C. V. Vishveshwara (Vishu) on the Black Hole Trek*

Naresh Dadhich and Rajesh K. Nayak

With his seminal and pioneering work on the stability of the Schwarzschild black hole and its interaction with gravitational radiation, Vishu had opened a new window on black hole astrophysics. One of the interesting conjectures that soon followed in John Wheeler pronouncing "a black hole has no hair" ; it is entirely specified by three parameters—mass, spin and charge—and nothing more. The discovery of gravitational waves in 2016 produced by the merger of two black holes and observed by the LIGO–VIRGO collaboration, carried the definitive signature of quasinormal modes, the phenomenon of black hole ringdown, exactly as predicted by Vishu in his 1970 *Nature* paper (see the introduction to Classics by R. Isaacson in this issue) 46 years ago. This was the crowning glory.

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The Worldline

We shall begin by tracing Vishu's worldline, a brief life sketch followed by recounting, besides science, the multifaceted aspects of his life.

C. V. Vishveshwara, whom we all fondly called "Vishu", was born on 06 March 1938 in Bengaluru. He did his BSc (1958) and MSc (1959) from the University of Mysore. Then he proceeded to the USA for higher studies, where he first did his second master's in physics in 1964 from Columbia University. From there, on the advice of his mentor, Robert Fuller, he proceeded to join Charles Misner's group of gravitational physics at the University of Maryland for doctoral studies. In 1967, John Wheeler coined the term black hole for the compact object described by the Schwarzschild

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metric, and that was also when Vishu was finishing his thesis examining its stability. His was thus the first investigation of the stability of a black hole in spacetime, earning him a PhD in 1968.

Keywords
Black hole, Schwarzschild metric, event horizon, static limit, quasinormal modes.

After his PhD, he took up a postdoctoral position at the NASA Goddard Institute for Space Studies and moved further on to research positions at the Universities of New York, Boston and Pittsburgh. In 1976, he returned to India to join Raman Research Institute, where he established a school of gravitational physics. From there, he moved to the Indian Institute of Astrophysics in 1992 and retired in 2005. In 1998, he was invited to be the Founder Director of the Jawaharlal Nehru Planetarium, Bengaluru. That is where his creative and imaginative prowess came into full bloom. The planetarium is a living tribute to his versatile genius, and the shows bear the distinctive stamp of his scholarship of mythology and culture on one hand and scientific history and beliefs on the other. He was a science communicator par excellence. He remained glued to his creation, the planetarium, until he breathed his last on 16 Jan 2017, so much so that he reviewed a new show to be launched just a few days before his demise.

He Had Many Hairs

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Though he proscribed black holes to have no hair, he himself had many hairs, indicating his multifaceted interests and concerns. Besides science, of which we would talk about later in some detail, he had a keen interest in and appreciation of literature in all forms and arts in all its presentations. He was a culturally accomplished person and a connoisseur of good music (Indian and Western), classical as well as modern, theatre and painting. In particular, he was quite accomplished in drawing and sketching and had the keen observation and eye of a cartoonist. His collections of cartoons laced with subtle and tickling humour bear testimony to his skill and accomplishment in this art. *All the figures and cartoons included here are due to him.*

On the other hand, his book, *Einstein's Enigma or Black Holes in My Bubble Bath*, demonstrates his prowess in prose writing of high quality and tenor. It reads like a travelogue novel with a generous sprinkling of humour, thoughtful perceptions and conversations. Thoroughly absorbing and engaging, it leaves one thinking and wondering. He inherited this literary bug from his father, a well-known Kannada writer and scholar.

Historical Backdrop

The Schwarzschild metric was the first exact solution of the Einstein equations, obtained within a year of the equations being written in 1916. It describes the gravitational field of an isolated static object. But the solution has unusual features at the surface, $R = 2M$ (in the prevailing spirit of relativity, we would always set the gravitational constant and the velocity of light to unity, such that one measures mass in length units!) where the metric becomes singular with $g_{tt} = 0$, $g_{rr} = \infty$.

