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Black Holes: Some Facts and Fancies

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Although I intend to leave the description of this empire to a particular treatise, yet in the meantime I am content to gratify the curious reader with some general ideas.[1]

Gulliver's Travels

Imagine that you hold in your hand a small marble which is about one centimeter in size and has a mass of a few grams. Now take a mass about twice that of the earth's and magically transform it to the ultimate state of collapsed matter, and you would have a black hole about the size of the marble. Were such magic possible, the possessor of that marble-sized black hole would indeed have a memorable experience. That small a black hole would not only have a mass twice that of the earth's but it would also have intense tidal forces of gravitational origin that would destroy the hand which tried to hold it. Furthermore, all those nuances of color and light which make many marbles attractive would disappear since no light comes or is reflected from a black hole. However, we are getting ahead of our story and hasten to add that no such magical transformation is possible. The very existence of black holes has not been conclusively demonstrated. Nevertheless, the concept of them forms one of the most interesting recent areas of scientific research.

Black holes are thought to exist in, and to contribute to, conditions which are far removed from those we commonly experience. Despite their unusual nature, black holes are thought to be interspersed throughout interstellar space and have properties so bizarre that a discussion of them sounds like science fiction. However, the concept of black holes did not originate in science fiction,

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[1]Jonathan Swift, *Gulliver's Travels*, volume 36 of *Great Books of the Western World* (Chicago: Encyclopedia Britannica, 1952), p. 27.

but as a consequence of well-accepted scientific theories which have given excellent descriptions of nature in less extreme situations. A detailed description of black holes requires the precise language of mathematics in the context of Einstein's General Theory of Relativity. Nevertheless, many properties can be described in qualitative terms and thus may be of interest to all persons desiring knowledge of the "bounds set to the heavens or . . . the sun, moon, or stars" (D&C 121:30).

In some cases, a black hole may merely be the remains of a dead star. For many years it has been known that the source of the enormous energy release of the sun, and presumably of other stars, is thermonuclear fusion. Nuclear fusion is the process by which the nuclei of light elements such as hydrogen, helium, etc., are "burned" (i. e., combined) into heavier elements such as carbon, oxygen, iron, etc., thereby releasing enormous quantities of energy. As this "burning" proceeds and the nuclear fuel is consumed, the star ages. A star may age in a number of ways. For a particular star, the most important parameter for determining its evolutionary course—insofar as it is currently possible to compute this evolution—is its mass. Chemical composition and rotation rate also play important roles.

Without pausing to discuss the various stages of stellar evolution, we focus our attention on the end. Some stars die in spectacular fashion by becoming supernovae, in which massive explosions disrupt the stars, and pour out great quantities of hot gases and radiation of all types. They literally go out with a bang. In some cases a collapsed, compact core is left behind. It is possible that these collapsed stellar remnants may also be formed without such massive display, though at present there is no consensus among the experts as to the details leading to stellar collapse. Despite our lack of knowledge concerning the precise details, examples of collapsed stars abound and may be observed with telescopes.

These collapsed stars come in at least two, and probably three, varieties. The most common class is a white dwarf, so called because of its high temperature (white hot) and its very small size (approximately that of the earth). These burned-out stars have a mass approximately equal to that of our sun and thus a density about a million times that of ordinary rock. A white dwarf star is prevented from further collapse by pressure due to electrons, if its

[2]For more detailed scientific studies see Roger Penrose, "Black Holes," *Scientific American* 226 (May 1972):38-46; and Kip S. Thorne, "The Search for Black Holes," *Scientific American* 231 (December 1974):32-43.

mass is not larger than about 1.2 times the mass of our sun. If the stellar remnant has a mass greater than this, but still less than about three times the sun's mass, then the mutual gravitational attraction is so strong that the electrons are squeezed into the protons, forming neutrons and resulting in what is called a neutron star. A neutron star is tiny indeed by stellar standards, having a size about ten miles across, yet having a mass about that of our sun. Consequently such a star would be more than a million million times more dense than ordinary rock.

