Dispelling Black Hole Pathologies Through Theory and Observation

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Astrophysical black holes are by now routinely identified with metrics representing eternal black holes obtained as exact mathematical solutions of Einstein's field equations. However, the mere existence and discovery of stationary solutions is no guarantee that they can be attained through dynamical processes. If a straightforward physical caveat is respected throughout a spacetime manifold then the ingress of matter across an event horizon is prohibited, in accordance with Einstein's expectation. As black hole formation and growth would be inhibited, the various pathological traits of black holes such as information loss, closed timelike curves and singularities of infinite mass density would be obviated. Gravitational collapse would not terminate with the formation of black holes possessing event horizons but asymptotically slow as the maximal time dilation between any pair of worldlines tends towards infinity. The remnants might be better described as dark holes, often indistinguishable from black holes except in certain astrophysically important cases. The absence of trapped surfaces circumvents topological censorship, with potentially observable consequences for astronomy, as exemplified by the remarkable electromagnetic characteristics, extreme energetics and abrupt extinction of quasars within low redshift galaxies.

1 Introduction

Quasars are exceptionally luminous objects located at cosmological distances [1]. Rapid fluctuations in their emissions arguably provide the most compelling hints that black holes of some description exist in nature. The empirically determined "M-sigma relation" points to a causal kinematic connection between black hole growth and galactic evolution, with motions of nearby gas and stars providing irrefutable evidence that $10^6 \sim 10^9\ M_\odot$ black hole candidates are present [2]. This has led many researchers to conclude that the universe is home to a multitude of black holes conforming to one of the stationary, asymptotically flat, black hole metrics – in accordance with the claim of a leading relativist that the "black holes of nature are the most perfect macroscopic objects that are in the universe" [3].

Potentially pre-dating the earliest stars, quasars may have fostered galaxy formation [4]. However, the question of how their central engines operate remains clouded in considerable uncertainty. Furthermore, astronomical observations have not been satisfactorily reconciled with theory. For instance, the abrupt cessation of quasar activity during the early universe calls for some efficient shutdown mechanism [5]. It is now generally believed that virtually all galactic nuclei harbour a supermassive black hole, most galaxies have undergone a period of quasar activity in the past, black holes have at present scarcely lost any mass through Hawking radiation and a healthy fraction of galaxies are still rich in gas. It is therefore puzzling that the temporary revival of quasar activity is not occasionally observed, especially within gas-rich galaxy clusters. A glaring inconsistency arises with the currently in vogue gas-starvation model of quasar extinction.

Karl Schwarzschild provided the first solution to the field equations of general relativity (GR), obtaining a spherically symmetric metric describing an eternal black hole* with an event horizon [6]. After lengthy deliberation, Einstein remained dismissive of the notion that objects with an event horizon might actually exist in nature, pointing out that a clock arriving at an event horizon would totally cease to advance compared to more remotely situated clocks [7]. The more interesting case of dynamic gravitational collapse within GR, abandoning the assumption of stationary geometry, was tackled analytically that same year by Oppenheimer & Snyder [8]. The mathematical results, as valid now as they ever were [9], establish that from the perspective of a distant observer the implosion initially accelerates until the contraction becomes relativistic, whereupon the implosion rate declines – ultimately halting just as the critical radius is approached. From this vantage, an event horizon only forms in an asymptotic sense, after the infinite passage of time.

Oppenheimer & Snyder also commented on their results from the perspective of the infalling matter. They found that as external time approaches infinity, the proper time along the worldline of an infalling particle tends towards some finite value. They then considered what might happen at later proper times of the infalling particle, apparently without pausing to consider whether time could physically continue to advance for the infalling particle: "after this time an observer comoving with the matter would not be able to send a light signal from the star". It is currently fashionable to ignore Einstein's objection regarding infinite time dilation. But is

*The term "black hole" was not coined until some years after Einstein's departure, the alternative "frozen star" had previously been widely used.

that wise? The field of black hole physics is by now plagued by a variety of serious difficulties. Closed timelike curves seem to be unavoidable within rotating black hole spacetimes, with potentially disturbing connotations for causality and hence physics at its most fundamental level. The notion that information might be captured and destroyed by black holes has also troubled theoretical physicists for decades [10, 11]. This "information paradox" recently led to the suggestion that black holes only possess apparent horizons [12] as opposed to genuine event horizons: features traditionally regarded as the defining hallmarks of true black holes [13].

