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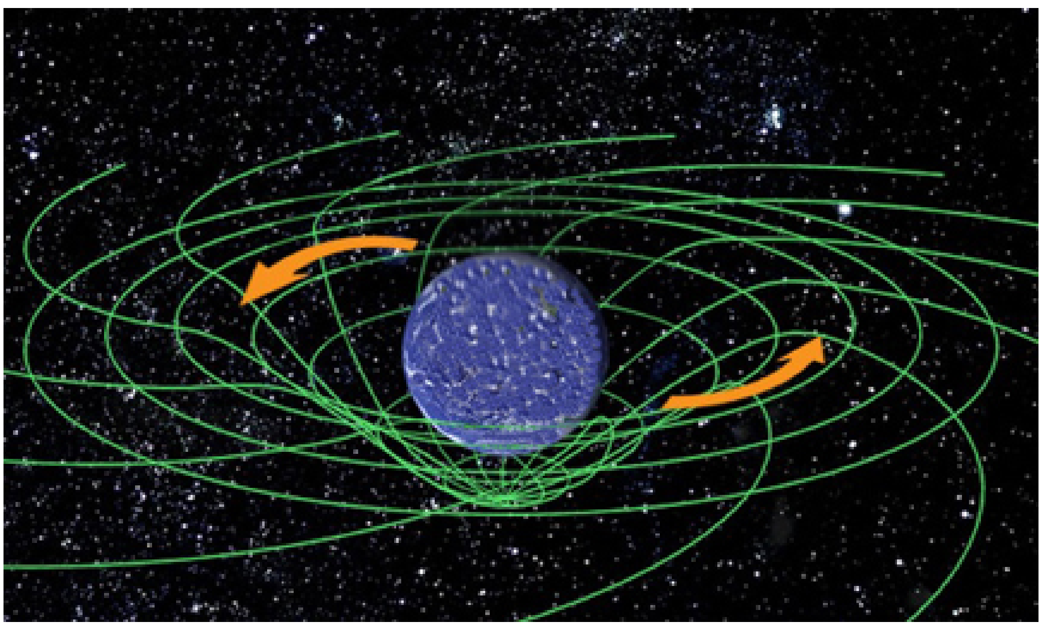
Honors University Physics II

Black Hole Formation and Primordial Black Holes as a Possible Source of Dark Matter

Black holes have been a source of mystery for as long as we have known of their existence. Studying black holes is a process of always reaching for what is just out of grasp. Traditionally, we use light from objects in space to learn about their composition and structure. Black holes are objects which are so dense that any electromagnetic radiation they emit is hopelessly sucked back in by the gravity of the mass itself. This means that we have no way of directly observing the mass that makes up a black hole. We can really only see the hole where light would have been. Despite the lack of observational data, researchers have been able to identify black holes and learn about their formation. Small black holes called primordial black holes are believed to have formed in the first few moments of the universe, and the distribution of small black holes throughout the universe is one possible explanation of how to account for the missing mass known as dark matter. A novel new method which analyzes the acoustic signature of stars will be able to detect the presence of a primordial black hole if it passes through a star. This would help prove the existence of primordial black holes, and help us estimate how many there are.

There are three main types of black holes, which fit into ‘weight categories’ – those which are formed from the explosion and subsequent collapse of a massive star, called stellar-mass black holes, smaller ones called Primordial Black Holes (PBH’s), which were formed in the first few seconds after the universe itself was formed, and supermassive black holes. Black holes in general are some of the most unique and mysterious objects in the known universe. They have gravity which is so strong that it bends space-time in the vicinity around it. By representing space-time as a sort of fabric, we can show that a mass creates an indention in the area around it, so that objects that approach close enough to a mass are drawn along the curve of space-time (See Figure 1). The force of gravity is dependent on distance from the source by a factor of $1/r^2$, so the force of gravity wanes greatly as the distance from the black hole increases. This fact has an important effect on matter near the black hole. The difference in the strength of gravity between separate points in space make it so that any matter which enters the vicinity of a black hole is torn apart due to what are called the tidal forces on the object (Pasachoff and Filippenko 2007).

