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NEW APPROACHES TO CTR: GENERAL RELATIVISTIC POWER PLANTS*

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MASTER

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*Research performed under the auspices of the U.S. Atomic Energy Commission.
†Also Fannie and John Hertz Foundation Fellow, and with Dept. of Physics, UC Berkeley.

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Introduction

Nature is known to generate thermonuclear energy in only two modalities: via inertial confinement of the fusion fuel in nuclear explosives, and by gravitational confinement of thermonuclear material in stars. We have previously proposed approaches to production of electricity from inertially ignited and confined thermonuclear microexplosions¹, and we now discuss means of power generation involving gravitational initiation and confinement of fusion detonation events. We have been concerned with creating thermonuclear microexplosions to generate clean and inexhaustible electricity; we are now investigating the prospects for reproducing on vastly smaller scales the explosions of stars themselves for powering human civilization. We recognize that gravitational CTR may appear to be enormously more difficult in a technological sense than the challenging program on which we are presently embarked to realize inertial fusion via laser-energized implosion, but we will also discuss some possible means by which these difficulties may be overcome.

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The key to our approach is the utilization of gravitationally collapsed objects (known as black holes) whose masses are much less than the mass of the Earth. The size of these objects is characterized by the radius at which the gravitational field is so intense that neither matter or light can escape from it. This is just the Schwarzschild radius, defined by

$$R_s = \frac{2GM_H}{c^2} = .88 \left(\frac{M_H}{M_\oplus} \right) \text{ cm}$$

where M_H is the mass of the black hole and $M_\oplus$ the mass of the Earth. At distances large compared to R_s , a black hole acts as a classically gravitating point mass.

Existence of Small Black Holes (SBH)

The existence of small black holes with mass from 10^{-5} to 10^{34} grams was predicted by Stephen Hawking² in 1971 on the basis of the extremely dense, chaotic conditions that are thought to have characterized the earliest phases of the universe. Briefly, most astrophysicists now believe that the Universe, as we presently know it, evolved from a nearly infinitely dense ball of matter that exploded ~ 15 billion years ago, leaving as evidence of its occurrence a uniformly expanding system of galaxies and a fireball of microwave radiation. Hawking pointed out that density and velocity fluctuations in the expanding matter could quite possibly be large enough so that the masses associated with these fluctuations would not continue to expand with the rest of the Universe, but would collapse under their self gravitation to form black holes.

While there is presently insufficiently detailed knowledge about conditions in the early universe to make quantitative predictions about the number and mass spectrum of black holes formed in this way, there is some evidence suggesting that the total mass of such holes may exceed that of all the presently observed matter in the universe. This comes primarily from observing the dynamics of clusters of galaxies and of the universe as a whole. In the former case, certain clusters of galaxies appear to lack by about a factor of 10 the mass necessary to gravitationally bind them³--a binding necessary for them to have remained in their present cluster configurations over the life of the universe. In the latter case, the observed deceleration of the expansion of the universe suggests (within large errors) that the matter density of the universe may be much greater than presently observed⁴ (up to a factor of $\sim 10^2$ - 10^3). In addition to such general indications of unobserved mass of some type, it has recently been pointed out⁵ that the Tunguska meteorite which in 1908 devastated a region of Siberia some 40 km across with an explosive force equivalent to a 2 - 20 Mton nuclear explosion (but which left no crater or identifiable debris) has many of the characteristics of a black hole of mass 10^{20} - 10^{22} g (2×10^{-8} - 2×10^{-6} $M_{\odot}$) striking the earth and passing on through it. While there are some difficulties with this hypothesis, it cannot be completely dismissed. Furthermore, the present theoretical impasse centering on the results of the Davis solar neutrino experiment might be the result of the unaccounted-for presence of one or more small black holes in the center of the sun.²

A firm upper limit of 10^{-6} $M_{\odot}$ on the amount of unobserved mass in a single body that may now be present in the earth-moon system has been set on the basis of lunar motion studies utilizing lunar laser ranging.⁶ There in fact exist presently unresolved discrepancies in these data that may correspond to a mass or masses $\sim 10^{-7}$ $M_{\odot}$. Considering the solar system inward of the asteroids, dark objects of up to 10^{-5} $M_{\odot}$ could presently exist undetected.

