ARE BLACK HOLE STARSHIPS POSSIBLE?

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ABSTRACT: We investigate whether it is physically possible to build starships or power plants using the Hawking radiation of an artificial black hole as a power source. The proposal seems to be at the edge of possibility, but quantum gravity effects could change the picture.

I. Introduction

According to Hawking, black holes (BHs) are not really black, but radiate what is approximately a black body thermal spectrum. The energy emitted is negligible unless the BH is very small, in which case it becomes extremely energetic.

The purpose of this paper is to investigate whether it is possible to build artificial BHs of the appropriate size, and to employ them in powerplants and starships. The conclusion we reach is that it is just on the edge of possibility to do so, but that quantum gravity effects, as yet unknown, could change the picture either way.

We discuss designs for a family of machines which would in combination realize our program. The machines are far beyond current technological capabilities. The BH generator would be a gamma ray laser with a lasing mass of order 10^9 tonnes.

Nevertheless, we think the possibility should be studied carefully, because it would have profound consequences for the distant human future, which no other proposal based on currently known Physics could duplicate.

This is only a preliminary study. Many questions which arise in this program lead to calculations in general relativity which have not been done. Whatever the other merits of our proposal, we are confident it will pose many interesting problems for classical and quantum relativity.

II. The difficulty of interstellar flight

A. Shielding

The dreams of manned spaceflight of the fifties and sixties have largely gone unrealized. This is to an important degree because it has been discovered that cosmic radiation has much more serious medical consequences than was originally believed [1].

Substantial human presence in space has only occurred in low Earth orbit near the equator, where the earth's magnetic field shields us from the cosmic radiation. Our visits to the moon were brief, and it is considered that a prolonged human presence there would have to be underground, necessitating the transport of massive "earth" moving equipment [1].

It is now known that any prolonged human presence deeper in space would need to be behind a shield of the effective strength of two feet of lead, which would weigh 400 tonnes for a small capsule [1].

It therefore becomes more economical to think of a larger vessel, weighing many thousands of tonnes, in which a group of people could live indefinitely. This possibility has not been very widely explored, particularly not in a practical direction, because of the enormous energies involved in accelerating such a body.

B. Specific impulse

The distances between the stars are so great that practical travel between them would require us to reach speeds comparable to the speed of light. This is extremely difficult to do because very few processes known to us release energies comparable to the masses of the matter involved. Nuclear reactions, for example, release only a fraction of a percent of the rest masses of the nucleii, so that an interstellar vehicle powered by fission or fusion would have to carry many thousands of times the mass of its payload in fuel.

Coupled with the shielding problem discussed in Section A above, this means an interstellar voyage using nuclear energy would deplete the Earth's resources of fissile or fusile materials to an intolerable degree.

Other than black hole radiation, which we study below, the only process we know of which is sufficiently energetic is matter-antimatter annihilation. This has been proposed, but there are two severe obstacles.

The first is that the efficiency of antimatter production in current accelerators is well below 10^{-7} (very few collisions produce a trappable antiparticle) [2]. Thus, making enough antimatter to propel a starship would use up ten million times as much energy as our proposal. The most optimistic projections of antimatter enthusiasts do not produce an efficiency above 10^{-4} , so that at best our proposal is still ten thousand times more efficient.

The second obstacle is containment. A microscopic particle of ordinary matter which drifted into the antimatter would cause an explosion, scattering the antimatter into contact with the ship, and destroying everything for millions of miles around. Any electromagnetic force which held the antimatter in would also drive normal matter in. One hears the suggestion that this could be solved by "magnetic bottles," but magnetism is a force which acts perpendicularly to the motion of a charged particle, and therefore does not in any simple way form a bottle. Experiments in the magnetic confinement of plasma for millisecond intervals have been very frustrating.

Paramagnetic forces can repel matter, but they are extremely weak, and treat matter and antimatter identically. So they would force normal matter in as much as antimatter. For these reasons an antimatter starship seems out of reach given Physics as we know it. We could imagine surprises in future Physics which would change this picture, but they seem remote. Dark matter, for example, interacts neither with normal matter nor antimatter.

Let us briefly contrast the idea of using antimatter with the synthetic black hole we will discuss below. It is currently possible to produce antimatter in extremely small quantities, while a synthetic black hole would necessarily be very massive. On the other hand, the process of generating a BH from collapse is naturally efficient, so it would require millions of times less energy than a comparable amount of antimatter or at least tens of thousands of times given some optimistic future antimatter generator.

As to confinement, a BH confines itself. We would need to avoid colliding with it or losing it, but it won't explode. Matter striking a BH would fall into it and add to its mass. So making a BH is extremely difficult, but it would not be as dangerous or hard to handle as a massive quantity of antimatter.

Although the process of generating a BH is extremely massive, it does not require any new Physics. Also, if a BH, once created, absorbs new matter, it will radiate it, thus acting as a new energy source; while antimatter can only act as a storage mechanism for energy which has been collected elsewhere and converted at extremely low efficiency.

(None of the other ideas suggested for interstellar flight seem viable either. The proposal for an interstellar ramjet turns out to produce more drag than thrust, while the idea of propelling a ship with a laser beam runs into the problem that the beam spreads too fast.)

Thus at this point, we are not even sure of a viable method for sending very small probes to other stars. Sending human beings is much harder, but in some sense it is what we really want, being what we are.

