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Role of Quantum Chromodynamics in Core-Collapse Supernova

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Abstract: ***This article examines the relationship between black holes, spacetime singularities, and the final stages of stellar evolution, with particular attention to the role of gravitational collapse and core-collapse supernovae. It outlines how a black hole eventually turns into singularity under conventional models. The discussion proposes that quantum chromodynamics may play a limiting role during extreme gravitational compression and consequent high energy situation. The article questions the physical reality of the present concept on singularity. The paper broadly outlines the life cycle of massive stars, from nebula formation to main-sequence evolution and core collapse. It further explains the processes involved in type-II supernova explosions, including neutron formation, neutrino emission, and heavy-element synthesis. The study highlights how the special characteristics of the quantum chromodynamics, particularly the asymptotic freedom of quarks trigger the supernova explosion of a black hole.***

Keywords: Neutron Degeneracy Pressure; Quantum Chromodynamics; Black hole; Singularity; Core Collapse supernova.

1. Introduction

A Type-II core-collapse supernova explosion is the most dazzling and powerful cosmic event. At the last phase of its life cycle, a massive dead or cold star explodes as supernova. The explosion releases hot gases and dust that spread over in the interstellar space as nebula. Depending on the mass of the star, after the explosion, a neutron star or a black hole is formed as the supernova remnant. Presently it is believed that the remnant black hole ultimately collapses to a single point where all the mass of the black hole gets compressed. This is a point where the density of the star becomes infinity. This point is called 'Space-time Singularity' or 'Black Hole Singularity or simply 'Singularity'. It is believed that all the laws of physics break down at the point of singularity.[1]

As per the present concept, when a non-rotating and uncharged cold star collapses at or below its Schwarzschild radius, no natural force, not even neutron degeneracy pressure can stop its collapse and ultimately all the mass of the black hole converges to a singularity.

This idea of singularity is not at all congruent with the theory of Quantum Chromodynamics (QCD)[2]. QCD is a (relatively) newly developed branch of quantum physics that deals with 'Quarks' which are elementary particles of matter (along with leptrons) that play a crucial role in the structure of the universe and the forces that govern it. The Standard Model of Particle Physics has thrown new light on our understanding of quarks leading to the development of Quantum Chromodynamics. This article will i) present a mathematical model to determine the limiting mass beyond which a black hole will explode as a supernova and ii) examine the validity of the concept of (space-time / black hole) singularity from the perspective of the unique behavior and properties of the quarks and the QCD theory.

2. Effect of Degeneracy Pressures on Core-Collapse of a Cold Star

A star having mass up to the Chandrasekhar limit, i.e., around 1.44 MΘ or less, after exhausting all its nuclear fuel in its core (mainly hydrogen) will become a cold or dead star. There will be no thermonuclear reaction within the core of the star and its main sequence phase will end. The star will cool down and will get compressed. The hydrogen entrapped in its outer shell will be heated up. The volume of the star, particularly its outer shell will be increased greatly and it will become a red giant star. After its main sequence phase, the Sun will become a red giant and its expanded outer shell is likely to engulf our Earth. When fusion of all the residual hydrogen in its shell will be completed, in the absence of thermonuclear reactions, the red giant star will start cooling down and its volume will be compressed. Since at that stage only gravity is acting, the core of the star will start collapsing. Initially the collapse will be faster without any hindrance. However, as the core collapse continues, after a certain stage when the giant star will be sufficiently compressed, formation of electron degeneracy pressure (EDP) [3] will start inside its core. Its radius, by this time, will be reduced to a great extent. This newly created EDP acts outwardly and starts counteracting the gravitational compressive pressure of the star and the rate of collapse of the star's core diminishes considerably.

Electron degeneracy pressure is a kind of quantum mechanical pressure that is created inside the core of the star at its subatomic level. In normal condition, as per Pauli's Exclusion Principle, identical electrons (electrons having same quantum numbers, i.e., Principal, Azimuthal, Magnetic and Spin quantum numbers) cannot occupy the same energy state at the same time. But when the core of a star is collapsed immensely, its huge gravitational pressure will compel the identical electrons to occupy the same energy states violating the Pauli's exclusion principle. Such violation of the Pauli's principle will generate a quantum pressure EDP inside the core of the star. EDP increases as the gravity increases and more and more electrons will get degenerated. At a certain radius, the EDP will ultimately become equal to the gravitational pressure of the star and the star will become a pressure-balanced 'White Dwarf'. Radius of a white dwarf is comparable to that of the Earth. A white dwarf star can neither become a neutron star nor a black hole. There will not be a core collapse supernova of a white dwarf star. However, a white dwarf may eventually accumulate mass by the process of accretion from a companion star and thus after crossing the Chandrasekhar mass limit may explode as a Type-Ia supernova. At the end of its main sequence phase, expectedly after around 5 billion years, Sun will become a white dwarf star only; it can neither become a black hole nor explode as supernova.