SBH Detection

Methods of detecting small black holes fall basically into three categories:

1) Gravitational effects, 2) Accretion effects and 3) Self-luminosity.⁷ In the first category, continued refinement of the lunar laser ranging experiments referred to previously and their extension to the precise tracking of artificial satellites could result in the detection of circum-terra black holes of mass in the range 10^{-6} to $\sim 10^{-9} M_{\odot}$. Laser or microwave ranging off circum-solar reflectors in Earth-like (low eccentricity, 1 A.U.) orbits could also be used to probe for objects in this mass range in the Lagrangian lobes of the Earth-Sun system, which appear to be the most extensive in the inner solar system, and thus one of the more likely regions for small black holes to be swept into. (Also, the gravitational scattering of particles of the solar wind might have observable (e.g. radiative) effects, either at the time of interaction, or during the subsequent interaction of the perturbed wind with the Earth's magnetic field.)

Detection of small black holes at great distances through their interaction with the solar wind incident upon their sphere of influence seems comparably promising to their detection via gravitational effects. As will be discussed subsequently, the electromagnetic radiation signature of holes in a plasma is both distinctive and relatively powerful. The continuous emission spectrum of plasma falling into black holes has been treated previously, and is formed primarily rather deep in the hole's throat, where the accretion shock brings the matter up to a temperature comparable to its gravitational potential. It should be noted, however, that very small black holes have a complete set of gravitational Bohr orbits connected by electromagnetic transitions for both nuclei and electrons, for hole masses $> 10^{-12} M_{\odot}$. The lower quantum number radiative transitions in the Lyman, Balmer and Paschen series for both species will result in characteristic hard line radiation in the x-ray and γ -ray portions of the electromagnetic spectrum.

to produce a very strong, visible, and detectable electromagnetic radiation. Such solar wind-bathed holes should thus be electromagnetic radiative beacons of a peculiar nature, visible via advanced state-of-the-art detection technology at distances approaching 1 A.U.

Hawking has very recently pointed out that electron-positron pair annihilation deep in the Swartzschild throat of small black holes should constitute a relatively strong and quite distinctive signature of small black holes, particularly the lower mass ones.⁷ The pairs are formed by gravitational breakdown of the Dirac sea when the tidal stresses across an electron Compton length become of the order of 1 Mev per electron rest mass, and consequently are generated more copiously and at a higher density around lower mass black holes, where the tidal stresses are larger. Black holes with masses of 10^{15} grams should be seen as the source of 10^{-1} moderately hard (> 100 keV) gamma rays $\text{cm}^{-2} \text{sec}^{-1}$ at 1 A.U. distances, a readily detectable flux. This flux scales as the inverse cube of the black hole mass, so that holes with masses lower than 10^{15} grams should be brilliant gamma ray beacons (and incidentally would not survive for $> 10^9$ years, because of their radiative losses) in the inner solar system, while holes with masses as great as 10^{17} grams should still be detectable in our cosmic neighborhood by their own annihilation radiation.

SBH Power Production

Small black holes can be used to generate usable energy in at least four ways: 1) The gravitational heating of matter accreting onto them; 2) the conversion of their self-annihilation radiation; 3) the thermonuclear fusion of matter contained in their gravitational potential well, and/or 4) gravitational scattering drawing on their kinetic or rotational energy.

