Non-thermal high-energy emissions from black holes by a relativistic capillary effect

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Gravitational spin-orbit interactions induce a relativistic capillary effect along open magnetic flux-tubes, that join the event horizon of a spinning black hole to infinity. It launches a leptonic outflow from electron-positron pairs created near the black hole, which terminates in an ultra-relativistic Alfvén wave. Upstream to infinity, it maintains a clean linear accelerator for baryons picked-up from an ionized ambient environment. We apply it to the origin of UHECRs and to spectral energy correlations in cosmological gamma-ray bursts. The former is identified with the Fermi-level of the black hole event horizon, the latter with a correlation $E_p T^{3/2}_{\gamma 0} \simeq E_\gamma$ in HETE-II and Swift data.

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I. INTRODUCTION

Non-thermal high-energy emissions are characteristic properties of active galactic nuclei and cosmological gamma-ray bursts. These emissions are commonly associated with ultra-relativistic baryon-poor outflows, representing the spinning black holes interacting with matter and electromagnetic fields. While black holes are described by merely three parameters of mass, angular momentum and electric charge, their interactions are mediated by the entire surrounding spacetime subject to radiation boundary conditions on the event horizon and infinity. For spinning black holes, Mach’s principle implies frame-dragging, in which zero-angular momentum states assume zero angular velocities relative to the distant stars while corotation with the black hole in its close proximity. Even though these two examples – AGN and GRBs – represent systems of hugely different scales, the inherently scale-free continuum of macroscopic black holes allows scaling across a wide range of black hole masses, and hence a common mechanism for producing non-thermal high-energy emissions in AGN and GRBs.

The identification of Ultra-High Energy Cosmic Rays (UHECRs) beyond the Greisen-Zatsepin-Kuzmin cut-off with nearby active galactic nuclei (AGN) poses the question on the physical origin with their remarkable energies of up to and beyond 1 exa-eV ($10^{18}$eV) \[1, 2\]. The observed exa-eV energies probably represent the raw potential energies generated by the inner engine of an AGN, rather than a generally less efficient prompt emission process in, e.g., turbulent shocks. As such, the UHECRs point towards a clean site for open, linear acceleration, which is largely uncontaminated by surrounding baryonic matter and is not subject to in-situ pair-cascade processes.

The association of gamma-ray burst emissions and their afterglows with non-thermal dissipation of the kinetic energy in ultra-relativistic baryon-poor jets poses the question on the physical mechanism producing these outflows \[3\], presumably out of ab-initio baryon-free leptonic outflows following pick-up of baryonic contaminants \[4\]. While spinning black holes should naturally be active, and pair-creation of leptonic matter is expected to be prominent in their vicinity, any viable mechanism for launching ultra-relativistic leptonic jets appears to be non-trivial in accounting for both the observed macroscopic phenomenology in energies, luminosities and durations, and detailed spectral energy correlations \[5, 6, 7\].

Spinning black holes provide an attractive alternative for the inner engines of AGN and GRBs in view of the potentially large amount of spin-energy per unit mass according to the Kerr metric \[8\]:

$$E_{spin} = \frac{1}{2} \Omega_H^2 I f_s^2, \quad f_s = \frac{\cos(\lambda/2)}{\cos(\lambda/4)}.$$

In geometrical units in which Newton’s constant and the velocity of light are set equal to 1, $\Omega_H = (1/2M) \tan(\lambda/2)$ denotes the angular velocity of the black hole of mass $M$, $I = 4M^3$ its moment of inertia in the limit of slow rotation \[8\], and $0.7654 \leq f_s \leq 1$ is a modulation associated with relativistic spin rates. With $-\pi/2 \leq \lambda \leq \pi/2$, $E_{spin}/M$ can reach a 29% – which is one order of magnitude larger than the specific spin energy of a neutron star. In view of \[1\], it is tempting to associate rotating black holes as the energy source in a wide variety of AGN and, more generally, in extreme transient sources (recently reviewed in \[10\]). For example, quasars may represent AGN that harbor a supermassive black hole which spins rapidly. The Kerr solution further elucidates some remarkable physical aspects black hole radiation processes. Perhaps first and foremost, spontaneous emission of a particle by a spinning black hole satisfies the Rayleigh criterion