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Then followed a long and sometimes acrimonious and confusing debate among relativists, including Einstein, whether $R = 2M$ represented a real singularity. Could an astrophysical real object be so compact to the limit that the Sun's mass gets squeezed within the radius of 3 km? Even Einstein thought that it was not physically possible. The debate raged on unabated for nearly half a century.

In 1939, Oppenheimer and Snyder [1], and B Datt of Kolkata [2] a year earlier[1], considered the gravitational collapse of homogeneous dust and showed that it collapsed down all the way to $R = 0$, where even the Riemann curvature became singular. This clearly indicated that a collapsing object could indeed reach the surface, $R = 2M$, where the Riemann curvature remains finite. It thus suggested that the central singularity, where the Riemann curvature diverges, may not be unavoidable, pointing to the incompleteness of general relativity.

Earlier, Chandrasekhar had shown by application of quantum mechanics to the equilibrium of a white dwarf that if the mass of an object exceeded 1.4 times that of the Sun, electron pressure could not counterbalance gravitational pull [3], and it had to collapse

[1]The difference between the two studies was that latter did not match the interior collapsing solution to the exterior vacuum solution at the boundary. Yet it would be in the fitness of things to term this as 'Oppenheimer–Snyder–Datt' collapse. Unfortunately, Datt died immediately afterwards, and his work was forgotten. It has now been duly acknowledged when it was reproduced in the *Golden Oldies GRG* series [2] with a commentary.

further. This is the well-known Chandrasekhar mass limit for the white dwarf where electron degeneracy occurs. It opened up the possibility of further collapse going down to the neutron degeneracy, and when that happened, there was nothing to check collapse, and that could then proceed unabated all the way down to $R = 2M$ or even beyond to the singularity, $R = 0$. Thus, the question of attaining such a compactness got theoretical credence and validity. The question, what does $R = 2M$ physically mean, is then quite pertinent and real.

The Raychaudhuri equation showed the inevitability of continual gravitational collapse with no reference to matter and spacetime symmetry properties, except requiring that energy density plus thrice pressure should be greater than or equal to zero.

Of course, one may raise the question that homogeneous dust is a very special state of matter, and hence, what is true for it may not be true for a general fluid collapse. That is, of course, a valid question. Then came another remarkable work in 1953, though published in 1955, from Amal Kumar Raychaudhuri of Kolkata regarding the discovery of the equation bearing his name—the Raychaudhuri equation [4]. This showed the inevitability of continual gravitational collapse with no reference to matter and spacetime symmetry properties, except requiring that energy density plus thrice pressure should be greater than or equal to zero. Following the Raychaudhuri equation[2], Penrose[3] and Hawking [5, 6] proved the famous powerful singularity theorems—the occurrence of central singularity is the robust prediction of general relativity.

[2]See *Resonance*, Vol.13, No.4, pp.319–333, 2008 and Vol.26, No.1, pp.47–60, 2021.

[3]See J. S Bagla, Compact objects and black holes, *Resonance*, Vol.25, No.12, pp.1659–1668, 2020.

In 1960 Kruskal discovered [7] a transformation connecting the regions $R > 2M$ and $R < 2M$, and continuously matching the two coordinate patches at the surface $R = 2M$. This cleared all the confusion at once, and $R = 2M$ was a coordinate singularity caused by the bad choice of coordinates. It disappears when proper coordinates are chosen in the two patches. The so-called Schwarzschild singularity thus gets demystified. It should be noted that the Riemann curvature, which measures the physical tidal force, however, remained finite and regular at this surface, which was again indicative of its spurious character.

Black hole has exotic properties; even light cannot escape from it, and its boundary is a one-way surface—things can fall in, but nothing can come out, including light.

About half a century later, the Schwarzschild metric was finally understood and realised that it described a bizarre object, famously christened a ‘black hole’ by John Wheeler in 1967. It has exotic properties; even light cannot escape from it, and its boundary is a one-way surface—things can fall in, but nothing can come out, including light. Since no information or signal can come out, it marks a horizon for events happening inside and is called an 'event horizon'.