III. Black Holes and Hawking radiation

In the present paper, quantitative discussions on BHs will assume BHs of the Schwarzschild type. This is the simplest type of BH; having mass but no angular momentum and no electric charge.

A. Effective radius

A Schwarzschild BH of mass M has an "effective radius" R given by (e.g., [3], pp. 15 - 16):

$$R = \frac{2GM}{c^2},\tag{1}$$

where G is the gravitational constant and c is the speed of light. Even though the geometry of spacetime is not Euclidean, the area of the event horizon of a Schwarzschild BH (in a quiescent steady state) is given by the Euclidean formula $4\pi R^2$ (cf. [3], p. 80). This justifies calling R an "effective radius." The effective radius provides a useful heuristic measure for the "size" of a BH. Coincidentally, Equation (1) can be deduced on Newtonian grounds whereby one seeks the radius R of a sphere of mass M such that the escape velocity at the surface of the sphere is equal to the speed of light.

B. Hawking temperature

In classical general relativity, BHs are regions of spacetime which are so peculiarly warped that matter and energy can flow in, but nothing can come out. However, quantum particles are known to tunnel through classically impenetrable barriers. Indeed, Stephen Hawking has argued that quantum particles trapped inside of a BH can tunnel their way out to freedom. Thereby BHs emit a form of thermal radiation called "Hawking radiation." Hawking calculated that, as observed from infinity, the effective temperature of a BH is proportional to the strength of the gravitational field at its event horizon (cf. [3] p. 350). In the case of a Schwarzschild BH, with an effective radius of R, the temperature T is given by (cf. [3] p. 351):

$$T = \frac{\hbar c}{4\pi kR},\tag{2}$$

where \hbar is the reduced Planck constant and k is the Boltzmann constant.

C. Power

The luminosity, or total radiated power P, of a BH emitting Hawking radiation is somewhat subtle to compute. For a "poor man's estimate," take the area of the BH to be $4\pi R^2$, and take T as given by Equation (2). The Stefan-Boltzmann black body law gives $P \propto 1/R^2$, where the constant of proportionality is about 7.86×10^{-22} W·m². This naïve approximation fails to take into account several important features however, such as the various different particle species that can be created. It turns out that the total amount of radiated power is, even at low energies, a bit underestimated in this way. As the black hole gets smaller and more energetic, the error is compounded. Since we are interested in very energetic BHs, the estimate provided by the Stefan-Boltzmann law is a bit too naïve for our present purposes.

Thereby we will use a more sophisticated calculation on the power of Hawking radiance which is based on work from References [4] (MacGibbon and Webber) and [5] (MacGibbon). MacGibbon calculated that the total amount of radiated power P produced by a BH with an effective radius of R is given by (cf. [5] or [6]):

$$P = \frac{af(T)}{R^2},\tag{3}$$

where a is a constant with a value of about 1.06×10^{-20} W·m² and f(T) is a temperature-dependent numerical factor having to do with the various particle

species emitted. One always has $f(T) \ge 1$. A precise computation of f(T) requires detailed knowledge about particle physics.

In the Standard Model, one has $f(T) \leq 15.4$ (cf. [5]). MacGibbon [5] argues that $f(T) \leq 100$ in supersymmetric and technicolor models.

Since the constant $a = 1.06 \times 10^{-20}$ W·m² has such a tiny magnitude, it follows from Equation (3) that in order for a BH to yield a significant amount of power via Hawking radiation, the BH must be of "subatomic" dimensions; having an effective radius much less than 10^{-10} m. Such "subatomic black holes" (SBHs), as we shall call them, are not known to occur naturally in the present-day universe. Hypothetical "primordial black holes," which would now be in their final (explosive) stages of evaporation, have not been detected.

Not all of the power generated by a SBH may be practically useful. Hot BHs create massive particles, so some of the emitted "energy" actually goes into the "rest mass" of these particles. Also, a certain percentage of the radiated energy will end up in the form of neutrinos, particles which interact only very weakly with matter. However, for the very hot BHs which are of interest to the present paper, this "neutrino drain" is not terribly significant and most of the radiated power is emitted in more readily accessible channels [6].

Following MacGibbon [5], we will approximate f(T) by the formula:

$$f(T) = 1.569 + 0.963 \exp\left(\frac{-0.10 \text{ GeV}}{kT}\right) + 0.569 \left[\exp\left(\frac{-0.0234 \text{ GeV}}{kT}\right) + 6 \exp\left(\frac{-0.066 \text{ GeV}}{kT}\right) + 3 \exp\left(\frac{-0.11 \text{ GeV}}{kT}\right) + \exp\left(\frac{-0.394 \text{ GeV}}{kT}\right) + 3 \exp\left(\frac{-0.413 \text{ GeV}}{kT}\right) + 3 \exp\left(\frac{-0.413 \text{ GeV}}{kT}\right) + 3 \exp\left(\frac{-1.17 \text{ GeV}}{kT}\right) + 3 \exp\left(\frac{-38 \text{ GeV}}{kT}\right) \right],$$
(4)

which should hold reasonably well in the case of a BH with an energy-equivalent temperature kT that is above 0.06 GeV but less than 100 GeV [5]. The effective radius of such a BH is between about 0.16 and 260 attometers. (1 attometer = 10^{-18} meters.)

