The Indian contribution to the physics of black holes: 2020 Nobel Prize

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Scientific discoveries are not made in vacuum; they all have a background (or shoulders of Giants to stand on in Newton's pronouncement) to anchor and build on. The famous and powerful singularity theorems of Hawking and Penrose of mid-1960s were strongly anchored on the remarkable Raychaudhri equation discovered in 1953. The most remarkable and profound prediction that followed from the equation was that gravitational collapse would inevitably lead to singularity in Einstein's theory of gravitation – general relativity. Hawking and Penrose generalized and located this result to a more general setting that Einstein's equation under very general conditions cannot admit a solution that has no singularity. They proved powerful rigorous mathematical theorems employing the techniques of global analysis that gravitational collapse would not only end up in singularity but before that a black hole would be formed. It is this robust prediction that has won Roger Penrose the 2020 Nobel Prize in Physics. In this note, I will recount the Indian contributions that have gone into making the background.

'If I have seen further than others, it is by standing on the shoulders of Giants'; thus spoke the great Newton in 1675. If Newton needed the shoulders to stand on, so would everyone else. No discovery in science is made in vacuum, it is always anchored in the background which serves as a conducive platform for creative and imaginative minds to see further than others and make new discoveries. In this note I will discuss some seminal Indian works that could be taken as 'the shoulders' on which Roger Penrose might have been riding on to see further and deeper into a collapsing star turning into a black hole.

The 2020 Nobel prize in physics has been awarded to Penrose[1] for proving the powerful mathematical theorems that established rigorously that a massive star collapsing under its own gravity ultimately ends up in singularity (Stephen Hawking had collaborated with Penrose in proving the famous singularity theorems, and he could have perhaps shared the Prize had he been alive), where its size goes to zero and energy density to infinity. Not only that, on the way to singularity it would turn into a black hole. This is the robust prediction of Einstein's theory of gravitation – general relativity. The other half of the Prize is shared by two astronomers, American Andrea Ghez and German Reinhard Genzel for detecting independently a supermassive star, believed to be a black hole, at the centre of our galaxy, the Milky Way. It should be noted that it is this remarkable observation that has lent the observational verification of the Hawking and Penrose prediction – a critical requirement for a Nobel Prize.

Black holes two centuries ago

The Indian connection to the term 'black hole' is the infamous incident that dates back to 1756, when Nawab Siraj-ud-Daulah squeezed 146 British soldiers into a dungeon, 14 × 18 sq ft, overnight in Fort William – which was known as the Black Hole of Kolkata. The message to be taken from and which is relevant for visualizing a physical black hole is that very large mass being confined to a very small volume with diverging density.

It is interesting that the first conception of the black hole as a scientific possibility was to follow pretty soon after by the British clergyman and scientist John Michell in 1784 and the great French mathematician Pierre Simon Laplace in 1796. They argued that if an object was very massive and dense, its gravity would be so strong that even light could not escape from it. Such an object if it exists would be all dark and invisible, as no light can come from it. This follows from the very simple back of the envelope calculation in the Newtonian gravity. The escape velocity is given by equality of kinetic and potential energy of the escaping particle, $1/2mv^2 = GmM/R$ giving $v^2 = 2GM/R$ in the usual notation. When it equals the velocity of light, then light will not be able to escape out. The radius of such an object would be, $R = 2GM/c^2$, which would trap all the light and turn absolutely black – a black hole.

Just to set the scale, the escape velocity for Earth is 11 km/sec while the velocity of light is incredible 300,000 km/sec. If the Sun has to become a black hole, its entire mass has to be squeezed into as small a radius as 1.5 km.