What happens when the mass of the collapsed star exceeds three solar masses, the upper bound for the mass of a neutron star? In this third case, no force known to scientists—not even neutron pressure—is sufficient to prevent further collapse into a black hole. Black holes may perhaps be formed in other ways, but the importance of the collapse process lies in the fact that well-established laws of nature essentially demand the existence of black holes. Let us examine some of their properties as predicted by theory.

FANCIES

When I found myself on my feet, I looked about me, and must confess I never beheld a more entertaining prospect.[3]

Gulliver's Travels

The only types of black hole solutions of Einstein's equations presently known are symmetric around the axis of rotation. If a black hole is not rotating, then it is also spherically symmetric. Theory tells us that the only parameters characterizing black holes are mass, charge, and angular momentum, and that we cannot expect them to have a certain fixed number of neutrons, protons, and electrons as does everything we see about us such as a star, a chair, or even the sheet of paper these words are printed on. Independent of how they may have formed, when two black holes have equal mass, charge, and angular momentum we must consider them to be identical in every respect, despite the fact that one may have formed from pure radiation and the other from a collapsing sphere of neutrons. In the following, only uncharged black holes are considered.

The size of a black hole is directly proportional to its mass. A black hole with the mass of our own sun would be approximately two miles in diameter. However, one should not think of the outer "surface" of the black hole as a material surface. There is not

[3]Swift, *Gulliver's Travels,* p. 9.

anything there that one can touch with a finger or any other measuring instrument. The outer surface of a black hole is an intangible surface which divides space into two regions. Any events taking place inside this surface will never be seen in any way by an observer outside. For this reason the surface is called an "event horizon." The event horizon acts as a one-way membrane. Light beams, material particles, etc., can pass inward through the horizon—but nothing ever comes out.

This event horizon can also be characterized in another way. Think of a lantern which emits light in all directions and hence can be observed from any direction. Let this lantern fall along a straight line toward the center of a black hole (radial infall). In the neighborhood of the black hole, some light emitted by the lantern is captured by the black hole. Figure 1 depicts the uniform emission of light in all directions by a lantern as it approaches the surface of a black hole. The blackened part of the circle indicates those directions of emissions for light which will end up captured by the black hole and can never be seen at infinity. Thus we see that as the lantern approaches the black hole, increasingly fewer emission directions allow the light to escape. Precisely at the surface of the black hole the cone of escape closes down to nothing and all light emitted by the lantern is captured by the black hole, irrespective of the direction of emission. The lantern at the surface of the black hole be-