A stream of matter flowing by a black hole is accreted out to a radius of $\sim \frac{2GM_H}{V_0^2}$ where M_H is the mass of the hole, V_0 is the velocity of the matter stream, and G is the gravitational constant.⁶ This accretion is due to collisions between atoms in oppositely directed orbits behind the hole and the resulting formation of a characteristic accretion shock there, where temperatures of order $-\phi_G M_A/k$ are developed, where ϕ_G is the gravitational potential, M_A is the mean atomic mass, and k is Boltzmann's constant.

After its capture by the hole, the accreted matter is further heated by viscosity acting between particles in neighboring "orbits" and this energy is then radiated away. This results in the spiraling of the matter closer into the hole, and its resultant rise in temperature due to the release of gravitational energy as given by the virial theorem, $T \sim \frac{1}{2} \phi_G M_A/k$. The ultimate fate of the matter depends on its composition and the mass of the hole. Since the angular momentum of a particle is quantized in units of $\hbar$, there is a minimum size orbit, $r_{\min}$, beyond which a particle cannot fall. In the regime where gravitation can still be described by a classical inverse square law, this is given by:

$$r_{\min} = \frac{\hbar^2}{m^2 G M_H}$$

where $\hbar$ is Planck's constant and m is the particle mass.

If $r_{\min} < R_S$, the Schwarzschild radius defined above, then the hole will have swallowed up the innermost particles, leaving room for more to fall in and be swallowed in turn. If $r_{\min} \gg R_S$, then time, τ_c , required for the innermost particles to be captured irrecoverably in the relativistic singularity in the center of its orbit is relatively long, and is given approximately by:

$$\tau_c \sim \frac{R_S}{V_p} \left(\frac{r_{\min}}{R_S} \right)^{3/2} \quad V_p = \frac{r_{\min} \omega}{1}$$

where V_p is the orbital velocity at $r_{\min}$. The dividing point between these cases occurs when:

$$M_{\text{crit}} = \frac{hc}{\sqrt{2} mG} = \begin{cases} 3.7 \times 10^{17} \text{ g } (6.2 \times 10^{-11} M_{\odot}) \text{ for electrons} \\ \frac{2.0 \times 10^{14}}{A^2} \text{ g } (3.3 \times 10^{-14} M_{\odot}) \text{ for nuclei} \end{cases}$$

with quasi-stable gravitational "atoms" being formed at lower masses, where A is the atomic weight of the accreted material. Since the orbits formed by the nuclei are $\sim 10^6$ times smaller than those formed by electrons, a concentration of protons, Z_{Hole} , will build up near or in the hole until the resulting electrostatic field reduces the nuclei capture rate to that experienced by the electrons. This occurs when:

$$Z_{\text{Hole}} = \frac{G M_H m_p}{e^2} = 2.9 \times 10^{15} \frac{M_H}{M_{\odot}} = 2 \times 10^5 A \Big|_{M_H} = M_{\text{crit}}^e$$

where m_p is the proton mass and e the electron charge and M_{crit}^e is the critical mass for electrons. This electrostatic field reduces $r_{\min}^e$ by a factor of $\sim 1800 A$, and reduces the effective critical mass for electrons, $M_{\text{crit}}^{\text{eff}}$ to $\sim 10^{-12} M_{\odot}$. For hole masses below this level, the accretion rate is then very roughly:

$$\dot{M} = A m_p / t_c = A m_p \left(\frac{m_p A}{m_e} \right)^{5/2} \frac{4 m_e^5 h^4}{5 c^4} \frac{M_H^4}{(r_{\text{H}})^4} = 1.5_{25} A^{7/2} \left(\frac{M_H}{M_{\odot}} \right)^4 \text{ g/sec}$$

For $M_H = 10^{-12} M_{\odot}$, $\dot{M} = 1.5_{13} \text{ g/sec}$, which is equivalent to only 15 watts, even if all the accreted particles rest mass is converted to radiated energy; gravitational "atoms" surrounding low mass black holes thus appear to be of little use for power production, via accretion.