We have taken the liberty to make a slight correction to the last term in Equation (4). This term corresponds to the contribution of the top quark. The correction is not significant, but at the time of MacGibbon's paper [5], the mass of the top quark was unknown and MacGibbon assumed its mass to be about 100 GeV. Today we know that the top quark has a mass of about 171 GeV [7] and thereby we have adjusted Equation (4) accordingly.

It is known that Equation (4) slightly underestimates the quark contribution, treating them as particles with ± 1 charge rather than fractional charge, but the correction is not very significant [5]. Also, Equation (4) does not include the W^{\pm} and Z^0 emissions (which are only worth noting at temperatures of about 15 GeV or greater [5]), but again this does not have a very significant impact on f(T) (see [5] or [6]). More generally, one can approximate the function f(T) as a sum $f(T) = \sum_i f_i(T)$, where *i* ranges over all of the particle species that can be directly created by a BH of temperature *T*. The terms $f_i(T)$ can be estimated via:

$$f_i(T) = h_i n_i \exp\left(-bq_i^2 - \frac{m_i c^2}{\beta_i kT}\right).$$
(5)

This equation for $f_i(T)$ is taken from Appendix B of Semiz's paper [6], in which some of the results from Reference [5] are nicely summarized. The values of h_i and β_i depend on spin and are listed in Table 1. The constant *b* has a value of about 0.034. The variable q_i is the charge (in electron units) of the *i*th particle species, n_i is the number of internal degrees of freedom for the particle, and m_i is the mass of the particle.

spin_i	0	1/2	1	2
h_i	0.267	0.147	0.060	0.007
β_i	2.66	4.53	6.04	9.56

Table 1: The values of h_i and β_i according to spin (as given in References [5] and [6]).

D. Life expectancy

By mass-energy conservation, a BH which emits an infinitesimal amount dE of energy must decrease its mass by $dM = -dE/c^2$ (cf. [5]). Thereby, the rate at which mass "leaks out" of a BH is:

$$-\frac{dM}{dt} = \frac{1}{c^2} \cdot \frac{dE}{dt} = \frac{P}{c^2}.$$
(6)

By substituting Equations (1) and (3) into Equation (6) we obtain:

$$\frac{dR}{dt} = -\frac{2Gaf(T)}{c^4 R^2}.$$
(7)

Hence, a BH with an initial effective radius of R_0 has a life expectancy of L where:

$$L = \int_{0}^{R_0} \frac{c^4 R^2}{2Gaf(T)} dR.$$
 (8)

By feeding on mass at a rate comparable to the mass-leakage rate P/c^2 , a BH can last well beyond its life expectancy.

As an isolated BH shrinks smaller and grows hotter, the value of f(T) does not in general remain constant. Generously taking $f(T) \leq 100$, the integral in Equation (8) can be estimated as:

$$\frac{c^4 R_0^3}{600 Ga} \le L \le \frac{c^4 R_0^3}{6 Gaf(T_0)},\tag{9}$$

where $f(T_0)$ denotes the minimum value of f(T) that an isolated BH of radius R_0 will radiate through over its remaining lifetime.

A SBH of radius 0.6 attometers has an energy-equivalent temperature of about 26.2 GeV. Using Equation (4), we find that at this temperature, $f(T) \approx$ 12.5. If f(T) is a nondecreasing function of T for the temperatures that an isolated SBH with a radius of 0.6 attometers will achieve over its remaining lifetime, then by (9) one finds that the life expectancy of such a BH is less than about 1.04 years. Indeed, MacGibbon [5] reports that a BH with a mass of 4×10^{11} grams (such a BH has a radius of about 0.6 attometers) has a life expectancy of approximately 1 year.

Let $R_Y = 0.6$ attometers and let Y = 1 year. Given that a BH with a radius of R_Y has a life expectancy of about 1 year, we get that for a BH of radius R_0 :

$$L - Y \approx \int_{R_Y}^{R_0} \frac{c^4 R^2}{2Gaf(T)} dR.$$
 (10)

If the radius R_0 is between 0.16 and 260 attometers, then Equation (4) applies and approximates f(T) by an increasing function of T. Therefore, the integral in (10) can be estimated as:

$$\frac{c^4}{75Ga}(R_0^3 - R_Y^3) \lesssim L - Y \lesssim \frac{c^4}{6Gaf(T_0)}(R_0^3 - R_Y^3),\tag{11}$$

where T_0 is the temperature of a BH with a radius of R_0 .

A more sophisticated approximation for L can be carried out by making use of the "mass-squared average" of $f(T)^{-1}$ over the lifetime of an isolated BH (see MacGibbon [5] for details). However, the estimate for L as given by the range (11) will suffice for the purposes of the present paper.

E. A note on charged and spinning black holes

For details on how things change if the SBH is electrically charged or spinning, we recommend that the reader consult an authoritative reference such as the book by Frolov and Novikov [3]. Note that if an isolated SBH is initially endowed with an electric charge, then it will quickly, and almost completely, radiate this charge away (see [3], p. 398). Spinning SBHs radiate more powerfully than non-spinning ones of equal mass (see [3], pp. 399 - 400, or Page [8]). However, the angular momentum of an isolated SBH is rapidly dissipated (see [3], p. 399, or [8]).

IV. Theoretical Feasibility

In this section we want to discuss whether the Physics of black holes discussed above, together with the laws of Physics of matter as we know them, make it possible to produce artificial BHs which would be useful, either as power plants or as starships. Since the mass of a black hole decreases with its radius, while its energy output increases and its life expectancy decreases, this is a delicate question.

