains the high-energy (photon energies of gigaelectronvolts — GeV) observed in the energetic long-duration gamma-ray bursts (GRBs) as originated in the vicinity of the black hole horizon. The theory, published today in *The Astrophysical Journal* [1] (<https://iopscience.iop.org/article/10.3847/1538-4357/ac5b6e>), led by an ICRA-ICRANet research team (some INAF associates), is based on the “*inner engine*” previously introduced by the team [2, 3]. The theory, which is also shown to work in active galactic nuclei (AGNs), proves that the rotational energy of a black hole can indeed be extracted from the horizon of the black hole, and efficiently used to power the most energetic and powerful objects in the Universe.

GRBs and binary-driven hypernovae. GRBs are one of the most complex astrophysical systems observed from ground and space in a wide window of the electromagnetic spectrum, including radio, optical, X-rays, gamma-rays in the megaelectronvolt (MeV) and the gigaelectronvolt (GeV) regimes, and ultrahigh-energy cosmic rays (UHECRs). GRBs are the most powerful transient sources of energies in the sky, releasing up to a few 10^{54} erg in just a few seconds. Therefore, the luminosity of a GRB is comparable to the sum of the luminosities of all the stars in the Universe!. The emission of an energetic GRB is characterized by seven *Episodes* produced by specific physical processes with widely different characteristic evolution timescales ranging from 10^{-14} s to 10^7 s or longer [4]. Although researchers soon identified that black holes must fuel GRBs, it is hard to think that a single object can explain all the above complexity. Another crucial piece of information is that one of such Episodes is an associated supernova explosion. How can a single astrophysical object lead to a supernova explosion, a black hole, 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., [4], and references therein). 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 supernova, forming at its center a newborn neutron star, while the ejected material causes a massive accretion process onto the neutron star 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 neutron star companion induces its gravitational collapse, forming a newborn black hole. Three-dimensional numerical simulations of the above process in a BdHN were presented in [5]. 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 black hole is formed are called BdHN of type I. In a BdHN I, the rotational energy of the fast rotating, newborn neutron star and its interaction with the ejected material in the supernova powers the synchrotron radiation that explains the radio, optical, and X-rays emissions (see, e.g., [6]). Only the observed GeV emission [3, 7] is associated with the black hole and the process of energy extraction that is the topic of the new publication.

Black holes are storehouses of energy. Black holes were initially conceptualized either as “*dead*” objects or as sinks of energy. Subsequently, it was realized that much as the thermodynamical systems, black holes may interact with their surroundings exchanging energy [8, 9]. This result led to one of the most important concepts in black hole physics and astrophysics: the Christodoulou-Ruffini-Hawking black hole mass-energy formula [8–10]. In its most general form, for a rotating charged black hole, it relates the black hole mass-energy to three independent pieces: its “*irreducible mass*”, its charge, and its angular momentum. It led to a corollary of paramount importance in astrophysics: up to 50% of the mass-energy of a charged black hole, and up to 29% of the one of a rotating black hole, could be in principle extracted!. This extraordinary result led to the alternative view of black holes as storehouses of energy which nature could potentially use, and since then this concept has permeated for fifty years as of this writing, relativistic astrophysics both theoretically and experimentally.

How much energy do we need to extract from black holes?. As we have mentioned above, researchers think that stellar-mass (i.e., of a few solar masses) black holes are involved in the emission of GRBs while, AGNs, releasing 10^{46} erg s^{-1} for billion years, must be powered by supermassive black holes 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 black-hole energy have evanesced by the implausibility of their realization in nature (see, e.g. [11]). The existing models of AGN explain the observed jetted emission with massive jets powered by accretion disks around black holes, and GRBs models have inherited the same idea. These models have avoided, in practice, solving the problem of energy extraction from a black hole. Therefore, finding an astrophysically viable process that extracts the energy from a black hole has remained elusive. Because the efficiency of accretion power is low and, as such, very

costly for nature, there was a need for new physics!.

From charge to effective charge. A much more efficient mechanism for the acceleration of particles should use electromagnetic fields instead of pure gravity. In particular, electric fields can be great accelerators of charged particles. One could think of allowing the black hole to have stably some net charge that produces a stable electric field. This has been a most debated topic in astrophysics because, in principle, a charged black hole could be rapidly neutralized by absorbing an electric charge of the opposite sign to its charge. In 1973, Ruffini and Treves calculated the ground state configuration of a conducting rotating sphere endowed with charge and magnetic field [12]. In classical electromagnetism, Faraday induction implies that a rotating conductor in an external magnetic field generates an electric field. Accounting for this effect, they obtained the electromagnetic field structure of the configuration and showed that in its ground state, the electric charge of the object is not a free parameter: it has a precise value that depends on the mass and size of the object, the angular momentum, and the magnetic field strength. In 1974, R. Wald studied a similar question by analyzing a rotating black hole in an external magnetic field [13]. In this case, Einstein's theory of general relativity predicts a unique effect based on the concept of *gravitomagnetism*: the interaction of the gravitational field of the rotating black hole 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! If we think of this electric field as produced by some charge, an effective charge, then the value of such an effective charge turns out to be determined, again, only by the black-hole angular momentum and the magnetic field strength. The existence of electric fields without electric charge has led to the possibility of astrophysical black holes being efficient particle accelerators without being electrically charged objects!