There is also a widespread expectation that naturally occurring black holes lack "hair" and comply with the principle of topological censorship [14], rapidly settling down either to a Kerr-Newman or, more realistically, a Kerr geometry corresponding to an electrically uncharged, rotating black hole. As will be discussed, astronomical observations cast significant doubt on the reliability of this common assumption. Moreover, due to the generality of results obtained in dynamical collapse scenarios such as Oppenheimer & Snyder considered, there is a suspicion that Einstein was right: it may be difficult or impossible to produce stationary black holes through physically realistic processes.

The goal of this work is to argue that these various conceptual problems can vanish, without departing from Einstein's gravitational theory, if a straightforward physical consideration is respected throughout a spacetime manifold. This caveat does not impinge upon general covariance and the mathematical apparatus of general relativity is unchanged. A discussion then follows of why quasar observations support the contention that black holes lack event horizons and might be better described as *dark holes*.

2 The Schwarzschild black hole

The Schwarzschild metric represents a non-rotating eternal black hole with the spherically symmetric spacetime

$$ds^2 = \left(1-\frac{r_s}{r}\right)c^2dt^2-\left(1-\frac{r_s}{r}\right)^{-1}dr^2-r^2(d\theta^2+\sin^2\theta d\phi^2) \quad (1)$$

where ds is the spacetime interval, t represents the proper time of a stationary clock at spatial infinity, (r, θ, ϕ) are the usual spherical coordinates ($2\pi r$ being the circumference of a circle at radius r). The event horizon is located at $r = r_s = 2Gm/c^2$, known as the Schwarzschild radius of a black hole. The gravitating mass of the black hole, m, is concentrated at the origin.

As is well-known, if the metric is expressed in this way it has a coordinate singularity at $r = r_s$, the (critical) radius of the event horizon, despite the lack of matter there (the spacetime itself is only singular at $r = 0$). The exterior solution, $r > r_s$, accurately approximates the spacetime outside a spherically symmetric star [15]. This region is well-behaved and suffices for the present discussion.

For a particle following a timelike worldline, $ds^2 \equiv c^2d\tau^2$ where τ is the proper time of the particle and $d\tau \equiv 0$ for null particles (light rays). Therefore, along the worldline of any particle, $ds^2 \geqslant 0$, and the following inequality must hold:

$$\left(1-\frac{r_s}{r}\right)c^2dt^2 \geqslant \left(1-\frac{r_s}{r}\right)^{-1}dr^2 + r^2(d\theta^2+\sin^2\theta d\phi^2). \quad (2)$$

It is convenient to rearrange this expression to obtain

$$\frac{1}{(1-\frac{r_s}{r})^2}\left(\frac{dr}{dt}\right)^2 + \frac{r^2}{1-\frac{r_s}{r}}\left(\frac{d\theta}{dt}\right)^2 + \frac{r^2\sin^2\theta}{1-\frac{r_s}{r}}\left(\frac{d\phi}{dt}\right)^2 \leqslant c^2. \quad (3)$$

The Schwarzschild metric is asymptotically flat and, for regions far outside the event horizon, $r \gg r_s$, the effects of gravitational time dilation are negligible. One then finds that $(dr/dt)^2 + r^2\ (d\theta/dt)^2 + r^2\sin^2\theta\ (d\phi/dt)^2 \leqslant c^2$ which, considering the spherical coordinate system, confirms the expectation that the speed of light is insurmountable in special relativity, with the possible exception of tachyonic particles.

3 Spacetime coherency

Spacetime is a four-dimensional continuum, a differentiable and connected Lorentzian manifold. In general relativity it is dynamically acted upon by gravitation so as to alter the geodesics of motion. General relativity is a global theory: the presence of mass-energy does not merely influence the local spacetime, but the entire spacetime manifold. Thus, gravity's range is limited only by the size of the universe. General relativity abides by the principle of general covariance allowing its physical laws to be expressed independently of coordinates.

The order in which events occur is observer-dependent in both special and general relativity. Nevertheless, the *relative rate at which time elapses along two worldlines* (i.e. time dilation/contraction) can be uniquely defined whether the separation between the worldlines is timelike, null or spacelike. Time dilation is a non-local, coordinate-independent quantity encoding genuine physics which is necessary for global consistency. For an arbitrary number n of distinct test particles with proper times $\tau_1, \tau_2 \ldots \tau_n$, it must hold that

$$\frac{d\tau_1}{d\tau_n} \times \prod_{i=1}^{n-1} \frac{d\tau_{i+1}}{d\tau_i} = 1. \quad (4)$$

