Indian Journal of Advanced Physics (IJAP)
ISSN: 2582-8983 (Online), Volume-5 Issue-2, October 2025

Calculation of the Radius of a Black Hole Just Before Its Supernova Explosion

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***Abstract:** When a stellar-mass black hole, while collapsing due to its own gravity, reaches a particular radius at which both its gravitational binding energy and quantum chromodynamic binding energy become equal, it explodes as a core-collapse supernova. Its outer shell, which is comparatively less dense than the compact core disintegrates in the explosion releasing gas and stellar dusts (and huge amounts of energy) in the galactic space that forms a nebula. The explosion leaves behind a dense core, a supernova remnant, either in the form of a neutron star or a (smaller) black hole. Since a black hole does not emit light or any electromagnetic radiation, it is impossible to directly measure the size of the black hole before exploding. A mathematical model has been developed for calculating the radius of the black hole just before and presented in this article. It has been mathematically proved that black holes explode when they reach a specific escape velocity (much higher than the velocity of light); and that the value is constant for all the black holes. Also, when a black hole explodes, the value of its mass multiplied by its 'acceleration due to gravity' attains a particular value which is also a constant. This constant value is the same for the intermediate-mass and supermassive black holes also. Further, the ratio of the Schwarzschild radius of a black hole and the radius just before its explosion as a supernova is also a constant which is the same for all types of black holes irrespective of their mass.*

***Key-words:** Core-Collapse Supernova; Escape Velocity; Neutron Degeneracy Pressure; Gravitational Binding Energy; Quantum Chromo-Dynamic Binding Energy.*

Abbreviations:
QCD: Quantum Chromo-Dynamics
NDP: Neutron Degeneracy Pressure

I. INTRODUCTION

A core-collapse supernova is the most luminous celestial phenomenon. At the later stage of its life cycle, a stellar-mass main-sequence star becomes a gigantic red supergiant star. When all the remaining nuclear fuels (hydrogen, helium, etc.) get exhausted from their outer shells, there will be no atomic fusion. The supergiant star starts cooling down, and its radius will begin shrinking. Initially, the collapse of the core of the star is relatively rapid, as there is no force to counter the gravity of the supergiant. However, when its radius is drastically reduced, it no longer remains a supergiant or a giant star.

Manuscript received on 23 May 2025 | First Revised Manuscript received on 05 June 2025 | Second Revised Manuscript received on 17 September 2025 | Manuscript Accepted on 15 October 2025 | Manuscript published on 30 October 2025.
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Its degeneracy pressures, initially electron degeneracy pressure and then neutron degeneracy pressure, start countering its gravitational pressure. The degeneracy pressures are sort of quantum mechanical pressures that build up at the sub-atomic level of the star, defying Pauli's Exclusion Principle due to the star's enormous gravitational pressure.

For a massive star (mass > 7.14 solar masses), though its neutron degeneracy pressure can counter its collapse to a great extent, it cannot entirely nullify its gravitational pressure. Therefore, its core continues to collapse. When the diminishing radius of its core reaches a value equal to its Schwarzschild radius, the star becomes a black hole. After becoming a black hole, it stops sending any signal as its enormous gravity prevents emitting light or any other electromagnetic radiation beyond its event horizon. So, it is impossible to observe a collapsing black hole physically. Even at the time the star becomes a black hole, its gravitational pressure is higher than its neutron degeneracy pressure, and the radius of the black hole continues to collapse further and ultimately explodes as a core-collapse supernova. The particular radius at which a black hole explodes as a supernova is such that its gravitational binding energy equals its Quantum Chromo-dynamic (QCD) binding energy. This radius is much less than the Schwarzschild radius of the black hole. As it is a black hole, the radius just before the supernova explosion cannot be measured directly using telescopes.

A mathematical model is presented here that helps to determine the radius of the black hole just before its supernova explosion.

II. MATHEMATICAL MODEL

A black hole having a mass more than 7.14 times the solar mass will never become a neutron star and instead will explode as a supernova. At and below this mass limit (this is the upper limit; the T.O.V limit, 2.928 MΘ, is the lower limit), a black hole will settle down as a neutron star since its neutron degeneracy pressure (NDP) will counterbalance its gravitational pressure and stop further collapsing of its core. (Drexel [1]). A stellar black hole of mass 7.15 MΘ and above will continue to collapse as its gravity prevails upon its neutron degeneracy pressure. Finally, the black hole will explode when it reaches a particular radius. At that particular radius the gravitational binding energy of the black hole will attain a value that equals (or just exceeds) to its Quantum Chromo-dynamic (QCD) binding energy. QCD energy binds the hadrons, in this case neutrons, as it holds their sub-atomic particles, quarks, together mediated by the gluons. (Wikipedia) When its gravitational energy attains this threshold QCD binding energy value, the neutrons disintegrate and the black hole explodes as a core-collapse (Type-II) supernova. When the outer shell of the black hole explodes, a massive amount of gas and stellar dust (also accompanying immense quantities of energy) is released and spread into space, forming a nebula. Normally, the explosion leaves behind a dense core, a supernova remnant, either in the form of a neutron star or a black hole, depending on the mass of the progenitor star. In some rare cases, the entire black hole, including its super-dense core, explodes, expelling the stellar materials into the intergalactic space as a diffuse nebula. (Wikipedia [2]). Nebula is the birthplace of new central sequence stars.