For $M_H > 10^{-12} M_\odot$, the accretion rate depends critically on how fast the orbiting matter's angular momentum is dissipated, thus allowing it to spiral into R_S . A crude upper limit is:

$$\dot{M} \lesssim \rho_S 4\pi R_S^2 c$$

where ρ_S is the density at the Schwarzschild radius, which may conceivably be as high as $\sim 4 \times 10^{11}$ g/cm³ if a quasi-static balance of gravitational and Fermi pressure exists near the Schwarzschild radius.

Numerically

$$\dot{M} \lesssim 1.5_{23} \left(\frac{M_H}{M_\odot}\right)^2 \text{ A g/sec}$$

If matter is accreted at this upper limit and its rest mass energy converted to electricity with 10% efficiency, a $10^{-11} M_\odot$ black hole would suffice to generate the present U.S. electrical production.

On the other hand, if the accretion dynamics are such that $\rho_S \sim 1$ g/cm³, then a $\sim 10^{-5} M_\odot$ would be needed to generate the same amount of energy. A detailed study of accretion dynamics is necessary to determine more precisely what accretion rates might be realized. See Figure 1.

An alternate approach to black hole power generation is to use the gravitational field associated with the hole to compress and confine a plasma hot enough to induce fusion, but not confine the fusion products. The radius at which the gravitational potential is ϕ_G is:

$$R(\phi_G) = \frac{1}{2} \left(\frac{m c^2 A}{\phi_G} \right) R_S = 4.164 \times 10^5 A \left(\frac{M_H}{M_\odot} \right) \frac{1}{\phi_{\text{kev}}} \text{ cm}$$

For $\phi_G = 10$ kev, the amount of mass within this radius is:

$$M_f = \frac{4}{3} \pi R(\phi_G)^3 \rho_f = \frac{1}{2} \left(\frac{m c^2 A}{\phi_G} \right)^3 R_S^3 \rho_f$$

where ρ_f is density of the fusing material. It appears possible by injecting

droplets of carbon fuel (e.g., 10^{-6} g) would be present in the region of $1 - 10 \text{ g/cm}^3$, with the necessary heating of the thermonuclear fuel to ignition temperature being provided by the accretion shock. For a $10^{-6} M_{\odot}$ hole, M_F would then be $\sim 0.1 - 1 \text{ g}$. This matter would fuse in $\sim 10^{-9}$ sec and the fusion products would escape at velocities $\sim 0.1c$.

If 100-1000 such droplets were exploded per second, the fusion energy generated would again be sufficient to supply the U.S. Quasi-CW fusion modes are probably also possible. The relative advantages of such a process over accretion thus depend on what accretion rates into the extremely small throats of small black holes ($\sim 100 \text{ A}$ for $M_H = 10^{-6} M_{\odot}$) turn out to be attainable. It is possible that reaction force from the departing fusion products would create an inward implosion sufficient to significantly augment the accretion rate. It is a unique and very useful feature of gravitational confinement that the fusion fuel is automatically compressed and heated to ever higher values, until it finally burns to an efficiency sufficient to blow the fuel mass back up the throat of the hole--all fusion fuels automatically fall into the throat to the point where they burn well. Both inertial and magnetic CTR lack this pleasantly self-regulating feature, which permits the utilization of any combination of light elements as fuel.

A third possibility for SBH power production is via the gravitational interaction of two or more black holes, analogous to that suggested by Dyson for stellar systems. For example, if two black holes were orbiting each other in an electro-magnetically or viscously resistive medium, a significant fraction of their rest mass energy could be extracted as they spiraled together. This scheme could make quite efficient use of holes with mass below $\sim 10^{-12} M_{\odot}$, and would require the use of little extraneous mass. Such black-hole systems, however, would probably have to be assembled, either by carefully arranged 3 body collisions or by

the direct injection of small masses into the holes.

straightforward---the gamma rays are degraded to high temperature heat, which is then utilized conventionally (except that waste heat must be radiated at reasonably high-- $\sim 1000^\circ\text{K}$ --temperatures in space to be practical). Unfortunately, a single black hole must have a mass less than about 10^{15} grams to output enough self-annihilation radiation to generate the present planetary energy needs, at 10% conversion efficiency.

