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The Mysteries of Black Holes

The very phrase “black hole” calls up in the popular imagination images of mystery, peril, and excitement. It is not uncommon in the realm of science fiction for the ominous and foreboding black hole to appear in the far reaching realms of space as a swirling vortex in which anything from complete destruction to time travel can occur if the brave space travelers are sucked into the maelstrom by the body’s powerful gravity. Clearly, black holes have become an intriguing concept in fiction, representing an aspect of the universe distinct and strange to that which is familiar on Earth. Nonetheless, the strangeness of black holes is not something unique to the film screen or the inventive pen of the imaginative writer. Black holes also tug on the imaginations of physicists as they try to delve deeper into the unexplained aspects of the universe. Though still theoretical in nature, black holes provide a new way of thinking about general relativity and quantum mechanics as well as provide an interesting example of how the laws of physics manifest themselves under extreme conditions.

Setting the Stage for Black Holes—Relatively Speaking

Black holes are celestial bodies of immense gravity. According to *The Encyclopedia Americana*, a black hole is "a region where gravity is so strong that nothing that enters it—not even a light ray—can escape" ("Black Holes" 34). This idea of the black hole is a direct result of Albert Einstein's General Theory of Relativity in which he fundamentally changes the way the scientific community views space and time, which is likewise the consequence of a revolutionarily new idea of gravity. The force of gravity, as any first year physics student can explain, is the result of mass multiplied by the acceleration due to gravity, 9.8 m/s^2. In most situations, this simple equation yields accurate results on a macroscopic scale. However, it was not until Einstein's General Theory of Relativity was published that the reasons behind the equation's results were understood.

In Einstein's book *Relativity: The Special and the General Theory*, the physicist sets up a hypothetical situation of a man in a windowless chest situated within the outlying regions of space. So far is this man in space that he is nowhere near any large celestial bodies which could exert a gravitational influence on the man such as the gravitational force one feels at the surface of the Earth. Attached to this chest is a hook and rope which pulls the chest upward at a constant acceleration. Einstein writes that "the acceleration of the chest [is] transmitted to [the man] by the reaction of the floor of the chest. [The man] must therefore take up this pressure by means of his legs if he does not wish to be laid out full length on the floor" (Einstein

76). Due to the upward force exerted on the chest, the man must stand upright inside of the chest much like a man standing on the surface of the Earth.

A curious man, Einstein's hypothetical character decides to test the physics of his world inside the chest by dropping objects. No matter what object the man drops, when it leaves his hand it will fall to the floor of the chest such "that the acceleration of the body towards the floor of the chest is always of the same magnitude, whatever kind of body he may happen to use for the experiment" (76); therefore, the man will "come to the conclusion that he and the chest are in a gravitational field which is constant with regard to time" (ibid). Of course, this is not the case. The man is far removed from any gravitational field and the acceleration that he observes is a direct consequence of the force the rope exerts on the chest. This leads to a startling revelation which Einstein calls "the law of the equality of inertial and gravitational mass" (77). That is, there is no difference between gravity and acceleration.

So if gravity is acceleration, what is the cause of gravity? Brian Greene in *The Elegant Universe* writes that "gravity, according to Einstein, *is* the warping of space and time" (Greene 67). Before Einstein, space and time were viewed as a static environment in which objects move. However, the implications of the General Theory of Relativity show that space and time are anything but static. Space time moves, twists, and curves in the presence of matter. In order to better explain this idea, Greene presents as an analogy to space time a bowling ball sitting atop a rubber membrane. When one places a bowling ball on a membrane, such as a trampoline, the membrane will curve, or warp, around the weight of the ball. Greene writes that

> "Using the rubber membrane-bowling ball analogy, if we place a small ball-bearing on the membrane and set it off with some initial velocity, the path it will follow depends on whether or not the bowling ball is sitting in the center. If the bowling ball is absent, the rubber membrane will be flat and the ball bearing will travel along a straight line. If the bowling ball is present and thereby warps the membrane, the ball bearing will travel along a curved path…if we set the ball bearing moving with just the right speed in just the right direction, it will…in effect, 'go into orbit.'" (Greene 69)

Just as the heaviness of the bowling ball changes the direction of the rolling ball bearing, so do large bodies in our solar system effect the movement of other bodies due to their massiveness. Greene writes that "the shape of space *responds* to objects in the environment" (ibid); that is, space time warps due to the presence of mass. For example, the Earth orbits the sun because the substantial mass of the sun warps space in such a way that the Earth's movement follows the path of the curvature. Mass warps space time, and this is the cause of gravity in the universe.