If general relativity is applied to the universe then the proper elapsed time, τ, along any worldline cannot exceed the time since the big bang, even if the universe is spatially infinite. Hence, along any worldline, the proper time $\tau < \infty$ and the proper distance $\ell < \infty$. Recognising that proper time τ is an affine parameter along the worldline $x^\alpha(\tau)$, for a specified spacetime manifold the demand of finite proper time along all worldlines within the universe can be formally stated as

$$\forall\ \ x^\alpha(\tau) : \tau < \infty. \quad (5)$$

It should be self-evident that this constraint will be satisfied by any physically realistic spacetime manifold. Non-compliance, as would occur once the advancement of proper times along any pair of worldlines could not proceed in tandem, would break the global coherency and connectedness of the spacetime continuum. Such a basic physical requirement must have priority over all "philosophical" concerns, an issue returned to in the discussion. Spacetime is not merely a local union of space and time but a global one. Failure to appreciate that localised physics can have wider implications for a spacetime manifold may be at the root of some persistent confusions in current black hole research.

4 Time dilation between arbitrary particles

For lightlike particles, the Schwarzschild metric provides a relationship involving two time coordinates t and τ

$$\left(\frac{d\tau}{dt}\right)^2 = \alpha c^2 - \frac{1}{\alpha}\left(\frac{dr}{dt}\right)^2 - r^2\left(\frac{d\theta}{dt}\right)^2 - r^2\sin^2\theta\left(\frac{d\phi}{dt}\right)^2. \quad (6)$$

The parameter α is defined as $\alpha \equiv 1 - r_s/r$ for the range $r > r_s$ so that α is strictly positive with $0 < \alpha \leqslant 1$. This expression allows the time dilation relative to Schwarzschild time t, a coordinate independent physical quantity, to be determined for an arbitrarily moving test particle located anywhere outside the event horizon.

Although particles travelling at the speed of light experience no passage of proper time ($d\tau = 0$), photons travelling radially towards the event horizon are eventually brought to a halt since the original metric then reduces to $(dr/dt)^2 = \alpha^2 c^2$ and, in the limit as $r \to r_s$, one sees that $\alpha \to 0$. This represents a worst case scenario since, for non-radial motion of the photon, $(dr/dt)^2 < \alpha^2 c^2$. For a purely radial ingoing photon, $dr/dt = -\alpha c$ and so the minimum Schwarzschild time, $\Delta t_{\min}$, required for a photon to travel from an initial radius r_0 to a final radius r_*, with $r_0 > r_* > r_s$, is given by

$$\begin{aligned}\Delta t_{\min} = t_* - t_0 &= \int_{r_0}^{r_*}\left(\frac{dt}{dr}\right)dr = \int_{r_*}^{r_0}\frac{dr}{\alpha c}\\ &= \frac{1}{c}\int_{r_*}^{r_0}\frac{r\,dr}{r - r_s} = \frac{r_0 - r_*}{c} + \frac{r_s}{c}\ln\left(\frac{r_0 - r_s}{r_* - r_s}\right). \quad (7)\end{aligned}$$

Due to the denominator in the logarithm term, as $r_* \to r_s$, this time interval grows without limit. Hence, regardless of the location at which photons are emitted outside the black hole, gravitational time dilation prohibits them reaching the event horizon in finite time according to the clock of a Schwarzschild observer.

In order to broaden this result, a quantity v is now defined such that

$$v^2 = \frac{1}{\alpha^2}\left(\frac{dr}{dt}\right)^2 + \frac{r^2}{\alpha}\left(\frac{d\theta}{dt}\right)^2 + \frac{r^2\sin^2\theta}{\alpha}\left(\frac{d\phi}{dt}\right)^2. \quad (8)$$

With reference to (3), it is apparent that one can write $v^2 \leqslant c^2$. This is consistent with v representing a physical velocity whose magnitude, corrected for relative motion and gravitational time dilation, remains bounded by the speed of light. It can then be seen from (6) that

$$(d\tau/dt)^2 = \alpha(c^2 - v^2)$$

and consequently $0 \leqslant (d\tau/dt)^2 \leqslant 1$. The time dilation relation between two arbitrary worldlines with proper times τ_1 and τ_2 exploring the exterior Schwarzschild geometry can therefore be obtained from formula (9) where $\alpha_1 = 1 - r_s/r_1$ and $\alpha_2 = 1 - r_s/r_2$ with subscripts referring to worldlines 1 and 2 respectively. Thus, α_1 and α_2 have the same range as α such that consideration is strictly restricted to the region external to the event horizon. Since $v_1^2 \leqslant c^2$ and $v_2^2 \leqslant c^2$, neither the numerator nor denominator of (9) can be negative under any circumstances.

