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The birth and death of a star

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ABSTRACT

Scientists believe that nearly 15 billion (15 x 10^9) years ago the universe originated in a huge explosion, called the 'Big Bang'. At the time of big bang, the size of the universe was just like a point and all matter, energy, forces were condensed into this point of zero volume and infinite density. Thus the big bang is the creation of everything - all space, energy, force, radiation and even time. The concept of time has no meaning before big bang. In this article, we shall try to explain how a star is born from the giant molecular clouds of hydrogen and helium. Then how a star is evolved and what is the ultimate fate of it. The end products of a star may be a white dwarf or a neutron star. But for a massive star, ultimately it may end up to a black hole by ongoing gravitational collapse.

INTRODUCTION

At the dawn of creation, the universe was a blaze of radiations. With the passage of time, the volume of the universe went on increasing and simultaneously temperature decreasing. The temperature after a milli-second of the big bang was 500 billion degree and within a day dropped to 40 million degrees. Thermal radiations due to light quanta prevailed over matter in the beginning. It took about one million years after the big bang for the universe to cool off sufficiently to make the densities of radiation and matter equal. Thus while the radiation dominated during the first million years only, matter has prevailed ever since. It was only after the transition from the regime of radiation to that of matter during the remaining life of the universe that the evolution of galaxies began to occur. At this stage, further expansion of universe made matter gravitationally more important than radiant energy and gave rise to first step in the differentiation of the originally homogeneous gas of hydrogen and helium. In other words, the universe now become cool enough to let the matter show its innate property of gravitation. This led to the formation of giant gaseous clouds- from which the galaxies and other constituent stars evolved by gravitational break-up of newly created clouds of hydrogen and helium.

THE BIRTH AND EVOLUTION OF A STAR

Our galaxy contains large clouds of gases

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containing mainly molecules of H, He, C, N, O, etc. These are called 'Giant Molecular Clouds (GMC)', which are not homogeneous in composition. It has regions of high and low densities. The higher density regions have tendency to become even more dense by gravitationally attracting surrounding matters. Thus a GMC becomes more and more inhomogeneous until it fragments into subunits that go their own ways separately. Due to gravitational contraction, potential energy of the cloud is converted into heat energy. A typical subunit contracts on its own until its interior heats up and starts radiating. The heat from the deep interior is converted outwards and then radiated away from the surface of the molecular cloud at a uniform temperature of about 4000 K. Thus a 'protostar' is born and it takes about one million years to reach this stage. The typical size of a protostar is about 10^6 times of the radius of the sun.

During the next phase, the gravitational contraction heats up the core of the protostar to a temperature high enough to trigger off thermonuclear fusion reactions, which burn hydrogen to make helium and release energy. Here the radiative transfer of energy outwards is more efficient than convective transport. The star's surface temperature rises significantly but its luminosity rises only slightly. The star then reaches a steady state in which energy lost due to radiation is balanced by that produced by thermonuclear burning of hydrogen. In the steady state, the inward contraction due to gravitation is balanced by outward pressure due to gas and radiation. This state of the star is called 'main sequence', which is the present state of our sun. The sun already remains in this state for last 5 billion years and will remain so for another 5 billion years, giving a total lifetime of 10 billion years. Any star spends 90% of its lifetime in the main sequence stage.