$$a_p \geq 2M > M > a,$$

where $a_p$ denotes the specific angular momentum of a radiated particle, $a$ the specific angular momentum of the black hole of mass $M$ and radius $r_H = 2M \cos^2(\lambda/2)$ with spin rapidity $\lambda$, $\sin \lambda = a/M$. A specific astrophysical process is required, however, to engage black holes in radiation processes by suppressing canonical angular momentum barriers \[11\], which otherwise stabilize isolated macroscopic black against spontaneous spin-down. Most astrophysical processes involve an electromagnetic field, and this offers some novel prospects.
for black hole radiation processes according to the second law of thermodynamics [12]

$$\delta M = \Omega_H \delta (J_H + J_{em}) + T_H \delta S_H + [V^H_\infty \delta q], \quad (3)$$

where $-\delta M$ represents the energy output, $J_{em}$ refers to the angular momentum of the electromagnetic field in the presence of a voltage difference $[V^H_\infty]$ between the event horizon (with electric charge $q$) and infinity, and $T_H \delta S_H$ denotes the associated creation of entropy. Recent spectroscopic evidence for rapidly rotating outflows provides qualitative support for the magnetic fields in disks around supermassive black holes [13], consistent with launching outer jets in the form of baryon-rich disk winds by magnetic pressure [14, 15].

The Penrose process provides an explicit demonstration that black hole spin can be released to infinity [17]. Nevertheless, it gives a rigorous demonstration of principle which satisfies causality and the appropriate ingoing and outgoing radiative boundary conditions on the event horizon and, respectively, infinity. It hereby elucidates a “two-particle” description for the extraction of black hole spin energy.

Recently, we demonstrated the possibility for the emission of positive energy-angular momentum particles to infinity along a magnetic flux-tube along the spin-axis of the black hole. In an asymptotically uniform magnetic field [18], Hawking radiation is modified according to [23]

$$\frac{d^2 N}{dE d\Omega} = \frac{\Gamma}{e^{2(E-V_F)/\delta_H} + 1}, \quad (4)$$

where $\Gamma$ denotes the gray-body factor, $E$ the energy of the radiation particle and $V_F$ denotes the horizon Fermi-level

$$\nu \Omega_H = e \text{EMF}_\nu \quad (5)$$

associated with the angular momentum $\nu = \pm e A_\phi$ of particles with charge $\pm e$ along a magnetic flux-surface $2\pi A_\phi$. It demonstrates that black hole radiation processes are inherently non-local (on the macroscopic scale set by the size of the black hole), here comprising frame-dragging subject to the radiation conditions on the event horizon and infinity. The equivalent integral to (4) is the net electromagnetic force $\text{EMF}_\nu$ in (5), associated with a loop which extends and closes over infinity, the spin-axis, the horizon surface and the flux-surface $\nu$ at hand.

The result (5) shows that angular momentum barriers can be successfully circumvented by gravitational spin-orbit coupling through an equivalent level-shift [24]

$$\mathcal{E} = \omega J \quad (6)$$

of particles with angular momentum $J = -\gamma g_{\phi\phi}(\Omega - \omega)$, where $\Omega$ denotes the angular velocity relative to infinity, $\omega$ is the local angular velocity frame-dragging in the metric $g_{ab}$, and $\gamma$ denotes the time component $u^t$ of a velocity four-vector $u^a (u^tu^t = -1)$. Frame-dragging assumes a maximal magnitude on the event horizon, where $\omega = \Omega_H$. It decays algebraically according to $r^{-3}$ upon approaching infinity, where $r$ denotes the radial coordinate in Boyer-Lindquist coordinates. Thus, frame-dragging is differential in nature, i.e., $\partial_\nu \omega$ is strong near the black hole and weak at larger distances. It is hereby not a gauge-effect. Two particles with orbits at locations $r_1, r_2$ on a common flux-surface which share the same angular velocity $\Omega$, experience a potential difference

$$[\mathcal{E}] = -\frac{e g_{\phi\phi} \omega (\Omega - \omega)}{\gamma g_{\phi\phi} \omega_1 (\Omega - \omega_1) (r_2 >> r_\nu), \quad (8)$$

where $[f] = f(r_2) - f(r_1)$ and $(f) = f(r_2) + f(r_1)$. The results (6-8) are universal: they hold regardless of the origin of $J$ or $\Omega$, e.g., apply to mechanical or electromagnetic angular momentum.

In [14], electron-positrons have $J = \pm e A_\phi$. The result (6) reveals positive and negative energy orbits exist along the spin axis of a black hole of particles in (radiative) Landau states along a magnetic flux-tube. It is dramatically distinct from the ergo-sphere, where all circular orbits (of uncharged particles) have positive energy [19]. An open magnetic flux-tube along the spin-axis of the black hole, may now feature pair-wise radiation of positive and negative energy and angular momentum to infinity and, respectively, into the black hole—analagous to the aforementioned Penrose process in the ergo-sphere.