Table-I: Presents the Energy Calculations of Various Stellar Mass Black Holes

f	M (kg)	R (m)	E.V (m.s^-1)	Gr. B. Energy (Joules)	QCD B. Energy (Joules)	Remarks
7.14	1.42E+31	21049.72	**300000000**	3.834E+47	1.26E+48	Black Hole
7.14	1.42E+31	6417	**543475455**	**1.258E+48**	**1.26E+48**	Neutron Star*
7.15	1.422E+31	21079.201	**300000000**	3.84E+47	1.262E+48	Black Hole
7.15	1.422E+31	6414.5	543834710	**1.262E+48**	**1.262E+48**	Supernova
8	1.591E+31	23585.12	**300000000**	4.296E+47	1.412E+48	Black Hole
8	1.591E+31	7177	**543837094**	**1.412E+48**	**1.412E+48**	Supernova
9	1.79E+31	26533.26	**300000000**	4.833E+47	1.588E+48	Black Hole
9	1.79E+31	8074.1	**543837936**	**1.588E+48**	**1.588E+48**	Supernova
10	1.989E+31	29481.4	**300000000**	5.37E+47	1.765E+48	Black Hole
10	1.989E+31	8971	**543844672**	**1.765E+48**	**1.765E+48**	Supernova
20	3.978E+31	58962.8	**300000000**	1.074E+48	3.53E+48	Black Hole
20	3.978E+31	17942	**543844672**	**3.53E+48**	**3.53E+48**	Supernova
25	4.973E+31	73703.5	**300000000**	1.343E+48	4.412E+48	Black Hole
25	4.973E+31	22427	**543850734**	**4.412E+48**	**4.412E+48**	Supernova
50	9.945E+31	147407	**300000000**	2.685E+48	8.824E+48	Black Hole
50	9.945E+31	44856	**543838610**	**8.824E+48**	**8.824E+48**	Supernova

- At a radius of 6417 m, a black hole of mass 7.14 MΘ (1.42E+31 kg) will become a neutron star, as in that condition its gravitational pressure and the neutron degeneracy pressure will be equal (3.786E+35 kg.m^-2).
- The following constants and equations have been used for calculation purposes

  Solar mass, Mʘ = 1.989E+30 kg

  c (velocity of light) = 3E+08 m.s^-1

  R = Radius of the star, in m

  Escape Velocity, (E.V) = (2*G*M/R) ^0.5 m.s^--1

  G (Universal Gravitational Constant) = 6.67E-11 m^3.kg^-1. s^-2

  M = mass of the star = f * Mʘ. kg

  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

  Nn = Number of neutrons in the star = M / Mn

  Mn = Mass of neutron = 1.675E-27 kg

All these calculations are theoretical, and validation of the figures of the above table by astronomical measurements is quite complex, if not impossible, as black holes are invisible. Supergiant stars are dimly visible, but as they are located very far away from our solar system, it is not easy to monitor a particular red supergiant in our Milky Way galaxy or any other neighbouring galaxy and track it till it becomes a black hole. After becoming a black hole, the star becomes undetectable; it can only be traced due to its excessively high gravitational field. A black hole thus formed collapses very swiftly and explodes as a supernova within a (comparatively) short period. On the contrary, supernovae are the brightest cosmic events and are visible even with the naked eye for a specific period. It was impossible to detect a black hole in earlier days; however, now with the advent of new generation telescopes like 'James Webb Space Telescope', or emerging new AI based astronomical techniques it may be possible to monitor a supergiant and then the black hole, although indirectly, till it explodes as a supernova in our Milky Way galaxy or even in other galaxies. A core-collapse supernova explosion is a rare phenomenon, as it happens (probably) 2 to 3 times on average in a century in any galaxy.