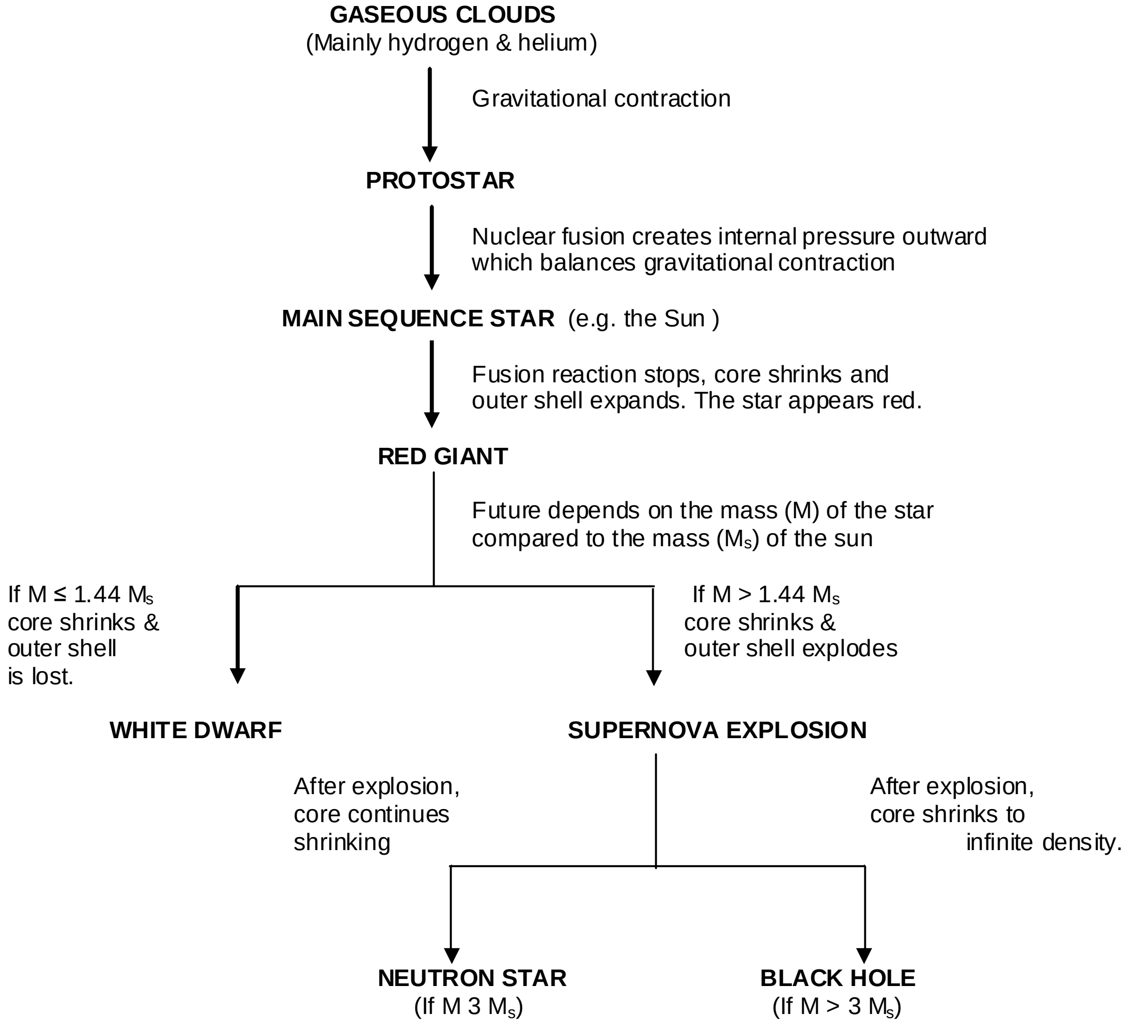
RED GIANT

Eventually, when most of the hydrogen in the star's core is burnt out, there is no longer enough fuel to provide the energy lost due to radiation. Gravitational contraction then resumes. Again compressional heating raises the core temperature. The outer layer of the star then expands and cool off, while the core shrinks. The star then appears red and due to its expansion, the outer layers become so large that, it is called 'red giant'. For example, after 5 billion years, when our sun will become a red giant, its radius will be about the radius of the orbit of the Jupiter. So one can imagine how big a red giant is!

THE DEATH OF A STAR

Of course the star does not stay as a red giant forever. After a while the core starts shrinking and once again a new stage of thermonuclear burning will be initiated. The helium gets ignited and produces carbon. Then when all helium are exhausted, core again shrinks and the carbon burning starts to produce oxygen. Different kinds of thermonuclear burn cycles are possible and at the end of each cycle, light elements become converted to slightly heavier elements through fusion reactions. The large the number of burning stages a star goes through, the greater is the variety of elements produced in the interior of the star. The fusion of the light elements to heavier elements proceeds till iron is formed in the core. Thereafter thermonuclear reactions are not possible on account of nuclear properties of heavier elements. When all the possible nuclear burning is over, the *star is dead.* The outward gas pressure and radiation pressure comes down and the gravitational contraction of the core starts again. The star now starts shrinking. Since the gas pressure and radiation pressure have practically disappeared and no more burning is possible, one would think that the dead star has no option but to go on shrinking and shrinking till it becomes a geometrical point! But this does not quite happen. So what is it that prevents this endless gravitational collapse?

The Birth and Death of a Star



WHITE DWARF

In 1927, an astrophysicist in England named Fowler said that when a star's core is crushed to a very small size, a new kind of pressure due to quantum mechanical effects is produced called 'electron degeneracy pressure'. This is a consequence of Pauli's exclusion principle, which prevents two electrons from falling into the same quantum state. This degeneracy pressure acts outwards and opposes gravitational contraction. The dead star does not shrink endlessly to disappear into a point, but the shrinking stops much earlier. What results is then an equilibrium state, known as 'white dwarf'. The density of the white dwarf is expected to be quite large, of the order of 10^6 gm/cc. This density is so large that one cup of white dwarf material will have weight more than that of 25 elephants put together.