For the ingoing radiation, see further [10].

In this Letter, we point out that the ab-inito interaction [11-14] creates an open linear accelerator upstream of an ultra-relativistic Alfvén front, whose characteristic energy is consistent with UHECRs. The resulting emission of UHECRs is accompanied by simultaneous absorption of negative energy and angular momentum particles by the black hole. We apply our model to the recent identification of UHECRs with AGN and to some recent spectral energy correlations in GRBs.

The gradient (10) with respect to $r$ is commonly interpreted in terms of the Lorentz invariant $E \cdot B$, which is non-zero in a vacuum Wald field [22]. It reflects the spin-induced non-zero curl of the electric field in Boyer-Lindquist coordinates (observers that are not rotating relative to the distant stars) [10] [23]. Its integral is $\text{EMF}_\nu$ in (5). It naturally induces a tendency for charge-separation, until the invariant $E \cdot B$ is small, especially so in regions with an effective pair-cascade process [27]. The $\text{EMF}_\nu$ is invariant under any such charge-separation in the zero-dissipation and force-free limit, as charge-separation merely produces a local redistribution of electric fields in a semi-infinite open magnetic flux-tube.

The above shows that a spin-induced $E \cdot B \neq 0$ gives rise to a relativistic capillary effect: an open magnetic flux-tube will rapidly develop a continuously extending, largely force-free ($E \cdot B \simeq 0$) section with uniform angular velocity (upon furthermore neglecting the inertia of the
charged particles away from the event horizon \[3, 27, 28\). It is bounded by two freely moving boundaries in the form of two ultra-relativistic Alfvén fronts (a double-transonic flow \[30\]). One moves outwards to infinity, and one moves inwards to the event horizon of the black hole. This pair of Alfvén surfaces represents two corotating Faraday disks \[10, 20, 30, 32\]. While the ingoing Alfvén surface never reaches the event horizon in a force-free state \[10, 31, 32\], the corotating outgoing Alfvén surface does communicate a near-horizon induction voltage out to a larger distance. The outgoing Alfvén surface will continue to move outwards to infinity in a continuous effort to reduce to \(E \cdot B \simeq 0\) along the semi-infinite flux-tube—a black hole spin-induced capillary effect. While near the black hole, copious production of \(e^\pm\) is expected, canonical cascade processes are insufficient to produce in-situ pair-creation upstream of the outer Alfvén surface. Here, the magnetic flux-tube remains in a Wald vacuum state, until the outgoing Alfvén wave passes by—a relativistic capillary motion.

Charge-separation, by capillary extraction of pairs from the pair-rich black hole environment, introduces a finite section between \(r_2\) and \(r_1\) which, if force-free and highly conductive, will have zero electrostatic potential difference as seen in Boyer-Lindquist coordinates. Because the EMF \(\nu\) defined above is unchanged under charge-separation (it performs no work), the potential difference \(\Sigma\) now emerges outside of the force-free section between \(r_2\) and \(r_1\). In what follows, we identify \(r_1\) and \(r_2\) with the aforementioned (time-dependent) Alfvén surfaces and denote their common angular velocity by \(\Omega_A\).

The Alfvén surfaces communicate a potential difference \(\Sigma\) along the semi-infinite region \([r_2, \infty)\) upstream of the outgoing surface and the finite region \([r_H, r_1]\) upstream of the ingoing surface. This state is astrophysically realistic, provided there is an external source of the magnetic field, such as may be supported by an ionized medium surrounding the black hole in the form of an accretion disk or torus. It then predicts (a) the formation of an outgoing leptonic outflow represented by region enclosed by the two Alfvén surfaces, (b) a linear accelerator upstream of the outgoing Alfvén front and (c) a characteristic energy scale given by the Fermi-level of the event horizon of the black hole.

We apply the relativistic capillary effect to the origin of UHECRs from AGN and ultra-relativistic outflows from the inner engine to cosmological gamma-ray bursts.