A more massive star, which's mass is above the Chandrasekhar limit and up to the Tolman, Oppenheimer and Volkoff (TOV) limit (2.928 MΘ), its gravitational pressure will overcome the EDP and the star's core will continue to collapse. Massive stars, depending on their mass, will be able to fuse (in the sequence of) helium, carbon, neon, oxygen, silicon, etc. as nuclear fuel at different stages and (more massive stars) finally end up in producing iron core. When at the final stage iron is produced in its core, nuclear fusion process is stopped as fusion of iron is an endothermic reaction. When all its fuels get exhausted, iron core of the star collapses; the radius of the star is hugely reduced and its gravitational pressure will be amplified exponentially. Under the tremendous pressure of the gravity the electrons and protons in the star's core will be forced to merge, forming charge-less particle neutrons. This phenomenon is called 'Electron Capture'. During the electron capture, nearly mass-less particles 'neutrinos' are also formed along with neutrons and are released from the star and those neutrinos travel in the space absolutely unhindered. The star will become a sphere consisting mainly of neutrons. As the gravity will go on exerting compressive pressure, the identical neutrons, having the same (+ve or –ve) spin, will be forced to occupy the same energy states again violating Pauli's exclusion principle. The degenerated neutrons will give rise to another type of quantum pressure called Neutron Degeneracy Pressure (NDP) [4] inside the star's core. Neutron Degeneracy Pressure is analogous to the Electron Degeneracy Pressure. Newly generated NDP of the star will act against its gravity and will start to impede its core collapse. Again, at a certain radius, the NDP will neutralize the gravitational pressure of the star and the collapse of its core will be stopped. At that equilibrium condition the cold star will become a pressure-balanced Neutron Star.

At the TOV limit the star exhibits a unique characteristic; its gravitational pressure is equal to its NDP and at the same time its Escape Velocity attains the speed of light. So, the star becomes a neutron star as well as a black hole concurrently at the TOV limit. A star having mass beyond the TOV limit, while core collapsing, will become a black hole first and then, as there exists a positive difference between the gravitational pressure and the corresponding NDP at that particular radius at which it becomes a black hole, i.e., at its Schwarzschild radius, the black hole will continue to collapse further till it becomes pressure balanced and turns into a neutron star. Since at that juncture the escape velocity of the star is much more than the speed of light, the star is a black hole as well.

Presently accepted theory suggests that black holes so formed will continue to collapse as at that condition gravity will supersede the NDP and there will not be any force, classical or quantum, to counter it. The black hole will ultimately get compacted into a single point called 'singularity'. At singularity its volume will be near-zero and its density will be infinite. All the laws of physics, it is believed, will cease to exist at that point.

3. Theory of Quantum Chromodynamics and its implication on Supernova Explosions

The quantum chromodynamics, however, does not corroborate the existing concept on singularity. A black hole cannot attain a zero size of infinite density as the quantum chromodynamics binding energy of neutrons has a definite value and the core collapsing black hole will ultimately explode at a much higher radius before attaining a near-zero volume. Concurrent formation of a neutron star and a black hole, as mentioned earlier, will continue only up to a specific limit. The maximum value of mass of such black hole cum neutron star is 7.14 MΘ. Beyond this limit, i.e., for cold stars having mass 7.15 MΘ and above, all black holes will ultimately explode as supernovae. The underlying theory behind this astounding astronomical phenomenon can be explained as enumerated below.

Theory of Quantum Chromodynamics as well as the study of quarks has advanced considerably since it was first proposed by physicists Murray Gell-Mann and George Zweig in 1964. QCD plays an important role in modern physics, particularly in formulating the latest version of the Standard Model of Particle Physics. Advancement in particle accelerators and detection technologies have helped scientists to probe deeper into the structure of matter, leading to new discoveries of sub-atomic particles and a better understanding of the universe.