List of criteria: We need a black hole which

1. has a long enough lifespan to be useful,

2. is powerful enough to accelerate itself up to a reasonable fraction of the speed of light in a reasonable amount of time,

3. is small enough that we can access the energy to make it,

4. is large enough that we can focus the energy to make it,

5. has mass comparable to a starship.

We could easily imagine that this would be impossible. Somewhat surprisingly, it turns out that there is a range of BH radii, which according to the semiclassical approximation, fit these criteria.

Using the formulae from the section above, we find that a black hole with a radius of a few attometers at least roughly meets the list of criteria (see Appendix). Such BHs would have mass of the order of 1,000,000 tonnes, and lifetimes ranging from decades to centuries. A high-efficiency square solar panel a few hundred km on each side, in a circular orbit about the sun at a distance of 1,000,000 km, would absorb enough energy in a year to produce one such BH.

A BH with a life span on the order of a century would emit enough energy to accelerate itself to relativistic velocity in a period of decades. If we could let it get smaller and hotter before feeding matter into it, we could get a better performance.

In Section V below, we discuss the plausibility of creating SBHs with a very large spherically converging gamma ray laser. A radius of 1 attometer corresponds to the wavelength of a gamma ray with an energy of about 1.24 TeV. Since the wavelength of the Hawking radiation is $8\pi^2$ times the radius of the BH, the Hawking temperature of a BH with this radius is on the order of 16 GeV, within the limit of what we could hope to achieve technologically.

Now the idea that the wavelength of the radiation should match the radius of the BH created is very likely pessimistic. The collapsing sphere of radiation would gain energy from its self-gravitation as it converged, and there is likely to be a gravitational self-focussing.

This is a problem that can be studied using standard techniques from classical general relativity in which Einstein's equation is coupled to Maxwell's equations in vacuum, or "electrovac." We intend to investigate this in the future.

Thus it seems that making an artificial black hole and using it to drive a starship is just possible, because the family of BH solutions has a "sweet spot."

This seems not to have been remarked before in the literature, except for the earlier work of one of us.

Perhaps this is just a cosmic coincidence. In the epilogue, we discuss possible philosophical ramifications of this observation.

V. Four Machines

Now we discuss how a technology for implementing our proposal could be implemented. These devices are far beyond current technology, but we think they are possibly capable of being implemented ultimately if a future industrial society were determined to do so.

A. The black hole generator

In a previous paper by the first author [9], it was proposed that a SBH could be artificially created by firing a huge number of gamma rays from a spherically converging laser. The idea is to pack so much energy into such a small space that a BH will form. An advantage of using photons is that, since they are bosons, there is no Pauli exclusion principle to worry about. Although a laserpowered black hole generator presents huge engineering challenges, the concept appears to be physically sound according to classical general relativity. The Vaidya-Papapetrou metric shows that an imploding spherically symmetric shell of "null dust" can form a black hole (see, e.g., [3], p. 187, or Joshi [10] for further details).

Since photons have null stress energy just like null dust, a black hole should form if a large aggregate of photons interacts classically with the gravitational field. As long as we are discussing regions of spacetime that are many orders of magnitude larger than the Planck length, we should be outside of the regime of quantum gravity and classical theory should be appropriate. However, the assumption of spherical symmetry is rather special, and an investigation into the sensitivity of the process to imperfections in symmetry is an interesting problem for classical general relativity. If a high degree of spherical symmetry is required, then this could pose serious engineering challenges.

Since a nuclear laser can convert on the order of 10^{-3} of its rest mass to radiation, we would need a lasing mass of order 10^9 tonnes to produce the pulse. This should correspond to a mass of order 10^{10} tonnes for the whole structure (the size of a small asteroid). Such a structure would be assembled in space near the sun by an army of robots and built out of space-based materials. It is not larger than some structures human beings have already built. The precision required to focus the collapsing electromagnetic wave would be of an order already possible using interferometric methods, but on a truly massive scale.

This is clearly extremely ambitious, but we do not see it as impossible.

B. The drive

Now we would like to discuss how to use a SBH to drive a starship. We need to accomplish 3 things.

Design requirements for a BH starship

- 1. use the Hawking radiation to drive the vessel
- 2. drive the BH at the same acceleration
- 3. feed the BH to maintain its temperature

Item 3 is not absolutely necessary. We could manufacture a SBH, use it to drive a ship one way, and release the remnant at the destination. However this would limit us greatly as to performance, and be very disappointing in the powerplant application discussed below.

We shall discuss these three problems in outline only here; at the level of engineering they will each require an extended discussion.

It is not hard to see how we might satisfy requirement 1. We simply position the SBH at the focus of a parabolic reflector attached to the body of the ship. Since the SBH will radiate gamma rays and a mix of particles and antiparticles, this is not simple. The proposal has been made in the context of antimatter rockets, to make a gamma ray reflector out of an electron gas [11].

It is not clear if this is feasible (e.g., [2]).

Alternatively, we could allow the gamma rays to escape and direct only the charged particle part of the Hawking radiation (cf. [2]), although this produces a less capable ship. To improve the performance, we could add a thick layer of matter which would absorb the gamma rays, reradiate in optical frequencies, and focus the resulting light rays. An absorber which stops only gamma rays heading towards the front of the ship and allows the rest to escape out the back causes gamma rays to radiate from the ship asymmetrically. In this way, even the escaping non-absorbed gamma rays contribute some thrust (cf. [12] or [13]). Modulo safety concerns, one would not want the absorber to be too massive. An extremely massive absorber could burden the mass of vehicle so much that the extra thrust it helps to deliver does not lead to an improved acceleration.