Within this framework, the idea of the black hole reemerges. In the context of general relativity, more mass results in a greater warping of space and thus a greater gravitational influence. Black holes take this correlation to a new level. Hawking in his book *The Theory of Everything* explains one instance of early theoretical evidence for black holes is that of physicist Subrahmanyan Chandrasekhar. Chandrasekhar, while contemplating the masses of stars, postulates that as stars decrease in size, they reach a point where the theory of relativity and the Pauli Exclusion Principle came into direct conflict. *The Encyclopedia Americana* explains that the Pauli Exclusion Principle "states that in a given atom no two electrons may share the same values for all four quantum numbers" and this principle is "valid for subatomic structures as well" ("Pauli, Wolfgang" 550). An important interpretation of this principle is that as a result of the four quantum numbers, a particle cannot share the same velocity and position.

At this point, Einstein's Special Theory of Relativity enters the discussion. Einstein writes that the speed of light "plays the part of a limiting velocity, which can neither be reached nor exceeded by any real body" (Einstein 41). Thus, particles are limited in how fast they can move and when this is considered in the context of Pauli's Exclusion Principle, particles are limited in relative differences of velocity. What Chandrasekhar realized, according to Hawking, is that when a "star got sufficiently dense, the repulsion caused by the exclusion principle would be less than the attraction of gravity" (Hawking 50). That is, the massive number of particles constituting the star would collapse inward due to the overwhelming force of gravity resulting from increasing density. The implications of this idea are astounding. Hawking suggests that it is possible that given enough mass, a star could theoretically collapse to a single point of infinite density (51). Such a point would wreak havoc on the surrounding space time continuum.

Since mass warps space time, the presence of an infinitely dense point would warp space time to such an extent that seemingly nothing could escape the gravitational field of the surrounding region. Hawking writes that "this region is what we now call a black hole" (54). Furthermore, such conditions create an environment in and around the black hole which are completely foreign to the environment of Earth, an environment in which strange phenomena of physics, impossible in the familiar, relatively mild warped areas of the universe, can occur.

<u>Freaks of Nature: Physical Properties and Weirdness of Black Holes</u>

On a macroscopic scale black holes can be described by two main features, the form of a rotating body and the event horizon. Stephen Hawking writes that following the logic of physicists such as Roy Kerr, Brandon Carter, and Hawking himself, “after gravitational collapse a black hole must settle down into a state in which it could be rotating but not pulsating. Moreover, its size and shape would depend only on its mass and rate of rotation, and not on the nature of the body that had collapsed to form it” (61). Thus, a black hole’s particular mass and rotation are completely identical to other black holes of the same mass and rotation. This assertion, based on mathematical calculations, provides respective uniformity within different subtypes of black holes.

The second uniform feature of black holes is the presence of an event horizon. The event horizon, as Brian Greene defines it, is “the one way surface of a black hole” that “once penetrated, the laws of gravity ensure that there is no turning back, no escaping the powerful gravitational grip of the black hole” (Greene 415). At the point of the event horizon, gravity becomes so powerful that not even light can escape. Of course, the gravitational field of a black hole does not start at the event horizon; it only reaches an insurmountable intensity at that point. In fact, even outside of the event horizon black holes exert a powerful warping on the space time continuum. Greene writes that the gravitational field of a black hole warps space time so much that it significantly slows the passage of time (80). Greene explicates this point by providing the hypothetical situation of an astronaut near the event horizon. Greene writes that “if you were to hover just above the black hole’s event horizon in this manner for a year…upon arrival at earth you would find that more than ten thousand years had passed since your initial departure” to the black hole (ibid). Amazingly, the warping of time due to a black hole provides a theoretical means for time travel into the future.

Aside from time travel, the event horizon also provides theoretical insight into the possibility of finding black holes. Because of the powerful gravity of black holes, matter will be dramatically accelerated towards the event horizon, an acceleration that increases as the object’s distance to the event horizon decreases. Hawking writes that as matter “falls toward the [black hole], it develops a spiral motion—rather like water running out of a bath—and gets very hot, emitting X-rays” (Hawking 65). These X-rays, emitted before the event horizon is reached, could possibly be detected from a safe distance from the black hole, perhaps even from regions surrounding or including Earth. For example, Hawking writes that the system called Cygnus X-1 is composed of a star orbiting an unknown partner and what is more, the system is also a strong source of X-rays (ibid). Such evidence suggests that the star of Cygnus X-1 is actually orbiting an unseen black hole.

Still, the question remains as to what actually happens to matter once it is sucked into a black hole. This inquiry brings up another major problem with black holes, which is related to entropy. Greene writes that according to the Second Law of Thermodynamics “the entropy of a system always increases” (Greene 334). This fundamental law of physics is important when considering black holes because it suggests that matter that enters black holes cannot simply disappear. If it did, it would mean that entropy decreased around black holes, violating the

Second Law. Jakob Berkenstein, as Greene writes, proposes the idea that "the only way to satisfy the Second Law of Thermodynamics would be for the black hole to have entropy, and for this entropy to sufficiently increase as matter is pumped into it to offset the observed entropic decrease outside the black hole's exterior" (335). This idea fundamentally changed the idea of the black hole's interior. Initially it seemed as if the gravity of black holes completely obliterated matter, but Berkenstein's assertion declared that black holes are not bodies of nothingness.