The Fermi-level in \(4\) supports, by aforementioned corotating Alfvén surfaces, a potential input to the largely force-free region upstream of the outgoing Alfvén surface. It hereby defines, to within a factor of order unity associated with current-induced potential drops, the generator voltage across the linear accelerator which extends to infinity upon taking the limit \(r_1 \to r_H\) in \(8\),

\[
\left[\Sigma\right] = -\gamma g_{\theta \phi} (\Omega_A - \Omega_H) \Omega_H.
\]

When the outer Alfvén surface has moved out to a large distance, \(\left[\Sigma\right]\) represents the generator potential in the linear accelerator upstream, while the sum of \(\left[\Sigma\right]\) plus the potential difference between the inner Alfvén surface and the event horizon equals \(V_p\), apart from aforementioned current-induced potential drops across the event horizon. The latter represents dissipation, according to \[29\]

\[
\frac{1}{2} \left[ A \right] \left[ A \right] + \nu \left[ I \right] \left[ I \right] = \left( \frac{M}{10^9 M_\odot} \right) \left( \frac{B}{10^4 G} \right) \left( \frac{\theta_H}{0.1} \right)^2 \text{exa-eV}
\]

where \(\text{exa}=10^{18}\) and \(\theta_H\) denotes the half-opening angle of the open magnetic flux-tube on the event horizon of the black hole.

The high-energy emissions from gamma-ray bursts have been attributed to the dissipation of kinetic energy in ultra-relativistic baryon-poor jets. Let \(c_1\) denote the ratio of observed peak energy \(E_p\) to \(\Sigma\), comprising the combined efficiency of converting \(\Sigma\) into kinetic energy in a neutron-enriched leptonic jet with subsequent conversion into high-energy gamma-rays in internal and external shocks. The associated luminosity in Poynting flux along the open magnetic flux-tube in the force-free limit \(8, 27, 28\)

\[
L = \Omega_A^2 A_{\phi}^2.
\]

Let \(c_2\) denote the efficiency of converting \(L\) into the true energy in gamma-rays, i.e., \(E_\gamma = c_2 LT_{90}\). Then \(30\) predicts a positive correlation between peak-energies in gamma-rays and the true energy in gamma-rays: \(E_{p T_{90}^{1/2}} = e_k E_\gamma^{1/2}\), where \(k = 2c_1/\sqrt{c_2}\). Assuming \(c_2 \propto c_1\) and in the approximation of \(\Omega_F, \omega\) to be of order \(\Omega_H\), the Ghirlanda relation \(6\)

\[
E_p \propto E_\gamma^{0.7}
\]

together with the Eichler & Jontof-Hutter correlation between peak-energies and kinetic energy of the outflow \(32\)

\(c_1 \propto E_p^{3/2}\) gives \(k \propto E_{21/40} \simeq E_\gamma^{1/2}\). It follows that

\[
E_p T_{90}^{1/2} \propto E_\gamma.
\]

The correlation \(33\) bears out remarkably well the current HETE-II and Swift data in \(3, 6, 7\), compiled in Fig. 1. It should be mentioned that alternative explanations on the basis of viewing angles are also consistent the Ghirlanda relationship \(6\).

To summarize, a frame-dragging induced capillary effect in an open magnetic flux-tube links the event horizon of a spinning black hole to infinity which predicts a leptonic outflow downstream of an outgoing Alfvén
FIG. 1: Shown is the correlation in the published data of \( E_p \) between the peak energy \( E_p \), the true energy \( E \), and gamma-rays of long-duration gamma-ray bursts with known redshifts and inferred opening angles, assuming a stellar-wind type environment to the gamma-ray burst progenitor and using redshift corrected durations \( T_{90} \). A linear fit gives a slope and Pearson coefficient \(( s, c ) = (1.01, 0.85)\) to \( Y = \log \left( E_p T_{90}^{1/2} \right) \) (circles) and \(( s, c ) = (0.71, 0.76)\) in the Ghirlanda correlation to \( Y = \log ( E_p ) \) (triangles).

surface and a linear accelerator upstream. The former is expected to be largely force-free and Poynting-flux dominated as envisioned in [27]. It serves to communicate the horizon Fermi-level to the the boundary of the latter, which itself remains largely charge-free as pair-production by spontaneous emission and/or canonical cascade processes are limited to the region around the black hole. The linear accelerator hereby will accelerate protons from an ionized environment up to the raw Faraday-induced potentials of spinning supermassive black holes, consistent with the observed UHECRs in AGN. It predicts repeat events in [2] within about 100 years at current detection statistics. The leptonic outflow itself predicts a correlation between peak-energies, durations and true energies in gamma-rays (corrected for geometric beaming) in cosmological gamma-ray bursts from rapidly spinning black holes consistent with recent HETE-II and Swift data.

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