The new physical mechanism. The engine presented in the new publication uses the above purely general relativistic effect of gravitomagnetism by considering a rotating black hole in an external magnetic field that induces the an electric field (see Figure 1). The theory exploits this induced electric field to accelerate charged particles (e.g. electrons/protons) in the vicinity of the black hole. Along the black hole rotation axis, the electrons are accelerated to energies of even thousands of PeV, so stellar-mass black holes in GRBs and supermassive black holes in AGNs can contribute to the observed flux of UHECRs using this mechanism. At off-axis latitudes, electrons accelerate to energies of hundreds of GeV and emit synchrotron radiation at GeV energies. This process occurs within 60° around the black hole rotation axis, and due to the equatorial-symmetry, it forms a double-cone of outgoing radiation.

The black hole energy extraction. The energy carried out by this electromagnetic radiation is paid by the black hole which, in turn, loses its mass and angular momentum with time. This proves that we can efficiently extract energy from a rotating black hole to power the high-energy *jetted* emissions of GRBs and AGNs. The *jetted* emission does not originate from an ultra-relativistic acceleration of matter in bulk (e.g., massive jets powered by accretion disks), but from very special energy-saving general relativistic and electro-dynamical process. A long march of successive theoretical progress and new physics discovered using GRBs has brought to this long-awaited result for about fifty years of relativistic astrophysics. We refer the interested reader to [1] for further details. As pointed out by the Referee: *this paper pursues a very important problem in astrophysics, the generation of GRBs ... the problem of ultra-high energy radiation production using clean general relativistic approach.*

Contact:

Prof. Remo Ruffini

Director, ICRANet

Phone: (+39) 085 2305 4201, mobile: (+39) 339 475 2566

E-mail: ruffini@icra.it

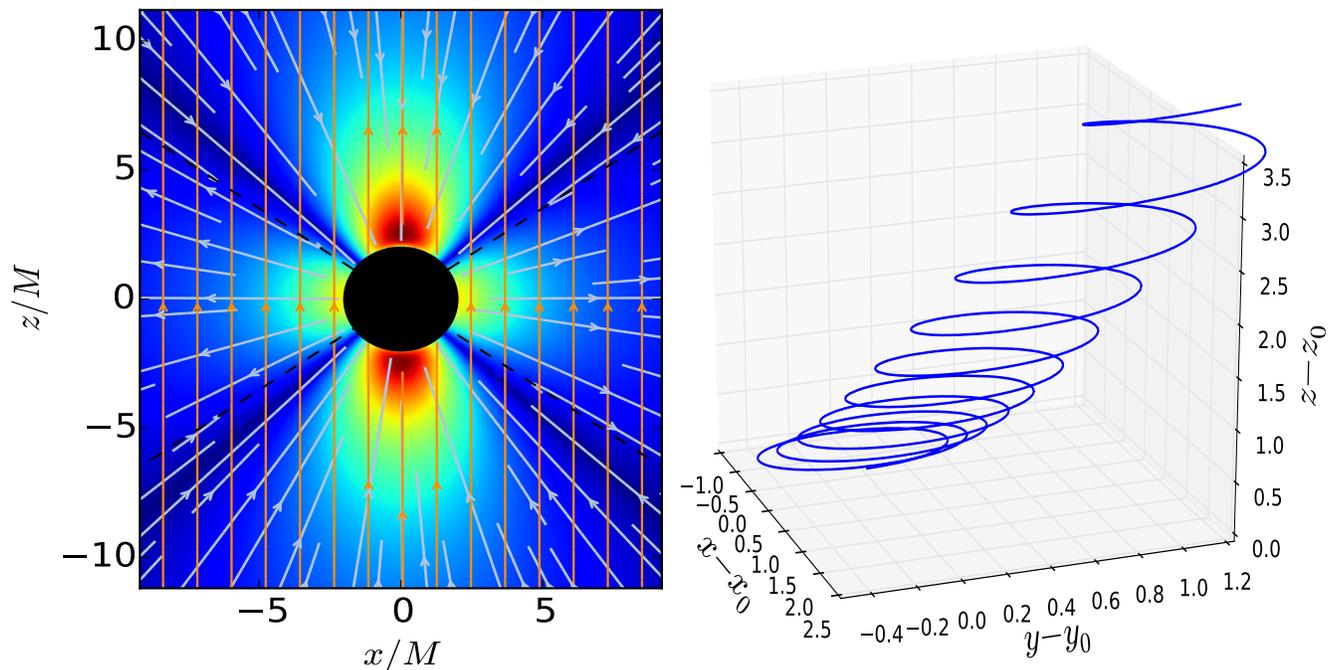


FIG. 1. Figures taken from [1] with the kind permission of the authors. Left panel: electric (light blue) and magnetic (orange) field lines surrounding the rotating black hole. Electrons located in these northern and southern hemisphere cones of semi-aperture angle of nearly 60° are outwardly accelerated leading to GeV photons. Right panel: helical motion of an electron around the magnetic field lines in the vicinity of the black hole leading to synchrotron radiation.

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