

Black holes and the LHC

S. Sahoo

Dept. of Physics, National Institute of Technology, Durgapur-713209, West Bengal, India.
sukadevsahoo@yahoo.com

Abstract

The life of a star is determined mainly by its mass. The more massive a star, the greater its energy output and the faster it evolves. That means a more massive star will die out faster than a less massive star. This goes against our common experience “the survival of the fittest”. Here, the fittest one is the less massive star. The three possible end stages of stars are white dwarfs, neutron stars and black holes. If the mass of the dying star is greater than $3.0 M_{\odot}$, the gravity becomes so strong that even light cannot escape from it. As a result, it becomes invisible. This is called ‘Black Hole’. Black holes are the end point of gravitational collapse, denser than white dwarfs or even neutron stars. In fact black holes are the densest objects in the universe. In this article, we have briefly discussed about black holes and their possibility of creation at the LHC.

Keywords: White dwarfs, Neutron stars, Black holes, LHC.

Introduction

In order to understand a black hole, first we should know about the life cycle of a star. A star is nothing but a huge mass of burning gas. The force of gravity prevents the gas from escaping from the surface of the star. The star remains in equilibrium under the action of two opposing forces i.e. gravity and outward pressure. Gravity tends to compress the star whereas the outward pressure tends to swell the star. If gravity dominates, the star collapses. If outward pressure dominates, the star expands. In stars, the internal pressure is due to the thermal motion of the atomic nuclei and electrons, and also the pressure of the radiation generated by the thermonuclear fusion reactions (Shapiro & Teukolsky, 1983; Resnick & Krane, 1992; Srinivasan, 1997; Venkataraman, 2002; Basu, 2004; Beiser, 2004). “Burning” in this context does not refer to the kind of burning we are familiar with, such as the burning of wood or coal, which is chemical burning. It refers to nuclear burning, in which the nuclei of smaller atoms (e.g. Hydrogen, Helium etc.) fuse into nuclei of heavier atoms. Since stars are of finite size, they will eventually use up their nuclear fuel and run out of energy by changing nuclei of one kind into nuclei of another kind.

When the star runs out of nuclear fuel and stops burning, the amount of heat production decreases inside it. So the gas pressure comes down while the gravity starts dominating. The star now starts shrinking under gravity till the density of matter rises to about 10^9 Kg/m^3 (million times that of water). According to English astrophysicist Fowler, when a star is crushed to a small size, a new kind of pressure called “degeneracy pressure” is produced due to quantum mechanical effects (Krishna Swamy, 1996). Degenerate pressure is produced mainly due to the degenerate (irratric) motion of electrons. This degeneracy pressure prevents the total collapse of the dead star and gives it a finite radius. What results then is a ‘White Dwarf Star’ (also called a *degenerate dwarf*).

The core of the white dwarf would have a variety of elements like hydrogen, helium, carbon, iron etc. Unlike gas pressure, degeneracy pressure is independent of temperature. Degeneracy pressure can exist even at the absolute zero temperature (Townsend, 1997). About 10% of the stars in our galaxy are white dwarfs. ‘White’ refers to the colour of the light it emits and the ‘dwarf’ refers to its small size. The maximum mass limit for the white dwarf was discovered theoretically by an Indian physicist, Prof. Subrahmanyan Chandrasekhar in 1930. This star cannot support masses above a certain value obtained as $1.4 M_{\odot}$, where M_{\odot} is the mass of the sun. This limit is known as *Chandrasekhar limit* (Venkataraman, 2002) and S. Chandrasekhar was awarded Nobel Prize in 1983 for this discovery.

For a core of mass $>1.4 M_{\odot}$, the electron degeneracy pressure is not sufficient to balance gravity and the star continues to shrink till its density rises to about 10^{14} Kg/m^3 . At this density, the electrons and protons start coming close to each other and combine to form neutrons (inverse beta decay). This is the beginning of formation of a neutron star. Star continues to collapse till its density rises to about 10^{17} Kg/m^3 . This is roughly the density of nuclei, at this density the entire core becomes a degenerate gas of neutrons. Thus, the star’s interior now almost entirely made up of neutrons, and some protons & electrons in its outer regions. Neutrons being Fermions can exert degeneracy pressure, and due to this pressure the collapse of this neutronic matter stops at some stage (Venkataraman, 2002; Beiser, 2004; Hazarika, 2005). At this stage, the star is termed as ‘*Neutron Star*’. Thus, the pressure of degenerate neutron gas balance gravity and get a neutron star provided mass of the core is not more than $3.0 M_{\odot}$. The radius of a neutron star would be around a few km (Table 1). A neutron star is smaller and

denser than a white dwarf. We have discussed black holes in the next section.