If a timelike particle following worldline 2 approaches the event horizon, $r_2 \to r_s$, then $\alpha_2 \to 0$ with the numerator of (9) remaining positive. For a timelike observer moving along worldline 1 sufficiently distant from the event horizon that $\alpha_1 \gg \alpha_2$ it is then apparent that $d\tau_2/d\tau_1 \to 0$, meaning that proper time ceases to advance along worldline 2. Noting that timelike particles take longer to approach the event horizon than light rays and that $d\tau_1/dt$ remains finite for any timelike observer comfortably outside the event horizon, one may conclude that

> *According to any external observer following a timelike worldline, light rays and timelike particles require infinite proper time to reach the event horizon of a Schwarzschild black hole.*

Because (5) must be respected it follows that

> *Since infalling particles cannot experience the passage of time beyond that corresponding to infinite proper time along all other worldlines, they are incapable of penetrating the event horizon of a Schwarzschild black hole.*

These statements are completely independent of the (arbitrary) choice of coordinate system. Furthermore, they do not require that observers be either stationary or infinitely remote. Indeed, observers could be relatively close to the event horizon without violating the assumption that $\alpha_1 \gg \alpha_2$. There is no optical illusion at play associated with the time of flight of photons – the conclusion holds for inanimate clocks lacking the faculty of vision just as well as it does for conventional observers.

Note also that there is no need for any special synchronisation procedure between the two particles: infinite time dilation prevents the ingress of matter across an event horizon as long as external clocks continue to mark time. If $\tau_2 = 0$ at the commencement of worldline 2 and the event horizon is approached as $\tau_2 \to \tau_h$, a finite proper time, then regardless of where and when worldline 1 commences it is still true that

$$\left(\frac{d\tau_2}{d\tau_1}\right)^2 = \left(\frac{d\tau_2}{dt}\right)^2 \div \left(\frac{d\tau_1}{dt}\right)^2 = \frac{\alpha_2 c^2 - \frac{1}{\alpha_2}\left(\frac{dr_2}{dt}\right)^2 - r_2^2\left(\frac{d\theta_2}{dt}\right)^2 - r_2^2 \sin^2\theta_2 \left(\frac{d\phi_2}{dt}\right)^2}{\alpha_1 c^2 - \frac{1}{\alpha_1}\left(\frac{dr_1}{dt}\right)^2 - r_1^2\left(\frac{d\theta_1}{dt}\right)^2 - r_1^2 \sin^2\theta_1 \left(\frac{d\phi_1}{dt}\right)^2} = \frac{\alpha_2\,(c^2 - v_2^2)}{\alpha_1\,(c^2 - v_1^2)}. \tag{9}$$

$\tau_1 \to \infty$ as $\tau_2 \to \tau_h$. This is manifestly so because

$$\tau_1(\tau_2 \to \tau_h) = \int_0^{\tau_h} \left(\frac{d\tau_1}{d\tau_2}\right) d\tau_2 = \int_0^{\tau_h} \left(\frac{d\tau_2}{d\tau_1}\right)^{-1} d\tau_2 \to \infty. \tag{10}$$

Proper times separating events along worldlines are invariant quantities, as are infinitesimal proper times. Thus, the same can be said of the ratio of the rate of passage of proper times along distinct worldlines. If the previous calculation were to be repeated using so-called horizon-penetrating coordinates (e.g. Lemaître, Novikov, Gullstrand-Painlevé, Kruskal-Szekeres, ingoing Eddington-Finkelstein [16]) the same results would of course be obtained by virtue of general covariance. The fact that the time dilation approaches infinity as $r_2 \to r_s$ has nothing to do with the Schwarzschild coordinate singularity at r_s, the coordinates being regular and well-behaved for all $r > r_s$, a range that was entirely adequate for the purposes of this analysis.

Therefore, contrary to some common assertions, an astronaut could not fall into a black hole without incident. Although τ_2 would remain finite in such circumstances, τ_1 would approach infinity as $\tau_2 \to \tau_h$. The astronaut encounters no immediate physical impediment at the event horizon but, due to the demand of global coherency and the need for proper times along worldlines to remain finite in (5), the condition $\tau_2 \leqslant \tau_h$ must be respected. Thus, the worldline of the astronaut would terminate as $\tau_2 \to \tau_h$, *corresponding to a situation in which the spacetime manifold totally ceases to evolve*. The astronaut simply would not experience proper times later than τ_h which, in effect, would be the moment when his or her worldline reaches future timelike infinity within the Schwarzschild spacetime. Times $\tau_2 > \tau_h$ would necessarily be fictitious and unphysical due to violation of (5).