Berkenstein's idea is drawn from another theory proposed by Hawking concerning the event horizon. Hawking writes that the event horizon of a black hole is always increasing (Hawking 75), an assertion that is similar, according to Hawking, to entropy which is also always increasing (75-76). Logically, it follows that entropy and the ever increasing event horizon must be intimately related. Greene explains that Berkenstein linked these two ideas by declaring that "the area of the event horizon of a black hole provides a precise measurement of its entropy" (Greene 335). This realization of Berkenstein leads to another strange property of black holes; that is, as Hawking has coined, they aren't really "black."

The fact that black holes have entropy makes the name "black hole" a bit of an oxymoron. Hawking writes that "if a black hole has entropy, then it ought also to have a temperature" and "a body with a nonzero temperature must emit radiation at a certain rate" (Hawking 79). Therefore, since black holes have entropy they must also emit something in correlation with their temperatures. This realization was revolutionary to the thought of black holes. Traditionally, the idea was that black holes don't emit anything; they were "black," meaning that nothing could escape their powerful gravitational field. Now it is theoretically shown through entropy that black holes do emit radiation.

But what exactly are black holes radiating? The answer lies not in the realm of General Relativity which has dominated discussion so far, but is embedded in the microscopic world of quantum mechanics. Greene writes that according to quantum mechanics every particle has an "antiparticle partner—a particle of identical mass but opposite in certain other respects such as its electric charge" to the first (Greene 8); for example, the antiparticle of the electron, the positron, has the same mass as an electron but differs in having the exact opposite charge (ibid). The only difference between the positron and the electron is that the first is positively charged while the second is negatively charged. Due to quantum fluctuations in space, Hawking writes, pairs of particles can erupt and then annihilate one another (Hawking 82). This is a result of Einstein's famous equation $E=mc^2$, which shows that energy can be converted into matter. Still, matter created this way is nearly instantaneously annihilated, and due to the transient properties of these particles, Hawking refers to them as virtual particles. That is, they are particles, but due to their extremely short life spans under normal conditions they only virtually exist. The extreme environment of the black hole, on the other hand, provides anything but normal conditions, causing virtual particles to behave in strange ways that in turn account for the emitted radiation of black holes.

In the presence of the strong gravitational field of a black hole, virtual particles can actually split from one another. Hawking writes that

> "It is therefore possible, if a black hole is present, for the virtual particle with negative energy to fall into the black hole and become a real particle. In this case it no longer has to annihilate its partner; its forsaken partner may fall into the black hole as well. But because it has positive energy, it is also possible for it to escape to infinity as a real particle. To an observer at a distance, it will appear to have been emitted from the black hole." (83-84)

Virtual particles can be separated in such a way that particles are emitted from black holes. In this manner, black holes are able to emit radiation in congruence with their entropy and temperature associated with entropy. The Second Law of Thermodynamics is still valid for black holes, and the fact that black holes emit particles could, in the future, be a means of discovering the existence of black holes in the far reaches of space.

Conclusion

Theoretical thought on black holes has lead to great insight into the celestial bodies. Not only are they rotating regions of extreme gravity, but they also emit radiation, have temperature, and conform to the Second Law of Thermodynamics. What is more, as Hawking points out, the study of black holes in regard to radiation "was the first example of a prediction that depended on both of the great theories of this century, general relativity and quantum mechanics" (Hawking 91-92). This first blending of the two major theories of modern physics is of paramount importance since the two theories have currently been largely incompatible. Finding a way to merge general relativity and quantum mechanics could lead to valuable insight and discoveries in the realm of physics, and perhaps, this merging could come out of more study on the subject of black holes. No longer limited to science fiction, the search for black holes has become a facet of physics which seeks to uncover the hidden mysteries of the universe as well as unify the two leading theories describing the physical world.

Works Cited

"Black Holes." *The Encyclopedia Americana: International Edition*. Vol. 4. 2000. Print.

Einstein, Albert. *Relativity: The Special and the General Theory*. New York: Three Rivers Press, 1961. Print.

Greene, Brian. *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory*. New York: Vintage Books, 2000. Print.

Hawking, Stephen. *The Theory of Everything: The Origin and Fate of the Universe*. United States of America: New Millennium Press, 2002. Print.

"Pauli, Wolfgang." *The Encyclopedia Americana: International Edition*. Vol. 4. 2000. Print.