Another remarkable discovery arrived in 1962 in terms of the Kerr solution [8] describing a rotating black hole. This turned out even richer and more exotic than the Schwarzschild static solution in its physical properties as well as astrophysical relevance and applications. Its most remarkable property is the dragging of space around it as it rotates; i.e., rotation is not confined to the black hole itself but is also shared by the surrounding space. This leads to a very interesting phenomenon of energy extraction from a rotating black hole, which is astrophysically very exciting. We will have something more to say about it later.

Kerr solution describes a rotating black hole. Its most remarkable property is the dragging of space around it as it rotates; i.e., rotation is not confined to the black hole itself but is also shared by the surrounding space.

Then arrived Vishu, and the stage was set for him to explore the new bizarre object called a black hole with its very strange and interesting properties. That is what we shall take up next.

Seminal and Pioneering Works

We shall discuss one by one three of Vishu's most insightful and interesting works, which include (1) event horizon and stationary limit, (2) black hole perturbations and quasinormal modes, and (3) rotation in black hole spacetimes.

Event Horizon and Stationary Limit

The first work involves consolidating the concept of event horizon in the black hole spacetimes. There are three intimately related ideas associated with a black hole, and they are (a) one-way membrane or event horizon, (b) static or stationary limit, and (c) infinite redshift surface.

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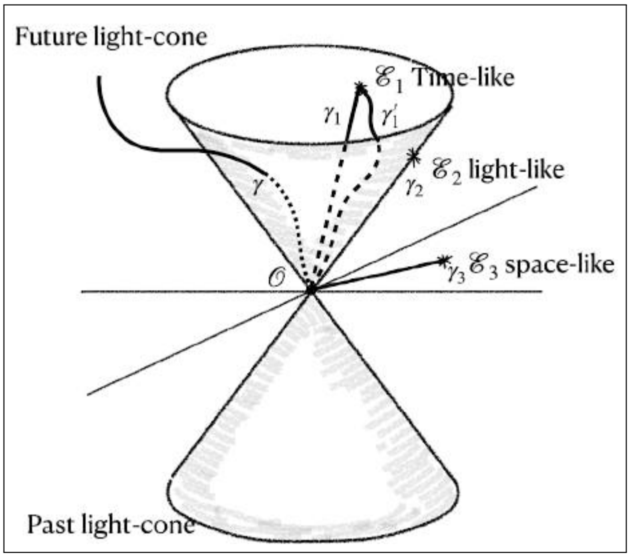
***The event horizon*:** The first concept is the idea of a one-way membrane as the definition of an event horizon, popularly known as a black hole. In all relativistic theories, the speed of light is

Figure 1. Light cone structure. Events inside the cone can be connected to location *O* with time-like curve.