Chandrasekhar mass limit

The modern story begins with Subrahmanya Chandrasekhar who, after finishing his B.Sc. in Madras in 1930, left for Cambridge, England for higher studies. On his voyage to Cambridge he did interesting calculations on white dwarfs. It was believed then that all stars would end their life by becoming a white dwarf – a final abode. This is a very enigmatic object which supports itself against the force of gravity because of the pressure exerted by electrons. In his mathematical investigation of such objects, the young Chandrasekhar combined Einstein's theory of special relativity and the then new theory of quantum mechanics. He made the startling discovery in 1931 that there is a maximum mass which a white dwarf can have. This is about 1.4 times the mass of our Sun. A white dwarf with mass greater than this value, now called the Chandrasekhar mass limit, must necessarily collapse to a smaller size. This was an outstanding breakthrough discovery which had shattered the quiet, peaceful abode of eternal rest for a star at the end of its evolutionary journey.

Chandrasekhar's mentor and friend, Arthur Eddington from Cambridge, who was the most creative and influential astrophysicist of the day, did not for some strange unfathomable reason accept this brilliant discovery and criticized it strongly. The argument was more rhetoric than objective and rational when Eddington surmised that he believed that there would exist some law of Nature that would prevent this kind of catastrophe to occur. Even so, it does not take away anything from the new light the monumental discovery has shone on evolutionary track of a star. Chandrasekhar, however, had the last laugh when he was at long last awarded the Nobel Prize in 1983, a good half a century after the discovery.

Stars consume nuclear fuel to produce energy that they emit as light and heat. When all nuclear fuel is exhausted, i.e. temperature is no longer high enough for nuclear fusion to continue, the star collapses to a smaller size into a cold state of white dwarf, which is entirely supported against gravity by electron pressure. What Chandrasekhar had calculated was the limit on electron pressure – electron degeneracy, that could counter gravitational pull due to mass of a white dwarf. It turned out that according to the theories of relativity and quantum mechanics, electron pressure cannot sustain any mass greater than 1.4 solar mass. This is how the Chandrasekhar limit was discovered.

When electrons have given way, the next avenue of resistance could then come from neutrons.

Gravitational collapse

What happens when a star cannot end its life as white dwarf because it is too massive for that? It turns out that as a star continues its collapse, it eventually becomes so dense that almost all matter in it is converted into neutrons. These neutrons can likewise exert pressure to counter the gravitational collapse giving rise to a stable configuration, and the object so formed is called a neutron star. Such an object is so dense that just a spoonful of its matter would weigh the same as all of humanity. As mass further increases, like electron, neutron degeneracy could set in – neutron pressure is no longer sufficient to counter balance gravitational pull to retain stable configuration of the neutron star. It turns out that this happens when the star's mass exceeds about 3 solar mass. This limit is not as sharp as the Chandrasekhar limit because we do not understand interior of the neutron star well and definitive enough, in particular its equation of state which is a relation between pressure and density.

If a neutron star is more massive than this limit, it must collapse indefinitely as there is no other kind of pressure available in the present theory to resist it. It collapses right down to zero size and infinitely large density – singularity. Even before the object reaches this singular state, it would pass through a stage $R = 2GM/c^2$, where light gets trapped and cannot escape. The Michell–Laplace black hole would be formed.

Black holes in Einstein's theory

So far we have discussed this phenomenon in the Newtonian gravity. What happens in Einstein's theory of gravitation, where gravitation is beautifully synthesized into spacetime geometry? It is described by curvature of spacetime and hence is no longer an external force but an integral part of the geometry of spacetime.

In a simple intuitive way it could be understood as follows: Einstein's law of gravitation is the Newtonian inverse square law in curved space instead of flat space[2]. This makes a profound impact on our understanding of the phenomenon we are discussing.

Since the velocity of light is universally constant, hence it cannot change under any circumstance. The only way it could be trapped and confined is to make space curved so that it cannot propagate out. This is precisely what happens in general relativity. It is the space curvature that gives rise to the bizarre phenomenon of a black hole. This is a more profound and geometric object than what was conceived by Michell and Laplace.

