Applied Physics Research; Vol. 7, No. 4; 2015
ISSN 1916-9639 E-ISSN 1916-9647
Published by Canadian Center of Science and Education

Black Holes as a Source of High-Energy Neutrinos

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Received: May 14, 2014 Accepted: May 26, 2015 Online Published: May 30, 2015

doi:10.5539/apr.v7n4p1 URL: http://dx.doi.org/10.5539/apr.v7n4p1

Abstract

Black holes are *hot*. Heating of the ultra-dense core of a black hole by incoming particles of interstellar matter is sufficient to generate a quark-gluon plasma. This plasma, which can include particles ranging from photons, gluons, neutrinos and quarks to hadrons and beyond, could be regarded as the final product of the stellar collapse that led to formation of the black hole. Because the energy of neutrinos inside a black hole is quantized and the number of levels between the core and the event horizon is finite, excess neutrinos must either react with the core or escape through the event horizon. The escaping neutrinos could be among the high-energy neutrinos that have been detected by the IceCube experiment.

Keywords: Black hole core, gravitational collapse, gravitational potential well, heating of black hole core by incoming matter, high-energy neutrinos, quark-gluon plasma, the IceCube experiment

1. Introduction

A recent paper (Phillips, 2014) by the present author pointed out that the existence of a mathematical singularity at the centre of a black hole is ruled out by the Heisenberg uncertainty principle. Looking a little deeper, one finds that the problem is not in the mathematics that led to the idea of a singularity, but in the physical model to which the mathematics was applied, a model which predates current awareness that a quark-gluon plasma can be formed from particles that collide at very high energy (Peressounko & Pokrovsky, 2000; Jacak, 2001; Fries, Greco, & Sorensen, 2008; Petráň, Letessier, Petráček, & Rafelski, 2014; Müller, 2015) (Reader please note: the study of the quark-gluon plasma is a very large and active field, and these references are representative of a list that would be longer than the present article.) A process in which particles of matter disappear into a genuine mathematical singularity of zero dimensions effectively involves collisions at infinite energy, which is another reason for believing that such a process cannot occur. It follows that, as stated in Phillips (2014), the centre of a black hole must be occupied by a spheroidal lump or core of ultra-dense matter. We can now add that the ultra-dense core is likely to consist of a very hot quark-gluon plasma.

In the same paper it was also shown that fermion neutrinos inside a black hole occupy a finite number of energy levels between the black hole core and the event horizon, which means that any excess of neutrinos over twice the number of energy levels available must either be absorbed into the core or escape via the event horizon. It is not supposed to be possible for anything to escape from a black hole through the event horizon except as one half of a short-lived pair of virtual particles, but in fact quantum mechanics provides the means, in the form of an extended wave function plus the Pauli exclusion principle, for a neutrino or other light particle to pass through the barrier erected by classical General Relativity.

The temperature of a black hole has generally been considered to be very low — lower even than that of the background radiation left over from the Big Bang. However, the calculation of the intensity of Hawking radiation (Hawking, 1974), from which the black hole temperature is derived, presumes the existence of a working mathematical singularity at the centre of the black hole and consequently does not consider either the ultra-dense core that is the engine-room of the black hole or the mass-energy that is conveyed to the core by incoming particles of interstellar matter. As noted above, the incoming mass-energy will eventually be either absorbed into the core or radiated from the black hole in the form of a flux of high-energy neutrinos, a process that is likely to be fast in comparison with the generation of Hawking radiation but in absolute terms is still quite slow. Because these processes are slow, the temperature of the black-hole core must be very high. The steady-state temperature will depend upon the heat capacity of the ultra-dense matter in the core, which can probably be estimated on the basis of the law of Dulong and Petit, and on the balance between the inward flow of interstellar matter through the horizon, and the sum of the rate of escape of energetic neutrinos in the opposite direction plus the rate of absorption of interstellar matter into the core. The balance will be somewhat dependent on where the black hole is located in the universe. The discussion in the next section leads to the conclusion that the temperature achieved will be sufficient to generate a quark-gluon plasma that could be a source of very high-energy neutrinos, such as those reported by the IceCube collaboration (Aartsen et al., 2013). The high temperature might also have something to do with the high value of black hole entropy that is an uncomfortable feature of current theory (Carroll, 2004) but that topic is outside our present field of interest.

2. Some Numbers

In Phillips (2014), potential well depths were estimated for individual fermion neutrinos of rest mass ~ 0.2 eV in the gravitational fields of black holes of sizes from 10^2 to 10^8 solar masses. The calculated well depths ranged from 10^{44} to 10^{50} kJ, values that appear very large and which become even more impressive when converted to units of GeV with the aid of the table at the back of the book by Misner, Thorne and Wheeler (Misner, Thorne, & Wheeler, 1973). The present note considers the kinetic energy that is acquired by neutrinos, electrons or neutrons when they fall into these gravitational potential wells and is converted to other forms when the fall is halted at or near the surface of the massive core. Because of the likelihood of scattering of incoming particles by matter previously captured by the well but not yet incorporated into the core, the entire energy of the well-depth might not be available for plasma generation, but the energies involved prove to be so large that this does not affect our conclusions. The well-depth calculations in Phillips (2014) were semi-classical estimates rather than relativistic predictions because they were intended to provide qualitative insight rather than precise numbers, and the same qualification applies here. Fortunately the enormous magnitude of the energies involved ensures that great precision is not required. Also, for simplicity, at present we consider only Schwartzschild black holes.