Table 1. End stages of stellar evolution

End states of stars	Mass range	Typical radius
White dwarf	$\leq 1.4 M_{\odot}$	$\sim 10^9$ cm
Neutron star	$1.4 M_{\odot} \leq M \leq 3.0 M_{\odot}$	$\sim 10^6$ cm
Black hole	$M > 3.0 M_{\odot}$	$2GM/c^2$ Schwarzschild radius

Black holes

If the mass of the dying star is greater than $3.0 M_{\odot}$, the contraction cannot be checked like either at the white-dwarf stage or at the stage of the neutron star. The contraction continues until gravity plays the dominant role. Gradually the gravity becomes so strong that even light cannot escape from it. As a result, it will become invisible. This is called 'Black Hole' (Krishna Swamy, 1996; Venkataraman, 2002; Beiser, 2004; Grandi & Palumbo, 2004; Hazarika, 2005). Black holes have three independent physical properties: mass, charge and spin. The shape of space and time around a black hole depends on the mass and spin (Hogan, 2007) of the black hole.

When a massive star contracts and passes the Schwarzschild radius ($R_s = 2GM/c^2$), it becomes a black hole, where G is the universal gravitational constant, M is the mass of the star, and c is the velocity of light in vacuum. The surface of a sphere of radius R_s around a black hole is called its event horizon. Nothing that occurs inside the sphere can be seen by outside observers. As a result, a black hole is completely dark to the outside world. Any matter or energy that passes too close to a black hole, within this critical distance (event horizon), is irresistibly drawn into the vertex of black hole. For $M = M_{\odot}$ (mass of the sun), $R_s \sim 3$ km. (A neutron star of same mass has $R \sim 10$ km.). Any object whose $R < R_s$, is collapsed to a single point, called *singularity* where the spacetime curvature becomes infinite. No known force in nature can resist this collapse to singularity with an infinite density (Kumar, 2009a,b). In order to understand this singularity we require quantum theory of gravity. Such a theory is not fully developed till now, though many physicists have suggested possible models.

Since a black hole absorbs all sorts of electromagnetic radiation, it is not possible to observe it through any optical telescope or radio telescope. The only manner by which they can be detected is by their strong gravitational interactions. A black hole which is a member of a binary-star system will reveal its presence by its gravitational pull on the other star. Further, due to strong gravitational pull, the black hole can suck matter from its companion star, which will be compressed and heated to such high temperatures that X-rays will be emitted. In 1970, the artificial satellite Uhuru was

launched to detect stellar sources of X-rays. Uhuru has found over 100 stars that give off X-ray. One of them is Cygnus X-1 in the constellation Cygnus. In 1974, it was designated as a black hole.

In 2001, astronomers (Baganoff *et al.*, 2001) confirmed that our Galaxy, the Milk Way, is revolving around a supermassive black hole, called *Sagittarius A**, which is about 2.6 million times more massive than the sun. This was the first black hole observed. Just after three years, in 2004, Jean-Pierre Maillard, an astronomer from the Institute of Astrophysics in Paris, France and his team (Peplow, 2004) observed a second black hole called *IRS 13* at the centre of our Galaxy. They declared that *IRS 13* is a rotating cluster of seven stars. Maillard told, "this is the first intermediate-mass black hole found in our Galaxy". Its mass is just 1,300 times mass of the sun. It spirals around *Sagittarius A** at a speed of 280 km/s.

Classically a black hole absorbs everything that comes too close and does not emit anything (Kumar, 2009a,b). Quantum mechanically, no such object can exist. In 1974, Stephen Hawking showed that quantum mechanically a black hole does emit thermal radiation which is called *Hawking radiation*. Black holes shine like black body with temperature inversely proportional to their mass.

Table 2. Different classes of black holes

Class	Mass	Size
Supermassive black holes	$\sim 10^5 - 10^9 M_{\odot}$	0.001 - 10 AU
Intermediate mass black holes	$\sim 10^3 M_{\odot}$	10^3 km $\sim R_{\text{Earth}}$
Stellar mass black holes	$\sim 10 M_{\odot}$	~ 30 km
Micro black holes (Mini black holes)	upto $\sim M_{\text{Moon}}$	upto ~ 0.1 mm

According to their masses there are four different classes of black holes: Supermassive black holes, Intermediate mass black holes, Stellar mass black holes, and Micro black holes (mini black holes) (Table 2), where 1 astronomical unit (AU) = 1.496×10^8 km.

Laws of black hole dynamics: There are four laws of black hole dynamics (Kumar, 2009b) in analogy with the four laws of thermodynamics. In black hole dynamics surface gravity and surface area of black hole are analogous with temperature and entropy of thermodynamics. The surface gravity (k) of a black hole is the acceleration of a test particle placed at the event

horizon. It is given by $k = \frac{GM}{R_s^2} = \frac{c^4}{4GM}$. The surface

area A of a black hole is the area of the event horizon: $A = 4\pi R_s^2 = 16\pi G^2 M^2 / c^4$.