For all $\tau_2 < \tau_h$, there is no consistency problem. One is not obliged to make an *either or* selection, exclusively choosing between the infalling or remote observer perspectives – they are mutually compatible projections of a globally coherent spacetime manifold. However, if one insists on abandoning coherency to consider the physically impossible case $\tau_2 > \tau_h$, a choice is then mandatory but the results are physically meaningless. That infalling matter indefinitely hovers above the horizon from the perspective of a distant Schwarzschild observer is a well-established result [15, 17]. In order to further clarify matters, it has been extended here to arbitrarily situated and potentially moving external observers who may be in quite close proximity to the event horizon.

The impermeability of the event horizon due to time dilation effects has in recent years been highlighted in the context of the black hole information paradox [18]. Furthermore, several core arguments promulgating that belief that event horizons are traversable have been dispelled [19]. While it is well-known that nothing can escape from a black hole, this analysis suggests that event horizons cannot be traversed in *any* direction whilst offering a readily comprehensible explanation as to why that is. Although angular momentum has been ignored here for simplicity, one would not expect its influence to alter the conclusions. Rotation would only represent an additional barrier, further hindering the arrival of particles at the event horizon of a Kerr black hole.

5 Dynamically formed black holes

A classic general relativity textbook originally published four decades ago argued that eternal black holes provide an excellent approximation to the outcome of gravitational collapse [15]. This advice may have been taken a tad too literally. Clearly, if event horizons are bidirectionally impermeable then the black hole information paradox would be trivially resolved. The interior geometry of the Schwarzschild metric may satisfy the field equations, but the constraint (5) suggests it cannot be arrived at through gravitational collapse, it is merely a hypothetical arrangement. Spacetime coherency issues aside, the equivalent rest mass energy of the Schwarzschild singularity goes no way towards counterbalancing its gravitational potential energy which, by any realistic assessment, is infinitely negative. Therefore, a Schwarzschild black hole and a collapsing star of the same mass forming a dark hole frozen in time have vastly different energies and are hence inequivalent on energy conservation grounds.

If the proper time for an infalling particle is advanced without regard for physics elsewhere then the spacetime can decouple and become non-connected, leading to a host of conceptual difficulties. For physically realistic gravitational collapse, however, it is not that infalling matter would hover in suspension above an event horizon – but that an event horizon would never form, in keeping with the external observer perspective of Oppenheimer & Snyder's analysis. However, in the unlikely event that the universe were host to fully-formed eternal black holes, their event horizons would behave as impenetrable barriers to infalling matter. Due to time-reversal symmetry, the geometry of spacetime in general relativity is as much a function of the future distribution of mass and energy as the past distribution, endowing the theory with a teleological quality. Thus, the event horizons of such hypothetical black holes could in principle expand in anticipation of infalling matter so that time dilation halts the ingress of matter sooner than it might otherwise do. Notice that such expansion need not involve any increase in the gravitational potential of infalling matter since the potential near the event horizon is independent of black hole mass.

Hawking radiation arises due to separation of virtual particle pairs in the vicinity of a black hole event horizon [20], causing eternal black holes to evaporate with a perfect thermal spectrum, devoid of information content. Conversely, frozen stars with their rich, history-dependent structure, are able to radiate in the regular black body manner – thus avoiding information loss [21]. However, this issue is of lesser importance to the present discussion than the need for spacetime to remain coherent and connected. Black hole research has not led to many testable predictions but this consideration can have readily observable astronomical implications.

6 Topological admissibility

Trapped surfaces are defined as surfaces from which light rays initially pointing outwards are obliged to converge inwardly. The existence of a trapped surface is a precondition of several well-known theorems in general relativity. The event horizon of a Schwarzschild black hole is a null surface inside which surfaces equidistant from the horizon are all trapped. According to the Penrose-Hawking singularity theorems [22–24], a trapped surface inevitably leads to a geodesically incomplete spacetime manifold, implying the imminent formation of a singularity. However, if time dilation and global spacetime considerations prohibit the formation of event horizons then trapped surfaces cannot naturally arise and the singularity theorems have no physical relevance. By the same logic, the closed timelike curves of rotating eternal black holes would be avoided. Speculations concerning the physics internal to an event horizon are invulnerable to falsification and hence, strictly speaking, outside the scope of empirical science. However, although the presence of event horizons cannot be directly verified [13], evidence of their non-existence could in principle be obtained.

Like the singularity theorems, the principle of topological censorship [14] assumes the presence of a trapped surface. Therefore, if time dilation guards against event horizon formation, the gravitational collapse of a rapidly spinning cloud of gas would be capable of forming an axisymmetric structure of toroidal topology. Due to its dynamic nature, this scenario also falls outside the scope of earlier constraints on black hole topology [25, 26]. If physically realistic astrophysical black holes can be toroidal, the astronomical implications could be observable from afar.