Figure 1 – Gravity in the fabric of space-time (Rhawn 2010)



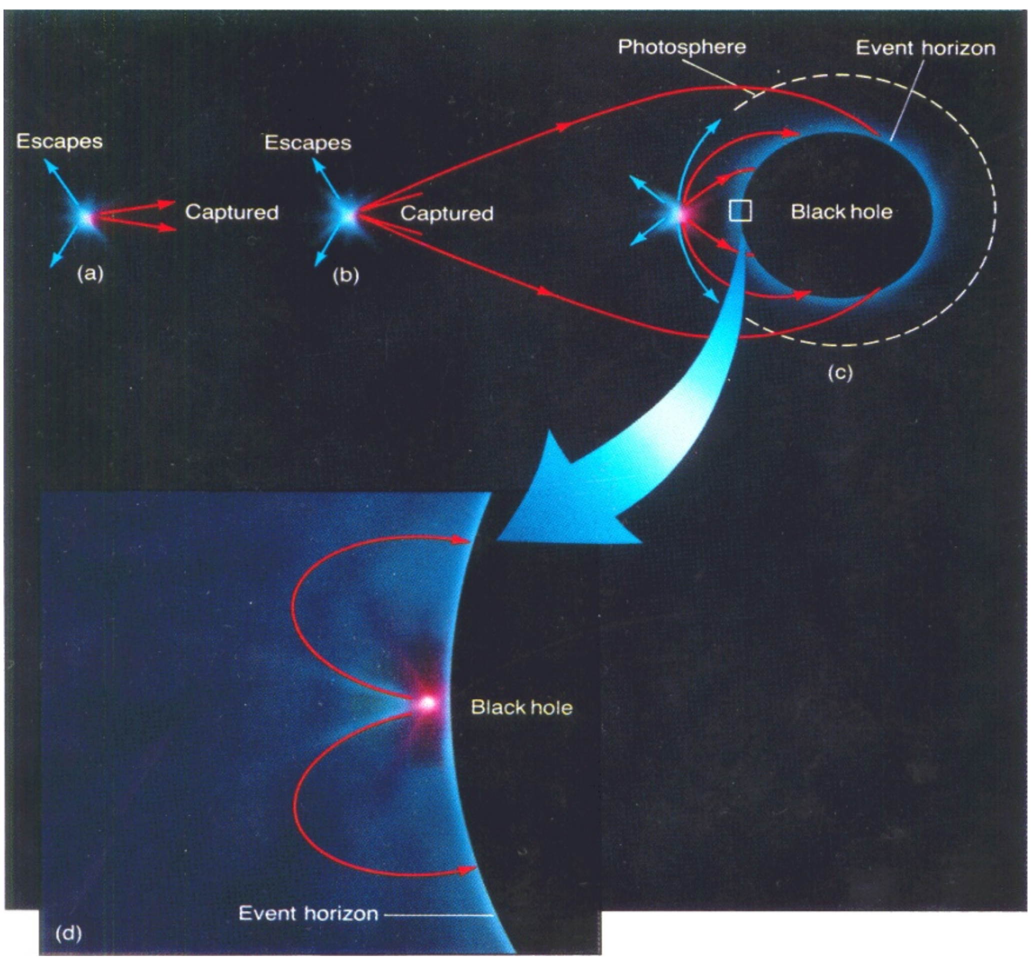
A black hole does not create an indention, but rather a bottomless well in the fabric of space-time, from which nothing can escape once pulled close enough. The warp in time means that if one were to observe a star collapsing to form a black hole, it would appear to stop collapsing at a certain point when time slowed enough that there was no more visible change. Since time slows as you approach the black hole, the positive direction of time is in the direction of decreasing radius, r; this means that time proceeds forward in the direction toward the black hole (Bouwhuis 2009). The black hole itself compresses until r = 0, and anything within the Schwarzschild radius which is not already at r = 0 must fall towards it (Bouwhuis 2009). When r is equal to zero, the center of the black hole is a singularity – one single point in space with no volume. One of the ways we know black holes exist is through gravitational lensing. Since gravity is strong enough to bend light, when a very massive object passes in front of a star one can observe a shift in the location of the star. The gravitational lensing of light by black holes has several effects on light in the vicinity of a black hole. As it collapses, any light shining from the star must be within a certain angle of the vertical in order to escape, creating what is called an exit cone. The exit cone grows smaller as the star collapses. Any light which shines exactly at the edge of the exit cone will not escape the star, but will enter into orbit around the star. The light which goes into orbit creates a light region around the collapsing star called the photon sphere. Light that shines farther from the vertical than this angle will bounce back onto the surface. Eventually, the gravity becomes too strong for even light perpendicular to the surface to escape, and no more electromagnetic radiation can be detected radiating from the black hole (See Figure 2). When the light from a black hole can no longer escape, the mass has shrunk to a certain radius which is known as the Schwarzschild radius. At this point, the escape velocity for any object within this radius would be greater than the speed of light. The Schwarzschild radius is given by:

$$R_S = \frac{2GM}{c^2}$$

In this equation, M is the

mass of the star, G is Newton's constant of gravitation, and c is the speed of light. The surface of the sphere with radius equal to R_S is the event horizon. The event horizon radius is exactly 2/3 that of the photon sphere (Pasachoff and Filippenko 2007). The more mass a star has, the larger the Schwarzschild radius will be. Although the Schwarzschild radius can be calculated for all stars, stars much less massive than our own sun would stop collapsing at the neutron star stage.

Figure 2 – Light around and inside a black hole (Rieke 2010)



A stellar mass black hole is one for which the mass is similar in magnitude to the mass of the sun after collapsing, for which the symbol $M_\odot$ is used. In the formation of a stellar mass black hole, a dying star undergoes a supernova explosion when it runs out of fuel for the nuclear fusion taking place in its core. As the supernova runs its course, the mass begins to collapse back in on itself. Usually this process comes to a halt when the electron or neutron degeneracy pressure of the collapsing mass balances out gravity (Pasachoff and Filippenko 2007). When electron or neutron degeneracy pressure can stop the collapse, it becomes a white dwarf or a neutron star. Black holes are formed when the degeneracy pressure of a star cannot stop the collapse under the force of gravity. If this occurs, the star continues to collapse through the stage where it would form a neutron star, and continues collapsing and becoming denser and denser. This happens when the mass remaining after the explosion is more than 2 or 3 solar masses.

Primordial black holes form when density perturbations existing in the very young universe collapse. This occurs when the self-gravity of the mass exceeds the support of the internal pressure (Kesden and Hanasoge 2011). According to Pasachoff and Filippenko, Stephen Hawking has deduced that small black holes evaporate over time due to the fact that they can emit energy from within the black hole in the form of elementary particles, finishing with a burst of gamma rays (Pasachoff and Filippenko 2007). In this way, primordial black holes serve as a sort of creator and destroyer of matter. It has been shown that particles and antiparticles can come into existence spontaneously, for a short duration of time, only to annihilate each other shortly thereafter. Similar to this manner, it is believed that primordial black holes strip elementary particles from their force of gravity and deposit the particles, stripped of their gravity waves, into the universe (Rhawn 2010).

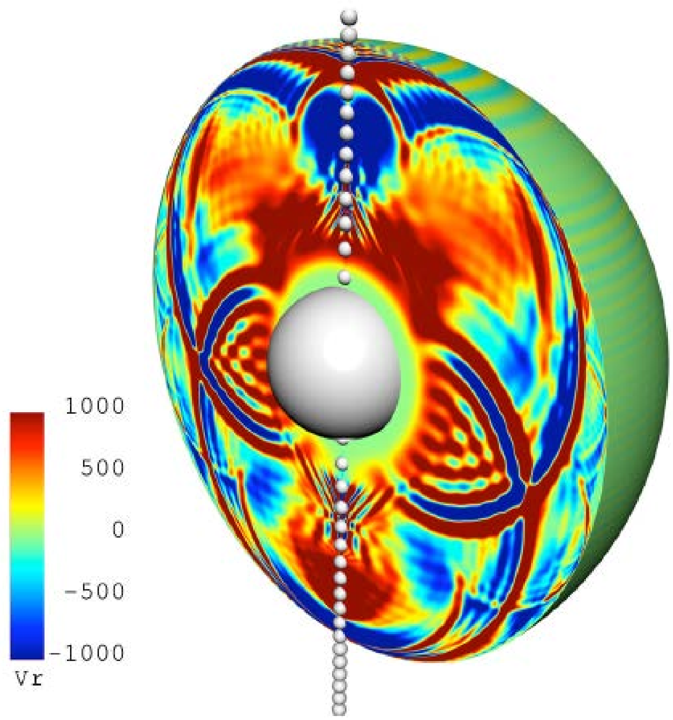
Supermassive black holes are formed by much larger masses undergoing collapse, those which contain millions or billions of solar masses, around the order of magnitude of $10^6 – 10^{10}$ $M_\odot$ (Kesden and Hanasoge 2011). These are formed in much the same fashion as stellar mass black holes. However, in black holes as massive as these, a much lower density is needed in order for a black hole to form; in some cases, the density would be close to that of water when the event horizon formed (Pasachoff and Filippenko 2007). Supermassive black holes exist in the nucleus of most galaxies, and the jets of gas which are excreted from the vicinity of supermassive black holes provide a source of observational data by which to study these objects (See Figure 3).