S. Chandrasekhar in 1930 showed that, there is an upper limit to a star's mass, for the star to end its life as a white dwarf. He applied relativity theory to the degenerate star and came up with the result that, if a star had a maximum mass of 1.44 times the mass of the sun (M_s), then it would end up its life to a white dwarf. But if the mass is more than 1.44 M_s, then the 'electron degeneracy pressure' would not be able to halt further gravitational contraction. The limiting mass of a star is called 'Chandrasekhar Limit'. For this theory, Chandrasekhar was awarded Nobel Prize in Physics, much later in the year 1983.

White dwarf is small and so it is not easy to detect in the sky. However, in 1925, the American astronomer Walter Adams identified the companion of a binary star called Sirius. The two stars were revolving around each other. The path of Sirius was not a smooth curve as most stars did but it went on a wobbly path. From the wobble of Sirius, people could estimate that the companion star has a mass roughly equal to that of our sun. Adams identified this companion as white dwarf and named it Sirius-B. So far many more white dwarfs have been identified in the sky and all confirmed Chandrasekhar's theory that none of the known white dwarfs had a mass above the Chandrasekhar's Limit.

SUPERNOVA EXPLOSION

It is natural to wonder what would happen if a star with a mass greater than 1.44 M_s were to run out of fuel and start shrinking. When such a star starts rapidly collapsing, the interior gets heavily compressed and therefore also very hot. If the compression is sudden then the shock wave from the collapsed core bounce outwards blasting the outer layers of the star with neutrons and neutrinos. Thus a violent explosion called, 'supernova explosion', could take place, tearing off the outer layers of the star and sending the debris out into space. A sudden and huge increase in brightness in the sky is then observed. The brightness is such that it outshines all other stars in the galaxy and remains in the sky for many days.

How do we know stars explode? Well, people have observed such explosions and the most famous of these occurred in A.D. 1054. We find detailed record of that event made by Chinese astronomers. Till today astronomers in different parts of the world have observed nearly 100 supernova explosions.

NEUTRON STARS

When a star more massive than 1.44 M_s starts shrinking, the core of the star might be compressed so hard that the electrons are literally forced into protons and create a gas of neutrons. This would mean that the core could suddenly collapse to a density comparable to that of nuclear matter and release an enormous amount of energy in the process. So we have a stellar material which is almost entirely made up of neutrons at its core and some protons and electrons mostly in the outer regions. Now neutrons being fermions can exert degeneracy pressure, just like electrons in a white dwarf. So the collapse of this neutronic matter should stop at some stage due to such pressure. Such a star supported against gravity by the 'Neutron degeneracy pressure' is called a 'Neutron star'.

The criterion for the neutrons to become degenerate depends on their temperature and density, and hence on the mass of the star. Calculations show that for a massive star to end its life as a neutron star, its mass should not exceed 3 M_s. Although the value of this limiting mass is not very exact, because the nuclear physics of extremely dense matter is not very clearly understood. The density of matter in a neutron star is nearly 10^{14} gm/cc and the typical radius of a neutron star may be 20-30 Km only. Now how on the earth does one try to spot a tiny star like this billions of kilometers away?

PULSARS

The answer to the problem mentioned above came in 1967 when astronomers detected a new class of rapidly pulsating objects, later called 'pulsars'. The discovery of first pulsar by a research student named Jocelyn Bell of Cambridge by her radio telescope gave the first evidence of the existence of neutron star. The first pulsar, named CP1919 emitting faint radio waves in the form of highly regular pulses with a period of 1.337 sec., led to the conjecture that the source must be a rapidly rotating neutron star. It must be carrying an electrically charged atmosphere round it, and the charges beaming radiation in an ambient magnetic field. The radiation comes out of portion of the star's surface and the star is also rotating. So people said that what Bell had discovered was a 'heavenly lighthouse'.

It is now estimated that about 10^7 pulsars are present in our galaxy and these pulsars are nothing but rotating neutron stars. Confirmations came when astronomers were able to link pulsars directly to supernova explosions and give an estimate of how many supernovae go off in our galaxy. The frequency is once in 20-40 years. Although many questions still remain about pulsar structure and its evolution, the identification of pulsars with neutron stars seems clear. Thus we know that what happens to a star of mass about 3 M_s when it exhausts its nuclear fuel? But what about stars which are even more massive? We shall discuss now the fate of a star more massive than 3 M_s.