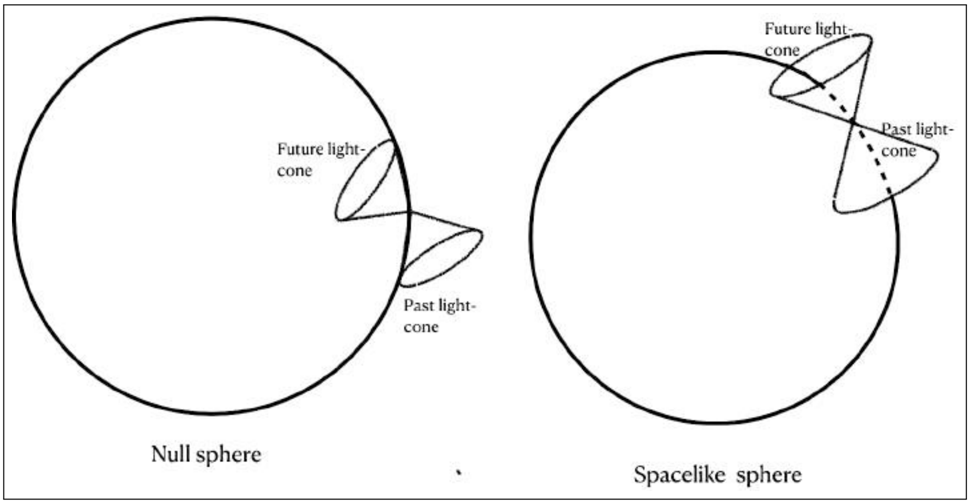
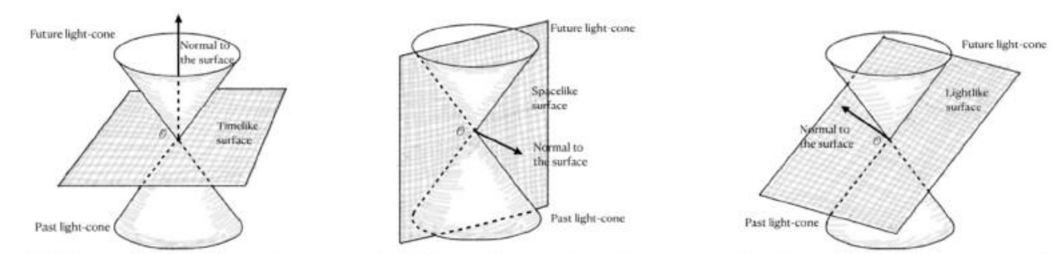


Figure 2. Light cone and event horizon.

the upper limit for communication between any two points. This constraint divides the interval between any two events in space-time into time-like, light-like or null and space-like. This idea further develops into the concept of the light cone. The collection of all light-like paths starting from an observer's location *O* gives the light cone, as shown in *Figure* 1.



(a) Time like surface has time like norm,

(b) Space time surface has space like normal vector

(c) For null surface, norm is null vector.

Figure 3. Time-like, light-like and space-like planes with light cone.

A massive particle can carry a signal or message from an observer at O to all the events inside the light cone. The light cone events are moving at the speed of light, and there is no way to reach them from the observer at O without moving faster than light. There is no way to communicate with events outside the light cone. A time-like curve, γ, sneaking outside the light cone, can never come back inside again without speeding up faster than light. As one goes closer to the horizon, the observer's light cone gets tilted inwards, and at the horizon, it is entirely pointing inwards (*Figure* 2). Similarly, surfaces can be classified into time-like, null or space-like depending on whether their normal vector is time-like, null or space-like, as shown in the *Figure* 3. Only 'time-like' surfaces having their normal time-like can be crossed both ways, going in and out. The surfaces we generally come across, like a classroom, are two-way crossable—an observer can go in and come out.

The most fascinating of them all is the null surface. A wavefront of light is a classic example of a null surface. The normal vector to a wavefront is the direction vector along which light propagates, which is null or light-like by definition. An observer can cross a wavefront, or a wavefront crosses an observer only once without violating the speed limit. This crossing once is the property of all null surfaces; hence, they are also known as one-way membranes. There is a one-way surface we encounter at every epoch, $t = const.$, which we all cross only once and one way. It is