Figure 3 – Jets from the black hole in Centaurus A (Chandra X-Ray Observatory)

Dark matter is a term used to describe the large amount of matter present throughout the universe which emits no electromagnetic radiation, yet exerts gravity on the surroundings. Our own galaxy is found to be much more massive than all of the mass that we can see making up the Milky Way. We are aware that a larger amount of mass than we know of exists in the galaxy because of the galaxy's rotation (Pasachoff and Filippenko 2007). Often times, we see galaxies for which the gas and stars are moving so quickly that they would easily escape if only the observable amount of matter existed there. Some of this matter can be accounted for by dead stars, called white dwarfs. However, there are not nearly enough dead stars to account for this missing mass.

The distribution of primordial black holes throughout the universe has been suggested as a possible explanation for dark matter. If thousands of tiny black holes existed throughout the universe, it is possible that they could add up to a large amount of unaccounted for mass. One method of searching for the existence of these tiny black holes takes advantage of the fact that stars are for the most part unaffected by primordial black holes passing through them. The primordial black hole (PBH) loses a very small amount of kinetic energy, and the gravitational field of the black hole squeezes the star and causes a variation in the acoustic signature of the star (Kesden and Hanasoge 2011). In this manner, a star can serve as a sort of "seismic detector" for the passage of primordial black holes (Kesden and Hanasoge 2011) (see Figure 3). The different colors in the figure represent regions of varying radial velocity which would occur due to the passage of a primordial black hole through our Sun (Kesden and Hanasoge 2011). These simulations were run by using data collected about our sun; the global acoustic oscillations in the Sun are characterized by supersonic turbulence near the surface, which can be observed by examining solar absorption lines for Doppler shift (Kesden and Hanasoge 2011). These photospheric velocities are the background in which to search for the disturbance caused by the passage of a small black hole (Kesden and Hanasoge 2011). If this method allowed astronomers to positively identify the existence of a primordial black hole, it would help new discoveries be made regarding the study of dark matter, the Big Bang, and black holes themselves.

Figure 3 – Simulation of a Primordial Black Hole Passing Through the Sun (Kesden and Hanasoge 2011)



There are an outstanding number of theories which aim to find where the mass of dark matter might be hidden from the view of those scientists looking for it. Though scientists cannot directly observe dark matter, the fact that we can observe the effects it has on our universe make the study of dark matter one of great importance. Some theories suggest that black holes may connect with other black holes in our universe or other parallel universes and act as wormholes, passing matter through great distances through a sort of shortcut tunnel (Rhawn 2010). The correct term for a wormhole is truly “Einstein-Rosen Bridge,” (Pasachoff and Filippenko 2007). Another possibility for explaining dark matter is a theory which says that subatomic particles which are left over from the big bang which have not yet been discovered, called WIMPs, “weakly interacting massive particles,” (Pasachoff and Filippenko 2007). This is just another of countless theories which attempt to explain the mystery we call dark matter.

In conclusion, black holes have been and still remain to this day one of the most mysterious phenomena in the known universe. The properties of black holes are not fully understood, but can only be guessed at and studied indirectly by observing the interaction of black holes with matter in our universe. All different sizes of black holes might exist, with a few different ways of forming and multiple roles to play in the dance of objects in the night sky. Supermassive black holes, providing the gravity to hold together galaxies with millions of stars, are some of the most powerful objects in the universe. Stellar-mass black holes are also unique, exhibiting time and space dilations and energy conversion in ways not found in other celestial objects. Primordial black holes, with their mysterious origins in the early birth of the universe, provide even more possibilities for the types and roles of black holes. Dark matter is one of the greatest mysteries without which our universe would not hold together, and attempts to explain the phenomena are just guesses as to the real truth. Could small, bottomless wells of gravity in space-time formed in the early universe explain why we can’t see most of the mass which exists in the universe?

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