Amongst the most energetic phenomena of the universe, quasars outshine galaxies by as many as three orders of magnitude. They were most abundant at redshifts of $z \sim 2$ when the universe was less than 20% its present age and are significantly more scarce by now [27]. They create bipolar outflows [28], axially aligned relativistic jets penetrating intergalactic space and ultimately forming gigantic radio lobes as their energy is dissipated. Often chaotically turbulent, the jets are comprised of electrically charged particles which can form knots via magnetohydrodynamic processes. The orientation of the jets exhibits long-term stability, hinting at a direct dependency on the angular momentum vector of a supermassive black hole as opposed to that of an accretion disk of relatively low mass which is vulnerable to significant disruption by the assimilation of roving stars. This is another weakness of models seeking to account for jet formation in terms of a magnetised accretion disk.

The discovery of various metrics describing stationary spacetimes in which black holes are completely described by mass, angular momentum and electromagnetic charge alone led to the "no-hair conjecture". Though the Schwarzschild and Kerr-Newman metrics are lacking in "follicles", it is very natural to expect macroscopic departures from these metrics during realistic collapse scenarios. Furthermore, since the formation of trapped surfaces would violate spacetime coherency (5), crucial assumptions underpinning the singularity theorems and the principle of topological censorship may not apply.

Providing its assumptions are satisfied, topological censorship requires the central aperture of a toroidal black hole to seal up so rapidly that a ray of light lacks sufficient time to traverse it. Numerical simulations have provided some support for this [29]. However, computational approaches almost invariably adopt horizon-penetrating coordinates and fail to enforce the physical requirement (5). Instead, event horizons are located retrospectively after simulations terminate, without global consistency checks.

Theoretically, metrics describing black holes with toroidal event horizons have been obtained for anti-de Sitter backgrounds with a negatively valued cosmological constant. In such situations, Λ can be arbitrarily small [30]. Thus, toroidal event horizons are only marginally prohibited when considering eternal black holes in asymptotically flat spacetimes. However, if trapped surfaces cannot realistically form during gravitational collapse then topological censorship is bypassed entirely, leaving the toroidal dark hole (TDH) a viable possibility. Most stars capable of undergoing core collapse are massive, hence rapidly reaching the ends of their lifecycles. They are likely to retain sufficient angular momentum from their formation that during implosion their cores will adopt a toroidal geometry, if only transiently. A toroidal core can be supported by degeneracy (electron/neutron) pressure but, for very massive and rapidly rotating stars, direct collapse to a TDH is conceivable. Any of these eventualities could have potentially explosive consequences, scattering ejecta deep into space [31].

The angular momentum of a Kerr black hole is bounded by $|J| \leqslant GM^2/c$. In the field of black hole thermodynamics, the temperature at which the event horizon radiates is proportional to its surface gravity. This vanishes for an extremal black hole, implying extremality is unattainable by the third law of black hole thermodynamics. However, for a TDH lacking an event horizon, angular momentum should approximately scale with the major radius of the torus. Thus, the Kerr bounds, $-GM^2/c < J < GM^2/c$, could easily be exceeded. Accumulation of angular momentum beyond the Kerr limit may buffer TDH topology, even if accretion is erratic. Evidence has recently emerged of a supermassive black hole within a galactic nucleus rotating at a near extremal rate [32].

Nature possesses only two long range forces and, of the two, electromagnetism is far stronger than gravity. Furthermore, gravity is purely attractive, making it ill-suited as a mechanism for launching relativistic jets of charged particles flowing directly away from a supermassive black hole. Therefore, it is virtually certain that electromagnetism is primarily responsible for jet production. There are no magnetic monopoles in nature but electrically charged particles make up all atoms. That ultrarelativistic jets of charged particles can be sustained for millions of years strongly suggests that the central black hole must itself be electrically charged.

Traditional models have nevertheless taken black holes to be electrically neutral due to common assumptions regarding their topology and the fact that plasma of a surrounding accretion disk can swiftly neutralise any electrical charge accumulating on a spheroidal black hole. A charged (Kerr-Newman) black hole would necessarily possess a magnetosphere due to its rotation but its flux lines would lead directly to the event horizon: oppositely charged particles would be strongly attracted to it, spiralling along the lines of magnetic flux to swiftly neutralise the black hole. Hence, theorists have struggled to explain the extreme energetics of quasars. The popular Blandford-Znajek mechanism [33] appeals to a strongly magnetised accretion disk whose flux lines thread the event horizon of an electrically neutral, Kerr black hole, enabling some coupling to its rotational energy. However, the model has been criticised because one would not expect an accretion disk to become strongly magnetised and the degree of magnetisation required seems infeasibly large [34].