Quantum Chromodynamics (QCD), in a nutshell, is quantum field theory (analogous to quantum electrodynamics, QED) that deals with the strong force which is responsible for holding elementary particle quarks (basically fermions) together within baryonic hadrons (proton, neutron) mediated by the 'Gluons' (gauge boson). There are six flavours (types) of quarks (up, down, charm, strange, top, bottom). According to the QCD, quarks and gluons carry 'colour charge'. Colour charge is one of the distinctive properties of QCD which is unique and it has no connection with the actual colours of light spectrum. The colour charges, that are related to the strong force that bind the quarks together, are present in both quarks and gluons particles in Red, Blue and Green. QCD stipulates that only colour-neutral combinations of quarks can exist as free particles protons and neutrons. Gluons mediate to bond the quarks. Quarks have other properties – mass, (electric) charges and spin, like electrons. However, unlike electrons, quarks possess fractional charges (2/3e +ve or 1/3e -ve). 'Quark Confinement' and 'Asymptotic Freedom' are two (among others) significant characteristics of QCD. The property of quark confinement ensures that at normal (or low) energy condition quarks remain confined in the hadrons and never be observed as free particles. Asymptotic freedom defines that at extreme high energy states quarks behave almost like free particles, with the strong force becoming ineffective. It is the property of asymptotic freedom of quarks that is responsible for the supernova explosion.

QCD binding energy deals with the mass and kinetic energy that bind the various quarks together inside hadrons. Core of a black hole is composed (predominantly) of neutrons. The QCD binding energy of a neutron is about 927.7 MeV [5]. Beyond this energy the neutrons will be disintegrated into free quarks as stipulated in the property of asymptotic freedom of the QCD theory. Particle accelerators (like Large Hadron Collider built by CERN) generate such huge amount of energy in the laboratory. In nature such enormous energy is released when a black hole explodes as Type-II core collapse supernova.

Just before its core collapses, escape velocity of a black hole, which is already more than the speed of light, increases further. Its gravitational energy, which is an intrinsic property of a star, also increases with its diminishing volume. As the gravitational energy of the black hole approaches its enormous QCD binding energy, which is in the order of E+48 Joules, the quarks, elementary constituent particles of hadrons (in this case neutrons), which otherwise remain confined in the hadrons in the low energy condition, start showing signs of asymptotic freedom at such high energy scenario. When the radius of a black hole of mass 7.15 MΘ becomes as less as 6414.2 meters after core collapsing, value of its gravitational energy attains the value of 1.262E+48 Joules. This particular value of gravitational energy equals the QCD binding energy of the black hole having mass of 7.15 MΘ at that particular radius. It may be noted that the QCD binding energy of a black hole is directly proportional to the number of neutrons of the star (in other words, the mass of the black hole), and is independent of its radius (volume). The QCD binding energy of a black hole of 7.15 MΘ is constant at 1.262E+48 Joules. When the gravitational energy of the black hole of 7.15 MΘ reaches this value, the quarks get disintegrated from the neutrons; become absolutely free thus triggering the breakdown of the star's core that leads to the supernova explosion of the black hole. During the supernova, as all the neutrons break up into quarks, tremendous amount of energy is released that lit up the outer space outshining the sun for a certain period; huge amount of hot gases and cosmic dust are also ejected into the interstellar space that create nebulae. A supernova in a nearby galaxy can be visible even in naked eyes from the earth. In most cases, a neutron star or a (smaller mass) black hole is created as supernova remnant. Rarely a whole black hole falls into pieces and gets totally annihilated forming nebulae. Nebulae are the birth places of stars. So, it can be said that supernova completes the life cycle of a star.

Thus, we find that Quantum Chromodynamics has an important role to play in supernova explosions. It also logically suggests that since a black hole of a particular mass is exploded as supernova at a particular radius, there is no possibility of becoming a (black hole) singularity.

4. Mathematical Representation of Core Collapse Supernova

Calculations presented in this paper are based on the following assumptions
1) The stars are cold (dead) and non-rotating.
2) Density of the cold stars remains constant while collapsing.
3) Accretion / companion star scenario has not been considered.

The cold stars rotate and their densities also vary while collapsing; however, with those conditions the results will marginally vary following the same pattern. In these calculations only Schwarzschild black holes have been considered.