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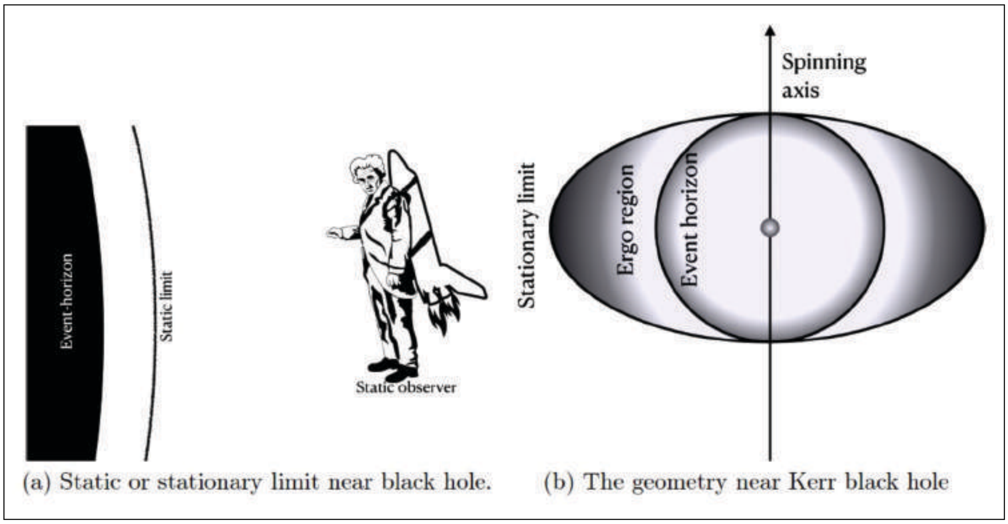

Figure 4. **(a)** Static or stationary limit near black hole. **(b)** The geometry near Kerr black hole.

different that many of us would like to cross it the other way too, but can't! It is, however, not bounded in space.

The precise definition of a black hole is an inward or future-pointing null surface that is finite and closed. Finite and closed because an observer will not be able to sneak out from any direction. The direction is along inward such that an observer would be able to go in but not come out, as shown in *Figure* 2.

However, there is a common sense indicator of the horizon where a freely falling massive particle attains the velocity of light. That is, as in the Newtonian gravity, velocity is given by $v^2 = 2\Phi(R)$, where $v = \frac{\sqrt{g_{rr}}dr}{\sqrt{g_{tt}}dt}$ is the proper velocity relative a local observer and $\Phi(R) = M/R$ is the gravitational potential. This is because the inverse square law remains unaltered in general relativity with 3-space being curved rather than flat, as is the case for Newtonian gravity. In fact, we can say, *Einstein is Newton with space curved* [9].

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***Static limit*:** The second concept associated with the black hole is called the static limit. An observer is said to be static in spacetime if his/her spatial velocity is zero. When we stay at rest on the Earth's surface, the gravitational force acts downwards towards the centre of the Earth, while the floor's reaction force (so-called

Newton's third law) acts upwards to balance the gravity. Without ground to support, one needs to put on a rocket suit to give an upward acceleration to remain at rest and avoid falling. Similarly, an observer can remain at rest around a black hole by providing an outward acceleration or rocket suit to counter the radial pull towards the hole. These are the static observers in static spacetimes, which are spherically symmetric, such as the Schwarzschild solution (*Figure* 4).

***Stationary limit*:** The case of the rotating black hole described by the axially symmetric Kerr solution presents a new situation. Since it is rotating about an axis, a direction gets identified, and hence, the spacetime has to be axially symmetric. Here, a particle is subjected to pull in two different directions, one in the radial direction as in the static case but also in the tangential direction to carry it around. This is because there is an inherent rotation, indicated by the frame dragging angular velocity $\omega = -g_{t\phi}/g_{\phi\phi}$ at every point in space surrounding the hole. That is, even a particle with zero angular momentum has to move with this angular velocity.

It turns out that first, the angular pull becomes irresistible, and that defines the stationary limit; i.e., below this limit, an observer cannot remain stay put at a location; he/she has to rotate around. That is, he/she can, though, remain stationary at fixed R by countering the radial pull, but has to rotate around with the angular velocity ω. At the stationary limit, radial pull could be resisted, but not the angular pull. As one goes further down, when radial pull also becomes irresistible, that is when the event horizon is defined. For the static black hole, both event horizon and stationary limits are coincident, which separate for the rotating Kerr black hole. The region separating the two is called the ergoregion (*Figure* 4). This lends to rotating black holes, the most exciting and interesting physical phenomena.