The difficulty is overcome in the TDH case, a strong candidate for the central engine of quasars [31]. It has been previously proposed that a toroidal black hole might be stabilised by quantum gravitational effects [35] but in the present work there is no need for any departure from classical general relativity. If a TDH amasses an electrical charge, e.g. via the proton-electron charge/mass ratio disparity, neutralisation processes involving ambient plasma particles will be suppressed due to topological considerations. Flux lines of the induced dipolar magnetosphere along which charged particles tend to spiral would not lead towards the TDH. Instead, they would locally run parallel to its surface, as depicted in figure 1. Plasma from an orbiting accretion disk would be channelled along the flux lines towards the central aperture, the region where the magnetic flux density is highest: the only location where the flux lines lead directly away from the TDH. Conditions for particle ejection are likely to be most favourable at a small displacement along the rotation axis either side of the symmetry plane. There, the magnetic field remains strong and aligned with the observed jets – but gravitational time dilation is less pronounced [31]. The relatively gentle decline in flux with axial displacement can be seen, for example, by considering the magnetic field strength, $B(z)$, of a current, I, flowing along a circular path of radius r at a distance z along the axis from the centre of symmetry:

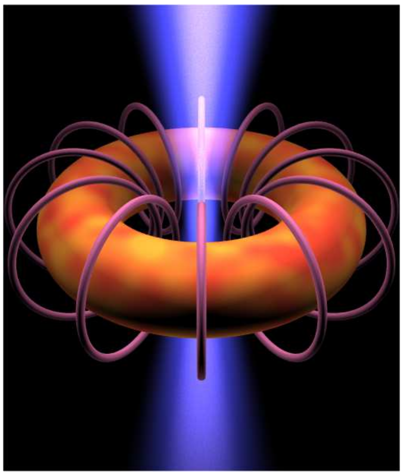

Fig. 1: A rotating toroidal black hole with a non-zero electrical charge generates a magnetic field whose flux lines are capable of resisting a neutralising flow of charged particles from the plasma of an orbiting accretion disk or imploding star. Flux lines point away from the black hole along the rotation axis where, due to extraction of the black hole's rotational energy, biaxial jets may be launched from the central aperture.

$$B(z) = \frac{\mu_0 I r^2}{2(z^2 + r^2)^{3/2}} \approx \frac{\mu_0 I}{r(2 + 3z^2/r^2)} \quad \text{for} \quad z \ll r. \tag{11}$$

For a current loop spread over a toroidal surface, the flux density within the central aperture, B_{ap}, whose radius is a can, due to the conservation of charge on the torus and the integrated flux threading the aperture, be approximated by $B_{ap} \approx (r/a)^2 B(0) \approx \mu_0 I r/2a^2$. Thus, the magnetic field would be strongly amplified when the torus approaches pinch-off, $a \ll r$. Plasma magnetically siphoned into the aperture from the surrounding accretion disk could interact directly with the TDH via this magnetosphere. Furthermore, the lack of an actual event horizon would not preclude an ergoregion [36]. Hence, energy extraction via the Penrose process [37] may also contribute somewhat towards jet production. With lower mass electrons being preferentially ejected, a net charge on the TDH could be reliably maintained, thereby supporting the black hole's magnetosphere. Emitted particles would tend to emerge in cones around the rotation axis, their convergence assisted by magnetohydrodynamic focusing. A population of neutral atoms and free neutrons in the accretion flow could feed TDH growth and support its long-term rotation against angular momentum losses.

Additional support for this model comes from the observed dichotomy between active and quiescent galaxies and the curious fact that quasars have distinctly finite lifetimes. Given that many galaxies still have ample reserves of gas to sustain accretion disks around supermassive black holes, and that the masses of these black holes cannot have decreased appreciably with time, it is puzzling that quasar activity is in such steep decline in the low redshift universe. One would expect nearby supermassive black holes, in particular those present in galaxy clusters, to at least feast upon stray matter sporadically. Only $\sim$10% of the primordial gas in galaxy clusters has so far been utilised by star formation. For comparison, the figure for the Milky Way is closer to 90%. Nearly all galaxies harbour supermassive black holes so one wonders where are the vestigial traces of radio lobes caused by fleeting flares? Observational data suggests that once a quasar becomes quiescent there is little or no prospect of activity being revived: the galactic nucleus not only seems dormant, but utterly defunct. With regards to this finite lifetime riddle and the apparent lack of even temporary revival of quasar activity in quiescent galaxies, a topological transition offers a very natural and appealing hysteresis mechanism [31, 38, 39]. It has long been appreciated that this is a difficulty for more conventional models [40].