Table I. Estimated potential well depths for different combinations of incoming particles and black hole masses expressed as a multiple of the solar mass. Also shown are r_{core}, the radius of the black hole core (dependent upon arbitrary assumptions about the core density (Phillips, 2014)), $r_{horizon}$, the radius of the Schwartzschild event horizon, and n_{levels}, the number of energy levels between the event horizon and the core (Phillips, 2014).

Particle	Black hole *msuns*	Well Depth *GeV*	r_{core} *km*	$r_{horizon}$ *km*	n_{levels}
neutrino	10^2	6.0 (74)	1.52 (2)	2.95(2)	5.1(68)
“	10^4	1.3 (77)	4.81(2)	2.95(4)	1.6(66)
“	10^6	2.3 (79)	1.52(3)	2.95(6)	3.8(63)
“	10^8	4.0 (81)	4.81(3)	2.95(8)	8.9(60)
electron	10^2	1.2(70)	1.52 (2)	2.95(2)	4.25(33)
“	10^4	2.6(72)	4.81(2)	2.95(4)	1.28(31)
“	10^6	4.6(74)	1.52(3)	2.95(6)	3.06(28)
“	10^8	8.1(76)	4.81(3)	2.95(8)	7.25(25)
neutron	10^2	6.0(69)	1.52 (2)	2.95(2)	2.97(18)
“	10^4	1.3(72)	4.81(2)	2.95(4)	9.24(15)
“	10^6	2.3(74)	1.52(3)	2.95(6)	2.26(13)
“	10^8	4.1(76)	4.81(3)	2.95(8)	5.24(10)

[Note: 6.0(74) = 6.0 x 10^{74}].

Table I lists values of the calculated well depth in GeV and related data for various incoming particles and black-hole core masses. The well depths were calculated with the same computer program that was used in Phillips (2014). The particles were arbitrarily chosen to be neutrinos of rest mass 0.2 eV and initial speed 10^6 m/s, electrons of rest mass 5.11 x 10^5 eV and initial speed 100 m/s, and neutrons of rest mass 9.396 x 10^8 eV and initial speed 10 m/s. The initial speeds are basically irrelevant inside the potential wells, because the particles become relativistic. The black hole masses were set at 10^2, 10^4, 10^6 and 10^8 times the mass of our sun.

The top quark, which is by far the heaviest of the known quarks, has a mass-energy of 175 GeV (Veltman, 2003) which is smaller than the well depths in Table I by a factor of the order of 10^{70}. The energy threshold for forming a quark-gluon plasma by collision of a pair of relativistic lead nuclei is less than 2.76 TeV per pair (Mischke, 2013), which is also very small on the scale of Table I. Thus even a particle as light as a neutrino, falling into a black hole's gravitational well and being halted abruptly by collision with the massive core, is capable of generating a quark-gluon plasma at the site of the collision. Energy-transfer collisions within the core, at the core's surface, and to a lesser extent within the event horizon will result in a thermal distribution of neutrinos over the available energy levels at a temperature approaching that of the quark-gluon plasma, which is typically stated to be ~ $3x10^{12}$ K. As a result, some of the neutrinos inside the event horizon will be much more energetic than average and these are the ones that are most likely to escape from the top of the well with assistance from wave mechanics and the Pauli principle.

The existence of a very high temperature at the core of a black hole will not be obvious to observers outside the event horizon because photons and most other particles cannot escape through the horizon, and must simply add their mass-energy to the black hole's core. However, the flux of high-energy neutrinos leaving the potential well should be observable from great distances with a neutrino telescope. It can occur because most if not all neutrinos are fermions (Dolgov, 2008) that can fill the energy levels inside the well to levels above the event horizon, and it is quite likely that such a neutrino flux has already been detected by the IceCube collaboration (Aartsen et al., 2013).

Neutrinos are ideal test particles for probing a black-hole core because their occupancy of energy levels in a potential well is strictly limited by the Pauli exclusion principle. Neutrinos can perform effectively as remote thermometers because they are able to overflow the close-spaced energy levels at and above the event horizon and so become available for interrogation by neutrino telescopes. Black holes appear to play a major role in stabilizing galaxies, but evidently we do not have to worry about them evaporating as long as there is plenty of inter-stellar matter available to be captured. As far as the present note is concerned, further work is needed to make the well depth calculations properly relativistic and to treat Kerr black holes, but the qualitative conclusions that black hole cores are very hot, that their gravitational potential wells are likely to be over-filled with neutrinos, and that energetic neutrinos can escape via their event horizons, are unlikely to change as a result.

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