(a) *Zeroth law:* The surface gravity at the event horizon of a stationary black hole is uniform at equilibrium.

(b) *First law*: The product of surface gravity and change in surface area of a stationary black hole is equal to increase in its mass i.e. $dM = kdA$.

(c) *Second law*: In any natural process, the surface area of the event horizon of a black hole always increases or remains constant; it never decreases i. e. $dA \geq 0$. Again if two black holes of surface areas A_1 and A_2 merge to form a new black hole of area A_3 , then $A_3 \geq A_1 + A_2$.

(d) *Third law*: It is impossible by any process, no matter how idealised, to reduce the surface gravity to zero by a sequence of operations.

Recent views about black holes

The eminent physicist Stephen Hawking was a pioneer of black hole theory in the 1970s. According to him the force of gravity inside the black hole is so strong that nothing, not even light itself, can escape. Hence, it is known as black hole. Any data about particles entering the black hole must be lost forever.

But quantum theory, which describes space and matter on very tiny scales, contradicts this. Quantum theory says any process can be run in reverse, so starting conditions can theoretically be inferred from the end products alone. This implies that a black hole must somehow store information about the particles that fell into it. Recently, Hawking's Cambridge University colleague Gary Gibbons says that an object falling into a black hole is not completely destroyed (Peplow, 2004). Instead, the black hole is altered as it absorbs the object. Although it is very difficult to retrieve any information about that object, the data are still there, somewhere inside the black hole. How would that information ever escape? The answer lies in one of Hawking's greatest discoveries: that black holes slowly evaporate into space by losing particles, called *Hawking radiation*. The black hole eventually shrinks to a tiny kernel, at which point radiation begins to leak out, potentially carrying the lost information with it. Finally, Hawking accepted this view and changes his mind about black holes.

In 2005, G. Chapline (Chapline, 2005; Ball, 2005), a physicist at the Lawrence Livermore National Laboratory in California thought that the collapse of massive stars, which was long believed to generate black holes, actually leads to the formation of stars that contain dark energy (Sahoo *et al.*, 2007). He claimed that "*It's a near certainty that black holes don't exist!*". Out side of a dark-energy star, it behaves like a black hole, producing a strong gravitational attraction. But inside, the 'negative' gravity of dark energy may cause matter to bounce back out again. Recently, in 2008, astronomers have found evidences that a supermassive black hole, having mass more than 4.0 million M_{\odot} , is located near the *Sagittarius A** region in the centre of the our Galaxy the Milk Way.

Black holes at the LHC

Gravitational collapse is not the only process to create black holes. Black holes can be created in high energy collisions. It is expected that the mini black holes would be produced in the Large Hadron Collider (LHC), the world's largest and highest-energy particle accelerator located at CERN near Geneva. Here, we briefly discuss the possibility of creation of different types of black holes at the LHC.

(i) *Primordial black holes*: In the early universe primordial black holes were formed. The mass of a black hole can be determined by using the formula (Sivaram, 2008):

$$M_{BH} = \frac{c^3 t}{8G}. \text{ For } t = 10^{-12} \text{ s}$$

(corresponding to LHC energies i.e. $T \approx 10^{17}$ K),

$M_{BH} \approx 10^{27}$ g i.e. around the mass of the earth. So primordial black holes of around the mass of the earth could have formed in the universe when the temperatures (energies) were several TeV (i.e. at $t = 10^{-12}$ s). We know that the total output power of our world is 10^{13} J/s. So in order to produce a primordial black hole 10^{20} years is required, which is 10 billion times the age of the universe. So it is not possible to produce a primordial black hole at the LHC.

(ii) *Hawking black holes of asteroid mass*: The mass of such black holes are $\sim 10^{10}$ kg. These were formed in the early universe when the temperatures were $\sim 10^{22}$ K (10^8 TeV), eight orders higher than the particle energies in the LHC. So it is not possible to produce such a black hole at the LHC.

(iii) *TeV mass black holes* (weighing $\sim 10^{-21}$ g): These black holes could be produced at the LHC. However, such TeV mass black holes decay very fast on time scales $\sim 10^{-24}$ s or less into a number of particles. So even if such black holes are produced, they would decay fast and not grow at all. Hence, there is no danger from such 'objects'!

The black hole is not yet conclusively observed. It is one of the greatest puzzles of astrophysics. The final and correct description of black holes requires a theory of quantum gravity (union of gravity and quantum theory), which is not fully established till now. It is expected that string theory (Schwarz, 2000; Sahoo, 2004; Vecchia, 2007; Sahoo, 2009) is the most promising candidate theory for a unified description of the fundamental particles and forces in nature including gravity, and in this sense be quantum gravity. Yet there is no direct experimental evidence that string theory is the fundamental theory of nature. This is widely considered

as one of the main goals of particle physics as well as astrophysics research for the next decade and beyond.

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