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The most remarkable feature of the ergoregion is that a particle can have its total energy negative relative to an observer at infinity. It turns out that in this region, spin-spin interaction energy, which would be negative for counter-rotating particles, could be-

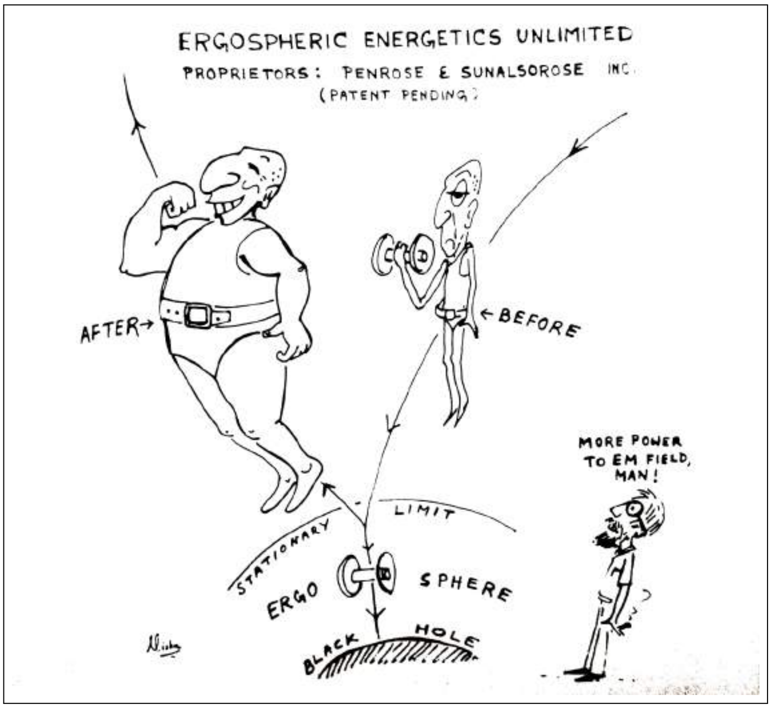

Figure 5. Ergoregion and Penrose process.

come dominant, thereby making the total energy negative. Using this property, Penrose in 1969 [10] proposed an ingenious process of energy extraction (known as the Penrose process) from a rotating black hole. It is envisaged that a particle of energy, E_1, falls from infinity and splits into two fragments having energies $E_2 < 0$ and E_3 in the ergoregion. Then the fragment with negative energy, $E_2 < 0$, falls into the hole, and the other, $E_3 = E_1 - E_2 > E_1$, comes out with enhanced energy. This is how the black hole's rotational energy could be extracted out (*Figure* 5). This doesn't happen for static black holes because there is no ergoregion there. Rotation causes the ergoregion; hence, the extracted energy is rotational.

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***Infinite redshift surface*:** The third concept is the infinite redshift surface. When light travels from a stronger gravitational field to a weaker gravitational field, it experiences a redshift called the 'gravitational redshift'. As the source of light approaches the black hole, the observer at infinity sees a more significant shift in light frequency. When the emitter reaches $R = 2M$ or $g_{tt} = 0$ in general, light will experience infinite redshift. This limit is called the infinite redshift surface.

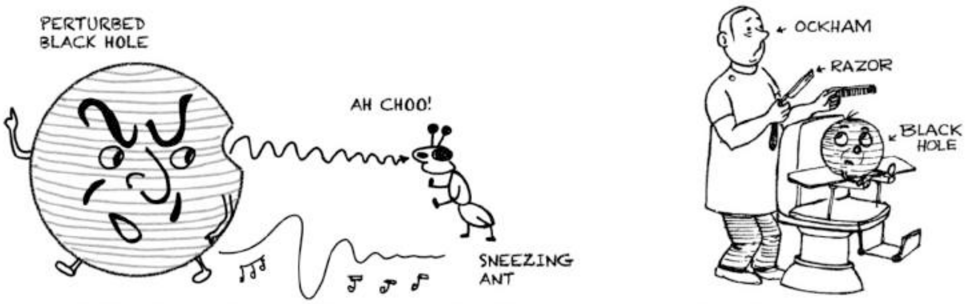
In spherically symmetric black holes such as the Schwarzschild solution, the event horizon, static limit, and infinite redshift coincide at the location $r = 2M$ or the Schwarzschild radius. However, rotation introduces considerable complexity and richness of phenomena. Vishveshwara, in his work, highlighted the differences and similarities in the geometry of rotating and non-rotating black holes.