Yet another idea for the utilization of gamma ray energy is to exploit pair production phenomena. By interacting with the electric field of atomic nuclei, high energy gamma rays can be converted into charged particle-antiparticle pairs such as electrons and positrons. These particles can be directed by electromagnetic fields. It is not likely that even half of the gamma ray energy can be utilized in this manner however (see Vulpetti [14], [15]).

It might be advantageous to use the Hawking radiation to energize a secondary working substance which can then be ejected as exhaust (as is done in thermal and ion rockets). However, the working substance must be ejected at relativistic speeds so that the specific impulse will be high enough for interstellar travel.

The most optimistic approach is to solve requirements 2 and 3 together by attaching particle beams to the body of the ship behind the BH and beaming in matter. This would both accelerate the SBH, since BHs "move when you push them" (see [3] p270), and add mass to the SBH, extending the lifetime.

The delicate thing here is the absorption cross section for a particle going into a BH. We intend to investigate this question in the future. If simply aiming the beam at the SBH doesn't work, we can try forming an accretion disk near the SBH and rely on particles to tunnel into it. Alternatively, we could use a small cluster of SBHs instead of just one to create a larger effective target, charge the SBH etc. It is also possible that because of quantum effects SBHs have larger than classical radii, due to the analog of zero point energy.

This point must remain as a challenge for the future.

C. The powerplant

This has already been proposed by Hawking (see [16] pp. 108 - 109). We simply surround the SBH with a spherical shield, and use it to drive heat engines. (Or possibly use gamma ray solar cells, if such things be.) This would have an enormous advantage over solar electric power in that the energy would be dense and hence cheaper to accumulate.

The 3 machines here really form a tool set. Without the drive, getting the powerplant near Earth where we need it would be very difficult. Without the generator, it would require the good fortune to find a primordial SBH to implement the proposal.

D. The self-driven generator

The industry formed by our first 3 machines would not yet be really mature. To fully tap the possibilities we would need a fourth machine, a generator coupled to a family of SBHs which could be used to charge its laser. Assuming we can feed a SBH as discussed above, we would then have a perpetual source of SBHs, which could run indefinitely on water or dust or whatever matter was most convenient.

A civilization equipped with our four machine tool set would be almost unimaginably energy rich. It could settle the galaxy at will.

VI. Open questions; quantum corrections

The reader has no doubt by now observed that a great many questions in this proposal are left open. We can mention the self-focussing of a focussing electromagnetic wave, and the possible effects of gravitational lensing and magnification on the various aspects of our problem.

Another open issue has to do with calculating the amount of gravitational radiation that would be produced by an SBH in a starship or other piece of SBH-powered technology (see below). When we come to quantum gravity effects, the questions are almost endless. The effect of a Planck scale cutoff on Hawking radiation, tunnelling, and modifications of our formulas by quantum self-energy are some of the obvious ones.

We think the proposal will be interesting for researchers in quantum gravity as a source of problems for their theories with a practical flavor, which could actually be studied in the distant future. The shortage of experiments in quantum gravity is so dire that even gedanken experiments would be helpful.

VII. A New Approach to SETI

As Freeman Dyson [17] has pointed out, when working with speculative ideas about technologies that appear to be physically possible, but beyond our grasp, we are faced with two options. We can either speculate on what humanity might achieve in the distant future or we can speculate on what a hypothetical extraterrestial civilization might have already done. The first line of thought postpones the possibility of any tangible results indefinitely into the future. On the other hand, the second line of thought raises a legitimate scientific question that could be settled by contemporary or near-term astronomical observations. We can ask ourselves what an extraterrestrial BH starship or other high technology would look like from Earth and proceed to look for it, if possible.

A SBH capable of driving a starship produces Hawking radiation which ultimately gives rise to gamma rays, neutrinos, antineutrinos, electrons, positrons, protons, and antiprotons [5]. Gamma ray telescopes are already in use and thereby one might think that a careful search through the gamma ray sky could conceivably turn up evidence of an extraterrestrial starship (cf. [18]). However, gamma rays produced by a SBH in a distant starship might be extremely difficult to detect if the starship is very energy-efficient and has well-collimated exhuast jets.

A BH starship using the technology we are proposing would emit gravitational radiation at nuclear frequencies. Current gravitational radiation detection experiments are optimized for much lower frequencies, and would not detect it.

We propose building gravity wave detection devices of a different design, with sensitivity in wavelengths of nuclear order. Since the wavelengths to be detected are much shorter, and since the energy outputs would be so high and the potential sources could be much closer, it would be possible to make detectors with a much shorter arm length, build them on Earth, and use them to scan for a signal. This would be a high risk high gain experiment; a positive signal would be an indication of extraterrestrial civilization.

It is also possible that such a detector would discover something truly unexpected; it is a new way to probe the universe.

We intend to undertake calculations as to the feasibility of such detectors in the future.