Values of different constants used in the calculations are:
G, Universal gravitational constant = 6.67E-11 m^3.kg^-1.s^-2
Solar mass, MΘ = 1.989E+30 kg
Velocity of light = 3E+08 m.s^-1
Reduced Planck constant, ђ = 1.055E-34 J.s
Mass of neutron, Mn = 1.675E-27 kg
Number of neutrons = Nn

Abbreviation used here are:
c = velocity of light (m.s^-1)
f = multiplication factor to the solar mass to arrive at the mass of a star
R = Radius of the star (m)
Gr. Pr. = Gravitational pressure (kg. m^-2)
NDP = Neutron Degeneracy Pressure (kg. m^-2)
EV = Escape velocity (m.s^-1)
Gr. B.E = Gravitational binding energy (J)
QCD B, E = Quantum Chromodynamics binding energy (J)

Following formulae have been used in the table:
Escape Velocity = (2*G*M/R)^(1/2) kg.m ^-2
Gravitational Pressure = (1/5)*(G*M^2)*[{π*(4/3)}^(1/3)]*{V^-(4/3)} kg.m^-2
Neutron Degeneracy Pressure = {π^3*ђ^2/(15*Mn)}*[{3*Nn/(π*V)}^(5/3)] kg.m^-2
Gravitational Binding Energy = (3/5) * (G * M^2) / R Joules
QCD Binding Energy = 927.7 * 1.602 * 10^-13 * Nn Joules
Schwarzschild radius = (2*G*M)/c^2 m.
Gravitational Binding Energy = (3/5) * (G * M^2) / R Joules
QCD Binding Energy = 927.7 * 1.602 * 10^-13 * Nn Joules

Table 1

f	Radius (m)	Gr. Pr. (kg.m^-2	NDP (kg.m^-2)	EV (m.s^-1)	Gr. B. Energy (J)	QCD B.E (J)	Remarks
2.0	9805.72	5.449E+33	5.449E+33	232632592	6.458E+46	3.53E+47	Neutron Star
2.9287	**8634.2176**	**1.944E+34**	**1.944E+34**	**3E+08**	**1.573E+47**	5.169E+47	**NS & BH (TOV Limit)**
3.0	8844.42	1.852E+34	1.794E+34	3E+08	1.611E+47	5.295E+47	Black Hole
3.0	8568	2.103E+34	2.103E+34	304800872	1.663E+47	5.295E+47	NS also BH
6.0	17688.84	4.631E+33	1.78E+33	3E+08	3.222E+47	1.059E+48	Black Hole
6.0	6799	2.122E+35	2.122E+35	483891965	8.383E+47	1.059E+48	NS also BH
7.0	20636.98	3.402E+33	1.065E+33	3E+08	3.759E+47	1.235E+48	Black Hole
7.0	6457.99	3.548E+35	3.548E+35	536284991	1.201E+48	1.235E+48	NS also BH
7.11	20961.275	3.298E+33	1.011E+35	3E+08	3.818E+47	1.255E+48	Black Hole
7.11	6423.45	3.74E+35	3.74E+35	541933419	1.246E+48	1.255E+48	NS also BH
7.12	20990.757	3.289E+33	1.006E+33	3E+08	3.824E+47	1.257E+48	Black Hole
7.12	6420.9	3.756E+35	3.756E+35	542422068	1.25E+48	1.257E+48	NS also BH
7.13	21020.238	3.279E+33	1.001E+33	3E+08	3.892E+47	1.258E+48	Black Hole
7.13	6418.16	3.773E+35	3.773E+35	542918701	1.254E+48	1.258E+48	NS also BH
7.14	21049.72	3.27E+33	9.968E+32	3E+08	3.834E+47	1.260E+48	Black Hole
7.14	6417	3.786E+33	3.786E+33	543348400	1.258E+48	1.260E+48	NS also BH
7.15	21079.20	3.261E+33	9.922E+32	3E+08	3.84E+47	1.262E+48	Black Hole
7.15	6414.2	3.804E+35	3.803E+35	543847427	1.262E+48	1.262E+48	SN Explosion
7.15	6413	3.807E+35	3.807E35	543898307	1.262E+48	1.262E+48	Already Exploded
7.16	21108.68	3.252E+33	3.807E+32	3E+08	3.845E+47	1.2637E+48	Blach Hole
7.16	6423	3.793E+35	3.786E+35	543854663	1.264E+48	1.264E+48	SN Explosion
7.16	6411	3.822E+35	3.822E+35	544363414	1.264E+48	1.264E+48	Already Exploded
8.0	23585.12	2.605E+33	6.823E+32	3E+08	4.296E+47	1.412E+48	Blach Hole
8.0	7176.5	3.039E+35	2.616E+35	543856039	1.412E+48	1.412E+48	SN Explosion
9.0	26533.26	2.058E+33	4.608E+32	3E+08	4.833E+47	1.5884E+48	Black Hole
9.0	8073.6	2.401E+35	1.766E+35	5438544776	1.588E+48	1.588E+48	SN Explosion
10.0	29481.4	1.667E+33	3.243E+32	3E+08	5.37E+47	1.765E+48	Black Hole
10.0	8970.6	1.945E+35	1.243E+35	543856797	1.765E+48	1.765E+48	SN Explosion