Once a dark hole grows too large, even a steadily supplied accretion disc cannot maintain sufficient influx of angular momentum to sustain the geometry. In addition, the angular momentum of the TDH is continually being sapped by jet generation. Closure of the central aperture is not easily reversed, especially as the ensuing charge neutralisation is rapid when flux lines lead directly to the dark hole. A potential explanation can also be found here for the gamma-ray burst phenomenon, relatively short-lived affairs compared to most supernovae. Such events may correspond to the temporary formation of a TDH/toroidal neutron degenerate structure during the core collapse of a massive spinning star.

7 Discussion

The development of general relativity was one of the greatest triumphs not only of theoretical physics but of all science, providing a description of gravitation compatible with the notion that space and time are part of a unified four dimensional continuum with experimentally verifiable implications. However, as with any intrinsically mathematical theory of physics, its interpretation must be guided by physical considerations and one should not lose sight of the scientific method. Indeed, some existing solutions in general relativity are already widely regarded as unphysical. Examples include the Tipler cylinder and the Gödel metric, which exhibits closed timelike curves threading all events within its spacetime. It is possible that Einstein's intuition was correct and that all metrics describing eternal black holes should be similarly regarded with a healthy degree of scepticism and replaced with a new dark hole paradigm.

The present work has attempted to reconcile astronomically observed characteristics of quasars, which have inspired suggestions that their central engines may not abide by topological censorship, with a theoretical understanding of why that might be. A global constraint has been highlighted which, if respected everywhere within a spacetime manifold, holds considerable promise for resolving other long-standing problems in black hole research. It requires merely that the advancement of proper time along any worldline never necessitates the physically impossible advancement of proper time along any other worldline. In many circumstances this is trivially satisfied, but the situation changes radically within a spacetime containing pairs of timelike worldlines for which the relative time dilation grows without limit. Some particle worldlines will then reach future timelike infinity in finite proper time, much as light rays/photons do. Worldlines of timelike particles can thereby be truncated. In the case of particles approaching the event horizon of an eternal black hole, this is a consequence of their asymptotically approached apparent velocity – particles moving at the speed of light experience no passage of time. On the other hand, if a spacetime manifold is initially free of event horizons or singularities, it will always remain free of them. A picture emerges of general relativity as a remarkably benign theory of gravitation gracefully accommodating all eventualities. Analytical solutions to the field equations of general relativity are confined to highly idealised situations. More complex and realistic scenarios can only be studied numerically. Nevertheless, the basic conclusions drawn here concerning the non-formation of event horizons for spherically symmetric situations are likely to carry through to more general circumstances.

The present proposal differs significantly from the *gravastar* model [41] which invokes new physics, replacing the interior black hole region with a de Sitter spacetime blending into the exterior Schwarzschild geometry via a carefully-tailored transition layer [42]. It is also distinct from the *eternally collapsing object* (ECO) scenario [43, 44] in that gravitational collapse can be stabilised without recourse to radiation pressure. Furthermore, there is no need to invoke the presence of some "firewall" or exotic new physics at or near the horizon in order to overcome the information paradox [45].

For several decades now, black holes with event horizons have been seriously entertained despite the lack of a single mathematical example of an event horizon forming in finite universal time and their dismissal by the architect of general relativity. There is a deep-seated expectation amongst relativists that all observers should enjoy equal status but one must not overlook the fact that general relativity is a theory in which global relationships exist between observers. By tracing the progress of an infalling observer beyond the event horizon, as Oppenheimer & Snyder did, one forsakes concern for external observers. In such situations, the worldlines of external observers must magically transcend what is, for them, future timelike infinity – and indeed, therefore, future timelike infinity for the entire spacetime manifold. Thus, the original notion of a "democracy" amongst observers is naïve if one interprets it in a purely local manner, eschewing the original spirit of relativity.

The proper times along all worldlines should remain finite in any physically realistic spacetime manifold. Whilst self-evidently true, this has profound repercussions for gravitational collapse. Global relationships within a spacetime manifold override local considerations. This can arrest dynamical collapse, prohibiting both the initial formation of event horizons and the ingestion of matter across pre-existing event horizons. Hence, any theorems reliant on the presence of trapped surfaces may have no physical bearing. Prevailing expectations that gravitational collapse inevitably leads to singularities and event horizons appear to be in error and fears that black holes destroy information misplaced. Furthermore, if topological censorship is circumvented, then electrically-charged toroidal dark holes could form the central engines of quasars, consistent with astronomical observations. Thus, quasars may already provide intriguing hints that nature's black holes lack event horizons, and that various physically disturbing pathologies associated with traditional black hole models are obviated in realistic situations – without need for any adjustment to Einstein's theory of gravitation.

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