Black Hole Perturbations and QNMs

The black holes as astrophysical objects need to fulfil another important criterion, i.e., they need to be stable under perturbations. When black holes are formed in a stellar collapse or by the merging of two stars, they are often subjected to extreme perturbations, and they need to be stable, at least on the life spent of a galaxy or the Universe itself. Examining the stability of a black hole was the problem assigned to Vishu by his supervisor, Charles Misner. Finally, it turned out to be a major topic by itself, so much so that Chandrasekhar had to write a book of over 500 pages, *The Mathematical Theory of Black Holes*, entirely devoted to black hole stability and perturbations.

To state the problem in another way, can one destroy a black hole? Let us try to understand the subject from an example of the ringing of a bell. When one strikes a bell with a small hammer, a small amount of energy is transferred to the bell and that distorts it slightly. The bell will start ringing with notes depending on the shape and the material of the bell. Designed to ring for a long time, they will eventually stop ringing when all the excess energy imparted is converted into sound waves. Finally, it settles back to its original state. These types of perturbations are linear, and bells are stable under linear perturbations. While hammering, if the energy transferred is considerable, the bell might get distorted permanently or even obliterated.

Vishu's seminal work includes perturbing a black hole with a small energy field. When disturbed, he first discovered that black holes ring pretty much like a bell by emitting gravitational waves. These characteristic modes of black holes are called quasinormal modes.



(a) Small perturbations and Quasi-normal modes

(b) Occam razor a serious threat to the no-hair theorem

Figure 6. No-hair theorem.

Vishu's seminal work includes perturbing a black hole with a small energy field. When disturbed, he first discovered that black holes ring pretty much like a bell by emitting gravitational waves. These characteristic modes of black holes are called quasinormal modes (QNMs)[4].

Since a black hole can harbour only mass, charge and angular momentum, objects that fall in can only add to these three parameters alone. All other modes get evaporated away before the object reaches the null horizon. In other words, it is a property of the closed null surface that it cannot sustain any parameter other than mass, spin, and charge. This is what is popularly known as the 'no-hair theorem'.

[4]See Gurbir S. Arora and P. Ramadevi, Quasinormal modes of black holes: Small perturbations of black holes, *Resonance*, Vol.25, No.10, pp.1353–1367, 2020.

In an amusing, but probably legendary, experiment, Galileo is said to have publicly demonstrated that two balls made up of different materials fall similarly when dropped from the leaning tower of Pisa. If the balls were to be dropped into a black hole, they would be converted into a pile of mass and angular momentum with no trace of their material structure. So do the waves emitted by spacetime, namely QNMs, depend only on the black hole's fundamental entities, i.e., mass, charge, and angular momentum (*Figure* 5).

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The QNM signals are one of the unambiguous signatures of black holes. If detected directly, they can be a powerful tool in understanding black hole physics. With QNMs, one may be able to