Black holes having mass below 7.15 MΘ, as shown in the above table, will become pressure balanced neutron stars and at that condition their respective values of gravitational energy is less than the QCD binding energy and therefore there cannot be any supernova explosion of those black holes.

The above table also shows that a cold star of mass **7.15** times the solar mass, while core collapsing, when attains a radius of 6413 meters will simultaneously become a black hole and a neutron star. However, before that, at the radius of 6414.2 meters, the gravitational energy of the star will reach the value of its QCD binding energy (1.262E+48 J). At that extremely high energy condition, the constituent quarks of the neutrons will become free. The neutrons will be disintegrated and the black hole will explode as a supernova. All stellar black holes of mass above 7.15 MΘ will explode as supernova.

5. Conclusion

From the discussions and the mathematical calculations presented above, following conclusions are drawn.

1) The cold stars of mass up to the Chandrasekhar limit, i.e. 1.44 MΘ, will become white dwarfs. Stars in the mass range the 1.44MΘ and TOV limit 2.928MΘ will settle as neutron stars. Stars below the TOV limit mass cannot become black holes. More massive stars, i.e., cold stars having mass more than TOV limit and up to an upper limit of 7.14MΘ will, after core collapse, become black holes first and subsequently as their gravitational pressures will balance their respective neutron degeneracy pressure at specific radii, will become stable neutron stars. In fact those stars will finally become black holes and neutron stars as well.
2) Black holes having mass beyond the TOV limit (2.928MΘ) and up to the maximum mass of 7.14MΘ will finally settle down as neutron stars; there won't be any supernova explosion of these cold stars as values of their gravitational energy will remain less than those of their respective QCD binding energy at the respective radius when black holes turn into neutron stars.
3) At 7.15MΘ, neutron degeneracy pressure of the black hole will approach to its gravitational pressure; however, as its NDP becomes equal to its gravitational pressure, the gravitational energy of the black hole at radius 6414.2 meters will attain the value of its QCD binding energy (1.262E+48 Joules) and consequently the black hole will explode as a core collapse (Type-II) supernova.
4) All the stellar mass black holes having masses above the 7.15MΘ will also explode as supernova.
5) Quantum chromodynamics has a direct role on supernova explosions. The characteristic of asymptotic freedom of quarks, as stipulated in the QCD, is the main cause of disintegration of the neutrons at extremely high energy scenarios that activate the explosion.
6) Black holes of mass 7.15MΘ and above will explode as core collapse supernova before becoming stable neutron stars. A star more massive than 7.14MΘ cannot become neutron star.
7) There is no possibility that a black hole, upon core collapse, will reduce its volume to size zero and become a 'Singularity'. Much before a black hole becomes a singularity, its gravitational energy will become equal to its QCD binding energy and as per the characteristic of

asymptotic freedom of the quarks, as laid sown in the QCD theory the quarks will be disintegrated from the neutrons and the black hole will explode as a supernova. So, it can be said that the concept of singularity is not convincing idea.

Black holes and core-collapse supernovae remain closely linked through the processes that govern the death of massive stars. General relativity provides a framework for understanding gravitational collapse and the formation of event horizons, while nuclear and particle physics offer insight into the behavior of matter under extreme conditions. The possibility that quantum chromodynamics may impose limits on unlimited collapse presents an alternative viewpoint to conventional singularity models and invites further theoretical and observational investigation. A deeper understanding of these mechanisms will contribute to a more complete picture of stellar remnants, black-hole evolution, and the fundamental laws that shape the universe.

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