Energy Conversion and Transmission

Black hole-centered gravitational power plants will obviously not be located on or near planetary surfaces, but rather at the distant locations where these general relativistic singularities are found or relocated to. (Somewhat surprisingly, it appears relatively feasible to maneuver small black holes ($\lesssim 10^{16}$ gm) around in the solar system -- one merely moves a small asteroid into orbit around one, and then pushes gently on the asteroid, the orbiting and pushing of the asteroid being done with thermonuclear explosion-generated asymmetric ablation of the asteroid surface as the source of reaction mass. Total explosive yields of the order of the solar orbital energy of the hole -- 10^5 megatons for a 10^{15} gram hole -- will suffice and are merely comparable to the total yield of nuclear explosives already extant on Earth.) The various forms of energy from the gravitationally initiated and confined fusion microexplosions or radiation from accreted matter may be efficiently and directly converted to electrical form by means which we have discussed previously for inertially confined microexplosions.

For instance, the explosion's x-ray output may be automatically converted to charged particles by absorption in a surrounding layer of high Z gas, which is thereby heated to 10^7 to 10^8 K. Merging together with the outwardly expanding explosion debris, the entire charged particle cloud may have its

energy directly converted to electricity by its interaction with the imposed magnetic field.⁸ Care in designing the field-generating superconducting solenoids and the Faraday induction coils will result in less than 1% of the energy of the generated electricity appearing as heat in the converter apparatus-- radiation and charged particle energy not converted to electricity merely streams off into space. Such direct conversion characteristics are an especially notable feature of the non-neutrogenic exotic fusion fuels, such as the p-B¹¹ system, which may be burned in such gravitational engines with the same high efficiency as DT, due to the self-adjusting nature of the gravitational confinement. See Figure 2.

The directly converted electrical energy is in radiofrequency form, and may be efficiently radiated to the Earth in a tightly focussed beam from a phased array of suitable aperture. Passing through the Earth's atmosphere unattenuated, due to its short pulsed nature, it may be collected by a system of large ground-based antennae and converted to transmission grid-exciting pulses with > 50% efficiency by use of conventional high frequency response power diodes.

The initial cost of such a gravitational engine power system might be relatively very low--it has no moving parts, and has very little to break down or wear out. If operated in the accretion mode, its fuel could be any element, and a feed rate of 100 kg/day would supply a global population of 10 billion with 10 times the U.S. per capita energy consumption--one Space Shuttle load of rocks every year or so would easily suffice. The fusion microexplosion mode would require weekly Shuttle loads of virtually any light element. Thermal, chemical and radiological pollution of the biosphere by such a gravitational engine-based electric power system would be zero.

Conclusion

While it is far from certain that any very low mass black holes exist in the Earth-Moon system (or even in the Solar system), methodical application of present ultra-high precision gravitational survey techniques (such as lunar and artificial satellite laser ranging) should suffice to locate any within the Earth-Moon system with masses greater than 10^{-9} Earth masses. Obvious places to look for such gravitational anomalies are the five dynamically stable Lagrangian points, and in relatively close lunar and terrestrial orbits--other regions probably don't afford stable orbits over geologic time. Search of the inner solar system with both gravitational and ionizing radiation detectors also appears technically feasible and potentially quite rewarding.

Locating such an object would not only be of the first importance to basic astrophysics, but would have enormous implications for the terrestrial energy economy, as the center of a general relativistic CTR power plant.

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GENERAL RELATIVISTIC ENGINE – GRAVITATIONAL CONFINEMENT OF FUSION MICROEXPLOSIONS

Figure 1

Figure 2