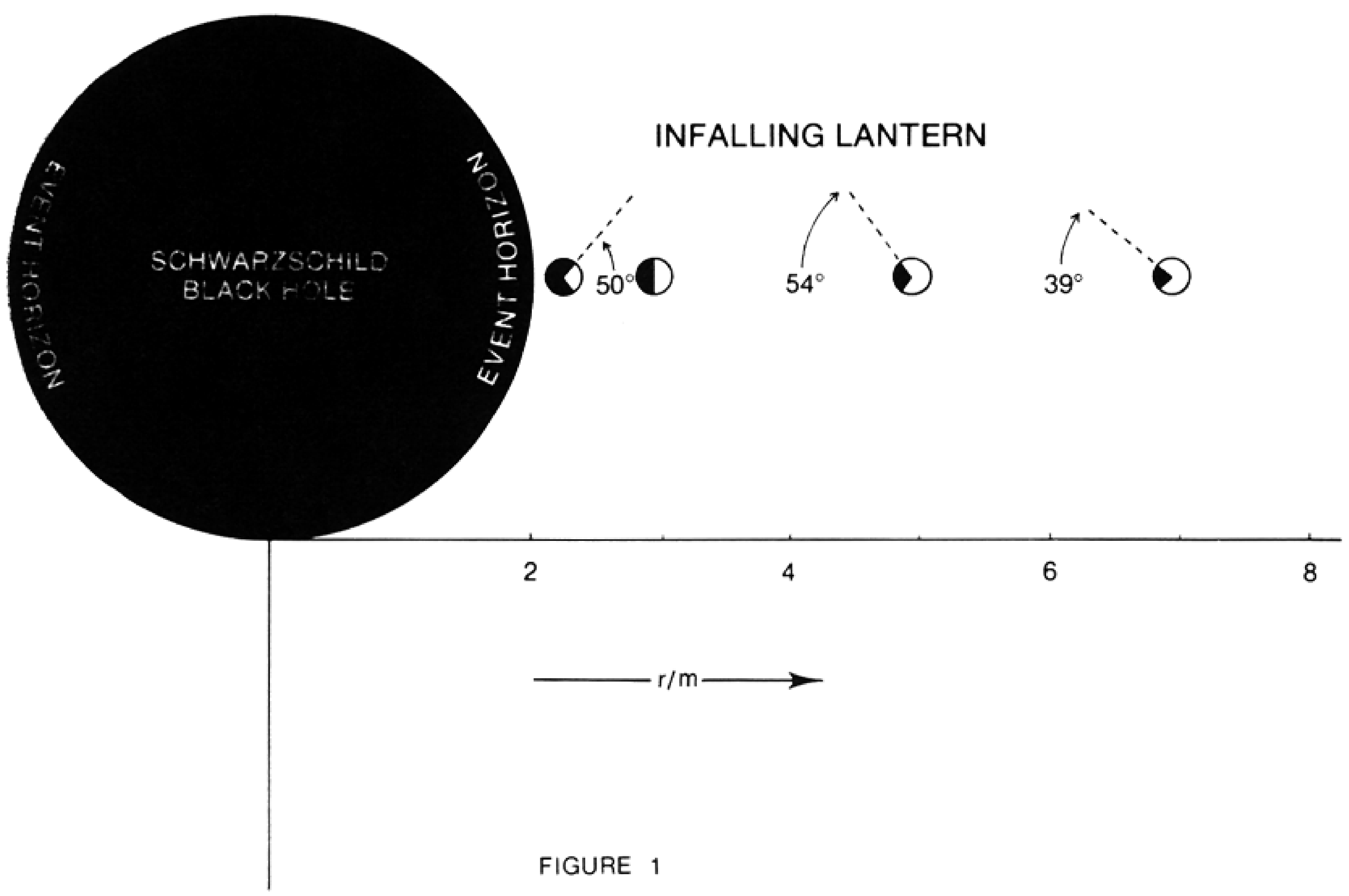

FIGURE 1

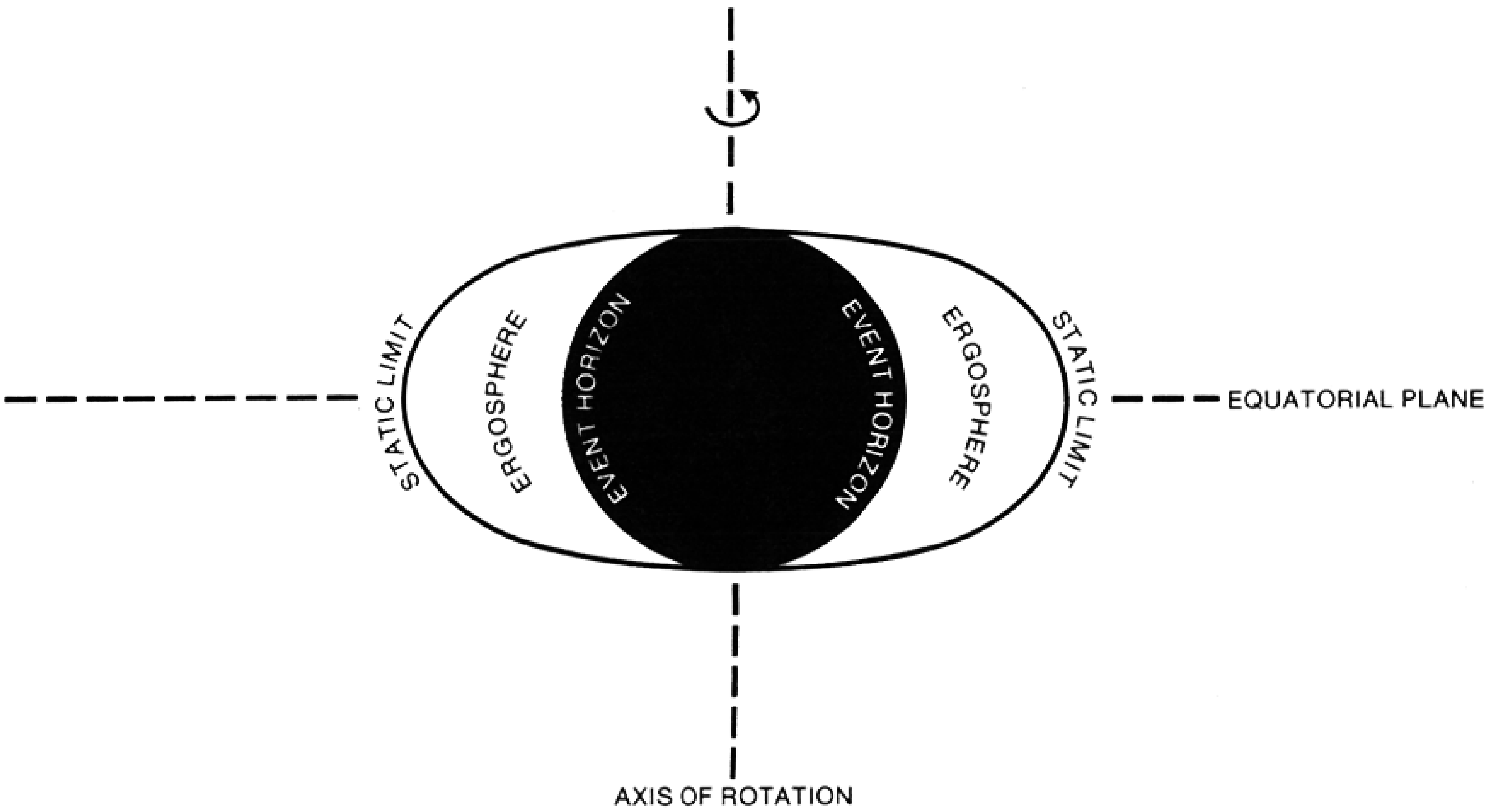

FIGURE 2

comes invisible to distant observers as does any other light source. Not only does this offer another characterization of the event horizon but also explains the "black" in black holes.

When black holes are rotating and consequently have some angular momentum, another intangible surface appears which is of some importance. This surface is called the static limit and the region between the static limit and the event horizon is called the ergosphere (*ergo* meaning energy). The relationship between the ergosphere, the static limit, and the event horizon is depicted in Figure 2. The actual separation of the static limit and the event horizon depends on how much angular momentum the black hole has. The maximum separation in the equatorial plane is just the radius of the event horizon.

The static limit can also be characterized by considering the so-called "dragging of inertial frames." Consider an object, like our lantern, falling radially into the black hole. As it nears the black hole, the hole's powerful gravitational field tends to drag the object around in the hole's direction of rotation. If the falling object had powerful rocket motors attached to it, the thrust of these motors could be used to control and maintain radial infall—until the object reached the static limit. At this surface no rocket motor, no matter how powerful, could hold the object to radial infall; it would be irresistibly dragged around in the direction of the black hole's rotation. In other words, rocket motors could be used to hold an object motionless outside the static limit, but not inside.

Within the static limit, in the ergosphere, it is possible for an incoming particle to split and have one fragment captured by the black hole and the second leave with more energy than the original particle had initially. Through this mechanism, called the "Penrose Process," it is possible, in theory, to extract the rotational energy of a black hole. Since this energy can be on the order of 50% of the total energy in a black hole, even more energy than is available in thermonuclear fusion could be extracted—however, only in principle.[4] The mechanisms imagined to date require so much energy to make the Penrose Process operable, that this extraction process is thought to be astrophysically unimportant.

Could an astronaut explore the event horizon of a black hole? The answer to this question depends on the magnitude of the tidal forces which exist at the event horizon and consequently on the mass or size of the black hole. Tidal forces at the event horizon are inversely proportional to the cube of the radius. Consequently, the smaller the size of the black hole, the stronger the tidal forces at its surface. The tidal forces at the surface of a one solar mass black hole would pull an astronaut apart and completely destroy all his equipment, whereas, an astronaut could pass through the event horizon of a black hole with the mass of a billion suns without noticing any effect.