Meanwhile, here is a very rough back-of-the-envelope calculation of possible relevance. If spin 2 massless gravitons g exist, then, due to the Hawking effect,

an isolated non-rotating electrically neutral BH will radiate them at a total power of $P_g = af_g(T)/R^2$. Since the graviton has two degrees of freedom $(n_g = 2)$ (see, e.g., [19] pp. xi, 39), we get from Equation (5) and Table 1, that $f_g(T) = 0.014$. An isolated SBH with an effective radius between 1 and 6 attometers will therefore radiate gravitons at a power on the order of 0.004 to 0.1 petawatts. This can be thought of as a lower estimate on the rate at which a SBH will radiate gravitational energy. If the SBH is being accelerated or perturbed in some other way by an external agent, then one would expect that more gravitational radiation will be emitted from the SBH. On the other hand, the gravitational radiation could not exceed the rate at which energy was being fed into the SBH, which in a steady state stardrive would equal the Hawking radiation from all particle species, which is on the order of 3 to 130 petawatts for SBHs with radii in our proposed range.

We note that the graviton emission of a rapidly spinning SBH could be a few orders of magnitude more powerful than the non-spinning case considered above (see [8]).

VIII. Conclusions

Quantum gravitational corrections could make this proposal easier or impossible. Within our current understanding of Physics, this proposal could make greater concentrations of energy available for human use than anything else we currently know. It may even allow us to go to the stars in person, rather than simply sending miniaturized probes.

The proposal we are making should be pursued as far as possible, and in as optimistic a spirit as the facts permit, because it allows a completely different and vastly wider destiny for the human race. We should not underestimate the ingenuity of the engineers of the future.

As an aside, let us note that building a single SBH would be the ultimate particle Physics experiment. As the remnant BH radiated it would go through every temperature up to the Planck scale. Careful study of its radiation would tell us exactly what particle types exist in nature, beyond the energy of any imaginable accelerator. Perhaps a future society would carry out such an experiment, even if all proposals for applications fail.

IX. Epilogue: The meduso anthropic principle

The origin of this proposal is very peculiar. The first author was reviewing the work of Lee Smolin, which was later published in a book entitled *The Life of the Cosmos* [20]. Professor Smolin proposed that the universe we see was only one of many universes, and that new universes arise from old ones whenever a black hole is produced. This then leads to an evolutionary process for universes in which universes with an unusually high number of stars were selected for. The first author proposed that the evolutionary process of universes should include life. This is possible if successful industrial civilizations eventually produce black holes, and therefore baby universes.

Note that if successful industrial civilizations only trapped already existing BHs, it would not alter the number of baby universes a universe produced, so that no evolutionary loop would result.

This led us to consider the possibility of producing artificial BHs, and to explore how they might be useful.

The meduso-anthropic principle (as this proposal was named) is at least falsifiable, in the sense that if it turned out artificial BHs were completely impossible or useless then the evolutionary cycle universes-civilizations-black holes -baby universes could never happen.

The result of our feasibility calculation is much too tenuous to be considered a proof of the meduso-anthropic principle. It is not in fact clear at all that black holes create baby universes, as the maximal analytic continuations of the standard BH solutions to Einstein's equation suggest.

Nevertheless, it is a bit eerie that only through this line of thought did we consider the possibility of synthetic BH creation. We are the first and almost the only authors to our knowledge to consider this. The only other author we are aware of is Semiz [6], who wrote: "...we would have to either find small black holes, possibly primordial, or manufacture them by means as yet unknown," in a rather popular discussion on BH powerplants and stardrives, which appeared after our first paper.

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Appendix: Finding the "sweet spot"

In this Appendix, we show that a BH with a critical radius of a few attometers at least roughly meets the criteria listed in Section IV.

Using the semiclassical formulae from Section III, we have calculated the Hawking temperatures, total power outputs, mass-leakage rates, and life expectancies for various SBHs of radii between 0.16 and 10 attometers. The results are presented in Table 2. The figures reported are the rounded results of complete calculations. In each case, the value of f(T), as approximated by Equation (4), is used to estimate the power outputs, mass-leakage rates, and life expectancies. Since it is known that Equation (4) slightly underestimates f(T), it follows that the power outputs and mass-leakage rates are slightly underestimated and the life expectancies are slightly overestimated.

According to Table 2, a BH with a radius of 1 attometer or less has a massleakage rate exceeding 1 kilogram per second. Such a BH will radiate very

R (am)	M (Mt)	$kT \; (GeV)$	f(T)	P (PW)	P/c^2 (g/sec)	L (yrs)
0.16	0.108	98.1	13.3	5519	61400	$\lesssim 0.04$
0.3	0.202	52.3	13.0	1527	17000	$\lesssim 0.12$
0.6	0.404	26.2	12.5	367	4090	1
0.9	0.606	17.4	12.2	160	1780	3.5
1.0	0.673	15.7	12.1	129	1430	5
1.5	1.01	10.5	11.9	56.2	626	16 - 17
2.0	1.35	7.85	11.8	31.3	348	39 - 41
2.5	1.68	6.28	11.7	19.8	221	75 - 80
2.6	1.75	6.04	11.7	18.3	204	85 - 91
2.7	1.82	5.82	11.7	16.9	189	95 - 102
2.8	1.89	5.61	11.6	15.7	175	106 - 114
2.9	1.95	5.41	11.6	14.6	163	118 - 127
3.0	2.02	5.23	11.6	13.7	152	130 - 140
5.8	3.91	2.71	11.1	3.50	38.9	941 - 1060
5.9	3.97	2.66	11.1	3.37	37.5	991 - 1117
6.0	4.04	2.62	11.1	3.26	36.2	1042 - 1177
6.9	4.65	2.28	10.9	2.43	27.1	1585 - 1814
7.0	4.71	2.24	10.9	2.36	26.2	1655 - 1897
10.0	6.73	1.57	10.5	1.11	12.3	4824 - 5763