It is evident from Table I that at the time of supernova explosion, the escape velocity of the black hole, irrespective of its mass and volume, attains a constant value of approximately **5.438 × 10^8 m/s.** So, it can be deduced that like a black hole is formed when its radius becomes its Schwarzschild radius and attains escape velocity of 3E+ 08 m.s^-1 (velocity of light), the same black hole that continue to collapse due to imbalance between its gravitational pressure and corresponding neutron degeneracy pressure, will explode as a supernova (before becoming a neutron star) when its escape velocity will attain the value of around 5.438E+08 m.s^-1. It is also clear from Table I above that at that radius, when the escape velocity reaches the constant value of 5.438E+08 m.s^-1, the corresponding values of Gravitational Binding Energy and the Quantum Chromo-dynamic Binding Energy of the exploding black hole are equal. A black hole explodes when its gravitational binding energy equals or exceeds its QCD binding energy.

Further calculations show that at the time of formation of black holes as well as at the time of their explosion as supernovae, the values of their mass multiplied by their acceleration due to gravity, 'g', reach constant values C1 and C2, respectively. The values are **C1 = 3.036 E+43** kg.m.s^-2 (approx.) and **C2**

Retrieval Number:100.1/ijap.B106305021025
DOI:10.54105/ijap.B1063.05021025
Journal Website: www.ijap.latticescipub.com

Published By:
Lattice Science Publication (LSP)

= **3.279 E+44** kg.m.s^-2 (approx). These constant values are also independent of the mass and volume of black holes.

The relevant calculations are Shown in Table-2 below.

Table-II: The Relevant Calculations

f	M (kg)	R (m)	E.V (m.s^-1)	g (m.s^-2)	M*g (C1) (m.kg.s^-2)	Constants	Remarks
7.15	1.422E+31	21079.202	300000000	2.135E+12	**3.036E+43**	**C1**	Black Hole
7.15	1.422E+31	6414.5	5.438E+08	2.306E+13	**3.279E+44**	**C2**	Supernova
8	1.591E+31	23585.12	300000000	1.908E+12	**3.036E+43**	**C1**	Black Hole
8	1.591E+31	7177	5.438E+08	2.06E+13	**3.279E+44**	**C2**	Supernova
9	1,79E+31	26533.26.	300000000	1.696E+12	**3.036E+43**	**C1**	Black Hole
9	1.79E+31	8074.1	5.438E+08	1.832E+13	**3.279E+44**	**C2**	Supernova
10	1.989E+31	29481.4	300000000	1.526E+12	**3.036E+43**	**C1**	Black Hole
10	1.989E+31	8971	5.438E+08	1.648E+13	**3.279E+44**	**C2**	Supernova
20	3.978E+31	58962.8	300000000	7.632E+11	**3.036E+43**	**C1**	Black Hole
20	3.978E+31	17942	5.438E+08	8.242E+12	**3.279E+44**	**C2**	Supernova
25	4.973E+31	73703.5	300000000	6.106E+11	**3.036E+43**	**C1**	Black Hole
25	4.973E+31	22427	5.438E+31	6.594E+12	**3.279E+44**	**C2**	Supernova
50	9.945E+31	147407	300000000	3.053E+11	**3.036E+43**	**C1**	Black Hole
50	9.945E+31	44856	5.438E+08	3.297E+12	**3.279E+44**	**C2**	Supernova

The radius of the black hole at the time of its formation is calculated by using the formula,

Schwarzschild radius = (2*G*M) / c^2 (m). This radius can also be derived by using the constant C1.

C1 = M*g = M*(G*M/R1^2)

or, R1 = (G/C1) ^0.5 * M = K1* M (m) = **1.48E-27*M** m where **K1** (m.kg^-1) = **1.482E-27 m.kg^-1.**

The value of R1 will be equal to the Schwarzschild radius of the black hole.

As the radius of a black hole just before the supernova explosion cannot be measured directly by any astronomical method, and there is no other known formula to determine the radius theoretically, the constant value of **C2** can be used to calculate the radius of the black hole just before its explosion.

C2 = M * g = M * (G * M / R^2)

or, R2 = {(G/C2) ^0.5 * M} (m) = **K2 * M (m) where K2 = 4.51E-28 m.kg^-1.**

So, when a supernova explosion occurs, the radius of the exploding black hole just before the supernova can be obtained by multiplying its mass by a constant value K2 = 4.51E-28 m.kg^-1.

It has also been mathematically deduced that these two constants, as referred to as **C1** and **C2** above, are valid for all massive and even for the super-massive black holes. The relevant calculations are shown in Table-3 below.