If the black holes emit no visible light and we can't go near any to explore them, one is tempted to conclude that black holes are doomed to remain in the world of theory. Not true!

FACTS

If the censure of Yahoos could any way affect me, I should have great reason to complain, that some of them are so bold as to think my book of travels a mere fiction out of mine own brain. . . .[5]

Gulliver's Travels

Even though a black hole isolated in space would very likely never be experimentally observed, we can expect many black holes to make themselves apparent in binary systems. Perhaps as many as 50% of all stars occur in binary or higher multiple star systems.

[4]All thermonuclear fusion processes together can release at most about 0.7% of the total energy in a star.

[5]Swift, *Gulliver's Travels,* p. xviii.

Since the rate of evolution depends on mass, the stars in many binary systems evolve at different rates. Thus we can expect to find binary systems where one stellar component is a collapsed star, and, in truth, many such systems are observed. For example, the familiar star Sirius consists of a normal star and a white dwarf. Consequently, many black holes may be expected to exist in binary systems as companions to visible stars. The question is how would such black holes make themselves evident? Certainly not by their own emitted light, since they are black. Also, there is no hope of observing a black disk against the background light of the companion star because the black hole is only about ten miles across and would intercept a negligible portion of the light from the visible star.

The binary nature of a great many stars is revealed only by a periodic variation in the light we receive from them, as the light from the brighter star changes its color slightly, due to its to and fro motion perpendicular to the plane of the sky as it moves around its dimmer, often unseen companion. Such stars are called spectroscopic binaries. A large fraction of binary pairs are also close binaries, so close, in fact, that the outer regions of their atmospheres may interact. If a black hole were to interact with the atmosphere of a stellar companion it is likely that large quantities of X-rays would be produced because the matter captured from the companion star is heated to high temperatures as it approaches the event horizon of the black hole. The energy for the X-ray emission comes from the large amount of gravitational energy released. Only for black holes or neutron stars is there enough gravitational energy available to produce X-rays.

Thus, the following scheme emerges: a binary star system is identified by the periodic variations in the light from the visible star. If this system is also observed to be an X-ray emitter then we can be reasonably certain that the unseen companion is a neutron star or black hole. In actual practice, the X-ray sources are discovered first and the attention of visual observers is then drawn to a certain region of the sky to discover the telltale optical variations.

The observations of the light from the visible companion alone allow one to derive a range of probable masses for both components of the binary system. If the range of possible values for the unseen component is above the upper bound for the mass of a neutron star, then we conclude that the unseen component is likely a black hole.

With the advent of X-ray telescopes in orbiting earth satellites hundreds of astronomical X-ray sources have been discovered. Some of these sources have been found to conform to the general features of a binary system as described above.[6] The current most likely candidate for a black hole is in the constellation Cygnus and is called Cygnus X-1. The black hole model of this system suggests that it consists of a giant yellow star of about thirty solar masses orbiting an unseen companion about eight times as massive as our sun. So far, the observations are all consistent with the hypothesis that the unseen companion is a black hole and, in fact, many observational details which are expected from such a system appear to be present.

There are, however, other models which have been constructed to explain the observations of Cygnus X-1 which do not involve black holes, although they appear at present to be more contrived and less likely explanations for the data. Nevertheless, one must bear in mind that the systems currently viewed as possibly containing black holes are unusual, and may be attributable to an uncommon combination of very ordinary physical effects.

On the other hand, the inevitability of black hole formation has been considerably strengthened in recent years, and the absence of black holes would be difficult to explain in light of our current understanding. Indeed, the recent astronomical X-ray observations offer hope that theory will be further bolstered by observational data. Regardless of whether these observations confirm current theoretical ideas or ultimately lead to revisions, the study of black holes promises insights into conditions never before imagined. Already it appears reasonable to conclude that black holes are more fact than fancy.

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[6]For an excellent discussion of the X-ray sources, see Herbert Gursky and Edward P. J. van den Heuvel, "X-Ray-Emitting Double Stars," *Scientific American* 232 (March 1975):24-35.