Table 2: This table shows effective radii R (in attometers), masses M (in millions of tonnes), Hawking temperatures kT (in GeVs), estimated f(T)-values, estimated total power outputs P (in petawatts), estimated mass-leakage rates P/c^2 (in grams per second), and estimated life expectancies L (in years). Note that the power-to-mass ratio P/M (not explicitly shown) is very high - especially for smaller SBHs.

powerfully, but have a short life expectancy. Unless the BH is fed mass-energy at a rate comparable to the mass-leakage rate, it will expire quickly. If it is not possible to feed such a BH then the BH must be safely disposed of in a timely manner. According to the semiclassical approximation, a BH "explodes" at the end of its lifetime. Such an explosion is powerful by terrestrial standards, but not by astronomical standards. A BH that explodes at a distance of 1 AU from Earth poses no danger. Simply on the basis that $f(T) \geq 1$, Inequality (9) shows that when the BH reaches a radius of about 8×10^{-22} m, its life expectancy is less than a second. Generously assuming that $f(T) \leq 100$, Equation (3) tells us that such a BH has a total radiated power of less than about 1.66×10^{24} W. The sun itself radiates about 230 times more powerfully than this. According to the semiclassical approximation, the BH will go on to radiate more and more powerfully until it finally expires, but Earth will only be exposed to this more intense radiation for an insignificant fraction of a second. Moreover, if the "explosion" occurs behind the sun, then the sun will act as a shield and Earth will be exposed to even less Hawking radiation. The upshot is that SBHs can be safely disposed of when necessary.

A. What BHs are long-lived enough and powerful enough for interstellar travel?

SBHs of radii less than 1 attometer are incredibly powerful. Note however that the life expectancy of a BH with a radius of 0.16 attometers is less than about 2 weeks. In order for such a BH to last significantly longer than that, an external agent must force-feed it mass-energy at a rate of many kilograms per second. As we have emphasized throughout the text, It is unknown whether SBHs, since they are so very small, can feed on anything at all, let alone many kilograms per second. If SBHs with radii on the order of 0.1 attometers could be force-fed at sufficiently high rates, by using a feeding system whose mass is small compared to the mass of the SBH, then it is not hard to believe that such SBHs could be very useful as power sources for starship propulsion systems if their power can be harnessed efficiently. In the following however, we will assume that SBHs cannot be fed. Even in this "worst case scenario," it turns out that SBHs could still turn out to be useful for interstellar travel.

We note that guiding a BH is less difficult than feeding it, because it is only necessary to scatter radiation off the BH to impart momentum to it. If even this is impossible, it is hard to see how to build any drive at all.

About the fastest type of interstellar voyage that human beings could physically tolerate would be a one-way trip from Earth to Alpha Centauri (a distance of just over 4 light years [21]) which accelerates at a proper acceleration of 1 g for the first half of the voyage and decelerates at 1 g for the second half. In this way, the travelers arrive at Alpha Centauri with zero relative speed. The trip would only take about 3.5 years from the perspective of the travelers (thanks to Special Relativity).

From Table 2, a BH with a life expectancy of about 3.5 years has a radius of about 0.9 attometers. Unless SBH lifetimes can be significantly extended via feeding, a manned interstellar vehicle powered by an on-board SBH requires SBHs of at least this initial size (and most likely quite larger).

Conceivably, unfed SBHs of radii less than 0.9 attometers, having less than 3.5 year life expectancies, could be used to rapidly accelerate interstellar robotic probes to relativistic speeds. Robotic probes do not necessarily need to "stop" and could tolerate much larger accelerations than humans. The problem of navigating such objects could be difficult however.

The SBH would have to be ejected (or otherwise escaped from) before it explodes.

A SBH with a radius of 0.9 attometers has a mass of about 606,000 tonnes and a power output of about 160 petawatts. Over a period of only 20 days a 160 petawatt power source emits enough energy to accelerate 606,000 tonnes up to about 10% the speed of light. Of course, it is unrealistic to suppose that the emitted energy can be converted into kinetic energy with 100% efficiency, but even if the conversion occurs with an efficiency of only 10%, it only takes 10 times longer to deliver the requisite kinetic energy.

If we cannot use SBHs that are more powerful than 160 petawatts (i.e., smaller than 0.9 attometers) for manned starships, then it may not be feasible to use SBHs as power sources for interstellar rockets that maintain *both* constant proper accelerations of 1 g *and* extremely high exhaust speeds (near c). An ideal rocket undergoing a proper acceleration of 1 g, whose exhaust consists of perfectly collimated light-like radiation (exiting the vehicle at c), needs to consume about 3,000 petawatts per million tonnes of vehicle mass [21]. It turns out that the ratio of power dissipation to acceleration becomes more tolerable when lower exhaust speeds are used [21], but interstellar travel demands very high exhaust speeds.

On the other hand, interstellar travel does not necessarily require large accelerations. Small accelerations sustained over long periods of time suffice.