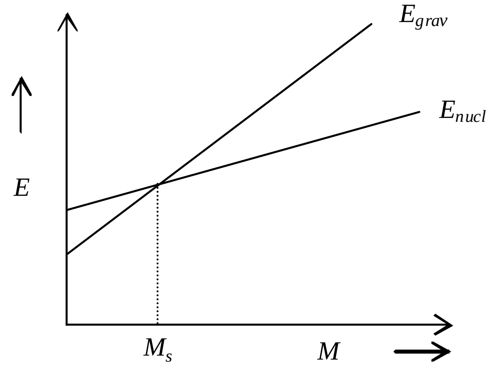
BLACK HOLES

It is a natural question - what happens to a star when it runs out of thermo-nuclear fuel? There are two possibilities –

(i) The end state is an equilibrium compact object (white dwarf or neutron star) supported against the force of gravity by a '*non-thermal source of pressure*' or

(ii) the star never reaches equilibrium and the end state is '*ongoing gravitational collapse*' leading to a *black hole.*

The second possibility must exist in nature because there is a maximum mass of non-rotating matter that can be supported against gravitational collapse by any kind of non-thermal pressure. A crude way of seeing why this happens is with the help of the concept of energy. We know that the gravitational energy of a body of mass M increases as M^2. The nuclear energy (or any other source of energy) within the body, on the other hand, is proportional to mass M. Therefore as we go on increasing the value of M, the gravitational energy ($E_{grav.}$) rises at a more rapid rate than does the nuclear energy ($E_{nucl.}$) (see figure below).



Hence in any scenario when equilibrium between two opposing forces is concerned, detail calculations show up a limiting mass MC with the following property:

For M < M_s it is possible for the gravity-opposing forces to generate strong enough pressure to maintain the body in equilibrium, but for M > M_s, it is impossible - it must lead to unhalted collapse.

The actual value of M_s depends upon what type of opposing force is considered relevant within the object. For example Chandrasekhar showed that the critical mass for the white dwarf stars is 1.44 M_s. When M > 1.44 M_s, collapse begins but finally it is halted again by neutron degeneracy pressure and the equilibrium end state is the neutron star. For neutron star, the critical mass is nearly 3 M_s. There are many stars more massive than this upper limit. It is likely that some must wind up in a state of ongoing gravitational collapse.

STELLAR MASS BLACK HOLE

The collapse of a massive star in supernova explosion can result in a 'stellar mass black hole'. The mass range for this type of black hole is 3 M_s to 20 M_s. When these are the members of binary star systems, they can be detected by their influence on orbit of the companion star and by the radiation from accretion disks that may be formed around them. Approximately two-third of all stars is members of binary pairs in which one star orbits another. In some of these binaries, a massive star may exhaust in its nuclear fuel and undergo gravitational collapse, producing supernova explosion. The explosion's remnant may be a binary system consisting of a compact object (a neutron star or a black hole) and a normal star. If the orbit is small enough, the normal star may shed material that falls onto the compact object, forming an accretion disk around the object.

Various dissipation mechanisms may cause the orbiting material in the disk to lose energy and slowly spiral deeper into the gravitational potential of the compact object. The released energy heats the inner regions of the disk to high enough temperatures that X-rays are produced copiously. A number of X-ray binary systems exist whose compact member has a mass above the upper limit for white dwarfs and neutron stars. These are presumed to be black holes. Observations of the X-ray binary source Cygnus X-1 is variable on all time-scales varying from months and years down to few milliseconds. The most dramatic variability is the 1-ms bursts, which set a maximum size for the X-ray binary source of $R<ct\sim300$ Km and establish the object to be highly compact, preferably a black hole. Similar few more X-ray binary sources have already been discovered.

SUPERMASSIVE BLACK HOLE

The deep gravitational potential wells at the centre of galaxies are natural sites of gravitational collapse. Galaxies may undergo collapse of their cores, endure collapse produced by merger with another galaxy or perhaps even be formed around black holes. The resulting supermassive black hole at the centre of galaxies range from 10^6 M_s to 10^9 M_s. There are convincing observational evidences for black holes at the centre of a number of galaxies that have been studied carefully, including our own galaxy, the milky way. There is a good evidence for a modest black hole of mass 3 x 10^6 M_s at the centre of our galaxy.

REFERENCES

1. Narlikar JV (1989). *The Frontier Between Physics & Astronomy.* McMillan, India.
2. Sapiro SL & Teukolsky SA (1983). *Black Holes, White Dwarfs & Neutron Stars.* John Wiley, USA.
3. Hartle JB (2003). *Gravity - An Introduction to Einstein's General Relativity.* Pearson Education
4. Srinivasan G (1992). *From White Dwarfs to Black Holes.* Universities Press.