In 1938, Bishveshwar Datt[3] of Kolkata, India, was to find an exact solution of Einstein's equation of expanding (the solution described an expanding cloud without boundary was therefore cosmological in character, rather than a collapsing cloud) (collapsing)[2] under its own gravity. Unfortunately he died soon after on the operation table, while being operated for hernia. A year later, Robert Oppenheimer and David Snyder[4] obtained the same solution as Datt did, and had also matched the interior solution with the exterior Schwarzschild vacuum solution at the collapsing boundary. It was truly a model of homogeneous gravitational collapse of a star-like object that proceeded uninterrupted down to the singularity, where spacetime curvatures and energy density diverge. It is famously known as the Oppenheimer–Snyder collapse in the literature.

Those were the Second World War years which had made the exchange of scientific information difficult in general, and more so from India. Due to this reason, and the sad and untimely demise of Datt, his contribution remained unsung until 1999, when the *Journal of General Relativity and Gravitation*[5] reprinted the original paper with an Editorial commentary in its series on 'Golden Oldies'. It would perhaps be appropriate to acknowledge Datt's contribution to the result that laid the foundation for a black hole formation in general relativity by naming it the Oppenheimer–Snyder–Datt (OSD) collapse.

Here one may raise the question whether occurrence of singularity is the artefact of special properties of homogeneity and isotropy on the one hand and spherical symmetry on the other?

Raychaudhuri equation

In 1953, Amal Kumar Raychaudhuri[6], when he was a lecturer in Ashutosh College, Kolkata, obtained a remarkable equation, which bears his name, governing evolution of a system of particles according to Einstein's theory of gravitation. It is the Raychaudhuri equation that establishes in all generality the profound result that the occurrence of a singularity is inevitable in general relativity. It may be noted that the special conditions of homogeneity and isotropy, and of spherical symmetry of the OSD collapse have been lifted-off, and the Raychaudhuri equation makes no reference to any symmetry and nature of matter distribution, except of course positivity of matter energy. It was the key to what was to follow a decade later in terms of the singularity theorems.

In the mid 1960s, Penrose building on the Raychaudhuri equation and employing global analysis techniques of topology and differential geometry made the profound prediction that formation of a black hole with a singularity at its centre is inevitable in Einstein's theory of gravity. In collaboration with Stephen Hawking, he proved powerful theorems establishing the result mathematically and rigorously.

Though the Raychaudhuri equation leads to the conclusion that singularity is inevitable in gravitational collapse in general relativity, what the powerful theorems of Penrose and Hawking have shown is that as collapse proceeds, before singularity is reached, trapped surfaces would be formed from which nothing, including light, could escape out. From this state onwards we can receive no signal from the collapsing object. The surface marking this property is called 'event horizon', indicating complete blockade of all information and signals from external observer of what is happening inside. Thus a black hole is formed. It is this new perspective illuminating formation of the darkest object in the Universe, and its inevitability in Einstein's theory of gravitation, is what has won Penrose the 2020 Nobel Prize in Physics.

It is however worth speculating, had Raychaudhuri had the benefit of strong and sophisticated mathematical backup, could he have perhaps discovered the singularity theorems?

In essence, the theorems explain and demonstrate the process of black hole formation in terms of spacetime geometry. Though the black hole bizarre and exotic, yet it is, according to Chandrasekhar, the simplest object in Nature, because it is a purely geometric construct.

In addition to the work cited in the Noble Prize, Penrose has several important and path-breaking contributions ranging from extraction of energy from a rotating black hole, to the transition from pre- to post-big bang state of the Universe. He has also worked extensively on the interface between science and philosophy, dwelling on the deep questions of physical reality and consciousness.

The order of profoundness in physics proceeds as follows: At the top is the discovery of a new law of physics. Then come the equations that govern the behaviour of various physical systems, like collapsing stars or the expanding Universe. And finally we have various important, useful and interesting results which follow from the equations. Einstein's theory of gravitation leads to the many profound and extraordinary results on black holes, the big bang and expanding Universe, and so forth. The role of the Raychaudhuri equation is clear in this hierarchy.