Table-III: The Relevant Calculations

f	M (kg)	R (m)	E.V (m.s^-1)	Gr.B.E (Joules)	QCD B E (Joules)	g (m.s^-2)	Constant (kg.m.s^-2) C1 / C2
1000	1.989E+33	2948140	**3E+08**	5.37E+49	1.765E+50	1.53E+10	**3.036E+43**
1000	1.989E+33	897134	**5.438E+08**	**1.765E+50**	**1.765E+50**	1.65E+11	**3.279E+44**
10^9	1.989E+39	2.948E+12	**3E+08**	5.37E+55	1.765E+56	15263.86	**3.036E+43**
10^9	1.989E+39	8.971E+11	**5.438E+08**	**1.765E+56**	**1.765E+56**	164846	**3.279E+44**
6.6E+10	1.313E+41	1.946E+14	**3E+08**	3.544E+57	1.165E+58	231.27	**3.036E+44**
6.6E+10	1.313E+41	5.921E+13	**5.438E+08**	**1.165E+58**	**1.165E+58**	2497.55	**3.279E+44**
10^12	1.989E+42	2.948E+15	**3E+08**	5.37E+58	1.765E+59	15.26	**3.036E+43**
10^12	1.989E+42	8.971E+14	**5.438E+08**	**1.765E+59**	**1.765E+59**	164.85	**3.279E+44**

The calculations shown in Tables 1, 2, and 3 also reveal a relationship between the two radii, specifically the Schwarzschild radius of a black hole and its radius just before the supernova explosion, which is approximately constant at 3.286. This value is also the same for all types of black holes, irrespective of their masses. So, the radius of a black hole on the verge of supernova explosion can also be calculated by dividing its Schwarzschild radius by 3.286.

III. CONCLUSIONS

From the calculations shown in the above Tables (1, 2, and 3), the following conclusions can be drawn.

A. A black hole is formed when its collapsing core attains a value equal to its Schwarzschild radius. At that instance, the value of its mass multiplied by its 'g' (M*g), referred to as **C1**, is a constant value of **3.036E+43 m.kg.s^-2, and its radius can be calculated as K1 multiplied by its mass M. The** Value of K1 is also a continuous, **1.482E-27 m.kg^-1**. The radius calculated by using the formula K1*M will be equal to its Schwarzschild radius.

B. A black hole having mass 7.15Mʘ and above will never become a neutron star and will finally explode as a core-collapse supernova.

C. Just before the supernova explosion, the escape velocity of a stellar mass black hole attains a constant value of around **5.438E+08 m.s^-1.**

D. At this escape velocity (5.438E+08 m/s), the gravitational binding energy and the QCD binding energy of a black hole are equal. This condition triggers the supernova explosion.

E. When a black hole explodes as a supernova, the value of its mass multiplied by its gravity (M*g), referred to as **C2,** attains a value of **3.297E+44 m.kg.s^-2.** This value is a constant for all exploding stellar-mass black holes, irrespective of their mass.

F. Radius of a black hole **just before its supernova explosion** can be calculated by multiplying a constant **K2, 4.51E-28 m.kg^-1,** by its mass, i.e., **R2 = K2 * M** (m).

G. Calculations also revealed a most startling finding that values of all the aforementioned constants (C1, K1 and C2, K2) are identical for super-massive black holes, at their formation stage and at the time of their explosion, also. It has been theoretically proved that even the value of the escape velocity of super-massive black holes just before supernova explosions is **5.438E+08 m.s^-1**, i.e., the same constant value for the stellar-mass black holes also.

H. It is a corollary of the above calculations presented in this paper that the Schwarzschild radius of a black hole is around **3.286** times the radius of the black hole just before its supernova explosion. This value (3.286) is also constant for stellar-mass, intermediate-mass and supermassive black holes, theoretically.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed solely by the author.

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AUTHOR'S PROFILE

Prosad Bhattacharya, age 71 Years, B. Mech. Engg. from Jadavpur University, Kolkata. I have 34 years of experience in the petroleum oil industry in Indian Oil Corporation Limited, a 'Fortune-500' and a 'Maharatna' company of India. Have varied experience in operations, maintenance, inspection, technical services, and construction & commissioning of crude oil, petroleum products, and gas pipeline transportation systems. On official assignments, I visited France, England, Sudan and Houston (Texas). After retiring from service in December 2014 as General Manager (Maintenance & Inspection), I devoted my time to studying different branches of Physics. It was the pioneering work of the revered India-born astrophysicist and Nobel Laureate Subrahmanyan Chandrasekhar that inspired me to study astrophysics. To understand astrophysics, I had to study both nuclear physics and quantum mechanics. My study was primarily conducted through free online sources. An article titled 'Deep Space Conundrum Excites Scientists About Neutron Star That Might Also Be a Black Hole', published in the New York Times in 2020, motivated me to delve into this subject. My technical background and experience helped me in my research work, which has been entirely a solo effort. Two articles I authored have been published in Indian journals.