SBHs with radii of a few attometers are more long-lived and could be used for long-term voyages. Since a "larger SBH has less power," and is therefore less capable of acceleration, one would accelerate the ship somewhat weakly at least during the initial part of the journey. As the journey progresses, the (unfed) SBH shrinks in size and becomes more powerful.

Assuming that SBHs cannot be fed, an interstellar voyage of 100 years would need a SBH with a life expectancy of at least 100 years. According to Table 2, a SBH with a radius of about 2.7 attometers has a life expectancy of about 100 years (but remember that the life expectancies in the table are somewhat overestimated, as noted above). A mission which needs SBH power for 1,000 years would require a SBH with a radius of about 5.9 attometers. Now a 1,000 year voyage is not very appealing, and we take this to be a generous upper limit on the amount of time that a single interstellar mission might take. (A SBH with a life expectancy of over 1,000 years would probably not be suitable in a stardrive anyhow - see below.) On the other hand, if the destination is reached well before the BH evaporates, then the BH could serve temporarily as a power plant after it has served in a stardrive.

According to Table 2, a 100 year BH has a mass of about 1,820,000 tonnes, and radiates at about 17 petawatts. It takes about 1.5 years for a 17 petawatt power source to emit enough energy to accelerate 1,820,000 tonnes to 10% the speed of light. If the emitted energy can only be converted into kinetic energy at an efficiency of 10%, then it takes about 15 years. If the efficiency is only 5%, then it takes approximately 30 years, but even this is good enough for long-term interstellar travel. (We are ignoring, for the moment, the fact that the BH radiates more powerfully over time.)

A 1,000 year BH has a radius of about 5.9 attometers, a mass of about 3,970,000 tonnes, and radiates at about 3 petawatts. It takes such an object almost 20 years to emit the amount of energy needed to accelerate 3,970,000 tonnes to 10% the speed of light. Assuming that the emitted energy could be converted into kinetic energy with only 10% efficiency, it would take closer to 200 years.

The above calculation hints that a SBH with a life expectancy of over 1,000 years (and a radius in excess of about 6 attometers) would not serve adequately as the power source for a starship. Even the adequacy of a 1,000 year BH is somewhat doubtful.

Indeed, it appears that a SBH with a radius of 10 attometers would be highly inadequate. Such a BH has a life expectancy of a few millennia, a mass of about 6,730,000 tonnes, and radiates about 1 petawatt. It takes about a century for a 1 petawatt power source to emit enough energy to accelerate 6,730,000 tonnes up to 10% the speed of light (and this even ignores the fact that the emitted energy could not be converted into kinetic energy with perfect efficiency). It seems to be a safe bet that one would not want to use such a BH in a stardrive.

The upshot is that SBHs with effective radii between roughly 1 and 6 attometers could be adequate power sources for starship propulsion systems - if their power can be harnessed efficiently. The smaller the BH, the more powerful it is. However, one must either be able to arrive at one's destination before the BH evaporates completely or one must be able to feed the BH in such a way as to prolong its life. In the most optimistic scenario, where one can feed the SBH very efficiently, one could have very capable manned starships driven by extremely powerful SBHs with radii smaller than our suggested range of 1 to 6 attometers.

B. Are these BHs so *small* that we can *access* the energy to make them?

We now consider the question of whether a SBH can plausibly be made using energy sources that could at least eventually be at our disposal. The most abundant energy source in the solar system is the sun, which has a luminosity of about 3.8427×10^{26} W [7]. Following a transition from a global Earth-based economy to an interplanetary Solar System-based economy (whereby off-Earth energy resources are utilized), a reasonable fraction of the sun's total power will be at our disposal. The sun releases the equivalent of 2 million tonnes of energy in less than half a second, which is enough energy to make a BH with an effective radius of a few attometers.

A perfectly efficient square solar panel with each side measuring about 370 km, in a circular orbit about the sun at a distance of 1,000,000 km, would absorb enough energy in one year to create a BH with an effective radius of about 2.2 attometers. As discussed in the text, one possible mode of production for an initial set of SBHs is to use a very massive nuclear laser. Such a laser can be constructed near the sun so that it can be "charged up" by solar energy before getting switched on.

C. Are these BHs so *big* that we can *focus* the energy to make them?

This is the "dual" side of the problem discussed in part B above. Suppose that we are to synthesize a BH with an effective radius between 1 and 6 attometers by focusing a spherically converging gamma ray laser at a single point. If the photons coming from the laser need to have wavelengths of no more than about the critical radius of the BH, then we need to use gamma ray photons of energies between about 210 and 1240 GeV. As discussed in the text, it could turn out that wavelengths significantly larger than the critical radius would be alright. If we can use gamma rays having energies roughly matching the Hawking temperature the SBH to be synthesized, then we need gamma rays having energies of the order 3 - 16 GeV. These are comparable to wavelengths within the Compton radii of nucleii, hence could be technically possible.

D. Do these BHs have masses comparable to that of a starship?

Since we are still pretty far away from building starships, the "mass of a typical starship" is a matter of speculation. It is a safe bet however that a starship would have to be very massive. It must shield its passengers and sensitive technological equipment from hazardous cosmic radiation. It would also have to accommodate a large population for a potentially long time (from decades to perhaps a century or more).

SBHs with radii ranging from 1 to 6 attometers have masses ranging from 673,000 to 4,040,000 tonnes. We conjecture that a starship powered by a *single* SBH would transport payloads having a total mass of somewhat *less* than this. Much larger payloads could be transported by very large starships powered by several SBHs.

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