In 1966, Fred Hoyle and Jayant Narlikar[7] asked the question how massive a star must be so as to arrest cosmic expansion of surrounding matter to form a galaxy like structure? They found that it must have a mass about billion times the solar mass to form a galaxy of thousand billion solar mass. Thus they argued that the centre of the galaxy should harbour a supermassive star (The term 'black hole' was coined by John Wheeler a year later in 1967, in response to an audience question in a conference in New York, USA). This is purely an astrophysical argument for the existence of a supermassive object at the galactic centre.

Ghez and Genzel, have shared the Prize with Penrose for detecting a supermassive object, which is believed to be a black hole, at the centre of our galaxy. It is interesting that what Hoyle and Narlikar had predicted on astrophysical grounds over half a century ago has actually been observed. It should also be noted that they were the first to suggest that centres of galaxies should harbour supermassive objects – a profound prediction and foresight.

Black holes are the simplest objects as they could be fully characterized by three parameters, viz. mass, rotation and electric charge. Another young Indian graduate student, C. V. Vishveshwara in Maryland, USA, took fancy to this exotic object in 1970 and explored its various properties in a series of papers. The most remarkable and important among them[8,9] was the one that showed how a black hole, which is purely a geometric object, rings like any other object when struck by matter. It rings down before it settles down to its original state. This proves two important properties: one, stability of a black hole under perturbations and second, as and when collision of a black hole occurs with another black hole or star, gravitational waves would be produced and would be observed through the ringdown process.

In 2015, gravitational waves were detected in the LIGO observatory, winning the Nobel Prize in 1917 for Reiner Weiss, Kip Thorne and Barry Barish. The observed ring-down curve had uncanny and remarkable resemblance to the one obtained by Vishveshwara a good 45 years ago in the pre-sophisticated computer era.

In 1985, the Penrose process of energy extraction from a rotating black hole was generalized[10] to include the presence of magnetic fields around the rotating black hole turning it into magnetic Penrose process, by a young graduate student, Sanjay Wagh, a postdoc, Sanjeev Dhurabdhar and Naresh Dadhich, Pune University (now Savitribai Phule Pune University, India). They showed that inclusion of magnetic field made the process highly efficient and hence could serve as powering mechanism for the most luminous objects, quasars in the Universe[11]. It is gratifying that fully relativistic hydrodynamic flow simulations beautifully bear out the prediction made some 30 years ago[12]. It is considered as the most favoured powering mechanism for quasars, active galactic nuclei and ultra high energy cosmic rays[13,14].

Setting the stage

The 1960–70s were highly charged times for great discoveries in relativistic astrophysics and cosmology. Though the solution describing a black hole was obtained immediately after Einstein discovered his equation, yet it was not understood as a black hole until 1960s, a good 45 years later. As mentioned earlier, the term 'black hole' was invented by John Wheeler only in 1967.

Roy Kerr obtained astrophysically the most remarkable and interesting solution of Einstein's equation describing gravitational field around a rotating black hole. On the other hand was the observation of incredibly luminous objects, quasars that give out energy ten orders of magnitude of stellar luminosity.

The crowning glory was of course the momentous discovery of the cosmic microwave background radiation at temperature 3 K, which was the greatest prediction and the distinguishing feature of the big bang theory of the Universe. The Universe had a singular beginning in a hot big bang, and the observed microwave radiation is carrying that message and signature.

The stage was thus set for a great discovery and prediction that formation of a black hole and consequently, the central singularity are inevitable and distinguishing features of Einstein's general relativity.

It is gratifying to note that the two purely general relativity Nobel Prizes, one for detection of gravitational waves in 2017 and the present one for prediction of the formation of a black hole and its detection at the galactic centre, had a strong Indian trail in the seminal works of Datt and Raychaudhuri for the former, and Vishveshwara for the latter.

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