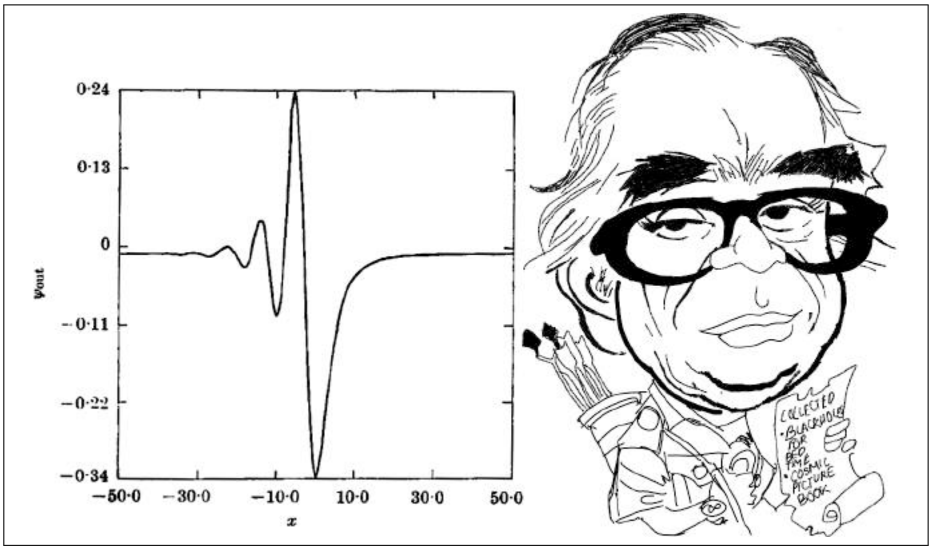

Figure 7. QNM and Vishu.

distinguish between black holes and other compact objects mimicking them. One can verify the no-hair theorem by analysing whether multiple QNM modes carry any signature other than mass, spin, and charge. If any other parameter, a black hole would leave an imprint on QNMs. QNMs are the only messengers we have from black holes, the only source of information. Since the existence of QNMs is a prediction of general relativity, their existence hence also marks its test (*Figure* 5).

The first detection of gravitational waves from a black hole merger, GW150914, by the LIGO and VIRGO collaboration, is a significant step in the direct identification of QNM signals. The final phase of the merger of black holes leaves a highly distorted black hole, emitting QNMs. It then settles down as QNMs damp out to a stationary state of rotating Kerr black hole. This phenomenon is called the 'ringdown phase'. The observed signal from GW150914 confirms the ringdown phase (*Figure* 6). Vishu was also one of the first to use the then-available computing facility for analysing the QNMs, as shown in the figure, and it is remarkable that the curve is pretty much like the one in the gravitational wave discovery observation. Work is underway to identify and characterise QNM frequencies. For GW150914, the

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signal strength is weak in the ringdown phase and is not adequate enough to draw any clean inference in the context of the no-hair theorem. What is needed is a closer and more massive black hole merger to get a sufficiently loud signal. In the coming years, QNMs will be one of the powerful tools to probe black hole physics directly.

Rotation in Black Hole Spacetimes

After his work on QNMs, Vishu mainly worked on the various physical phenomena in black hole spacetimes. Rotation brings in considerable complexity and interesting physical effects in general and in general relativity in particular.

After his work on QNMs, Vishu mainly worked on the various physical phenomena in black hole spacetimes. Rotation brings in considerable complexity and interesting physical effects in general and in general relativity in particular. We have already seen how the event horizon and stationary limit decouple in going from the Schwarzschild to the Kerr black hole. Unlike the Newtonian theory, in general relativity, a rotating object, in addition to pulling things radially inwards, also imparts a tangential push to take things around. That is, the entire spacetime is dragged around it, and this is referred to as the phenomenon of frame-dragging. If it were not so, a particle very close to the horizon would have no rotational motion; as it falls into the horizon, it would suddenly start rotating with the black hole. There would be a discontinuous jump from no rotation to rotation. If that happens, it should be reflected in some abrupt change in spacetime at the horizon, which would be reflected in the Riemann curvature. Nothing abrupt happens in the curvature at the horizon. For motion to transit smoothly from outside onto the horizon, a black hole has to share its rotation with the surrounding space.

The frame-dragging effect of the Kerr rotating spacetime is directly observable in the precession of a gyroscope carried by a rest-observer staying at a fixed location. The rest-observer is experiencing a torque due to the black hole's spin—a complex and subtle interplay between time and azimuthal angle due to rotation. Because of this phenomenon, the rest-observers are not the best ones to probe the rotational effects of a spinning black hole. Bardeen and coworkers [11] proposed locally non-rotating ob-

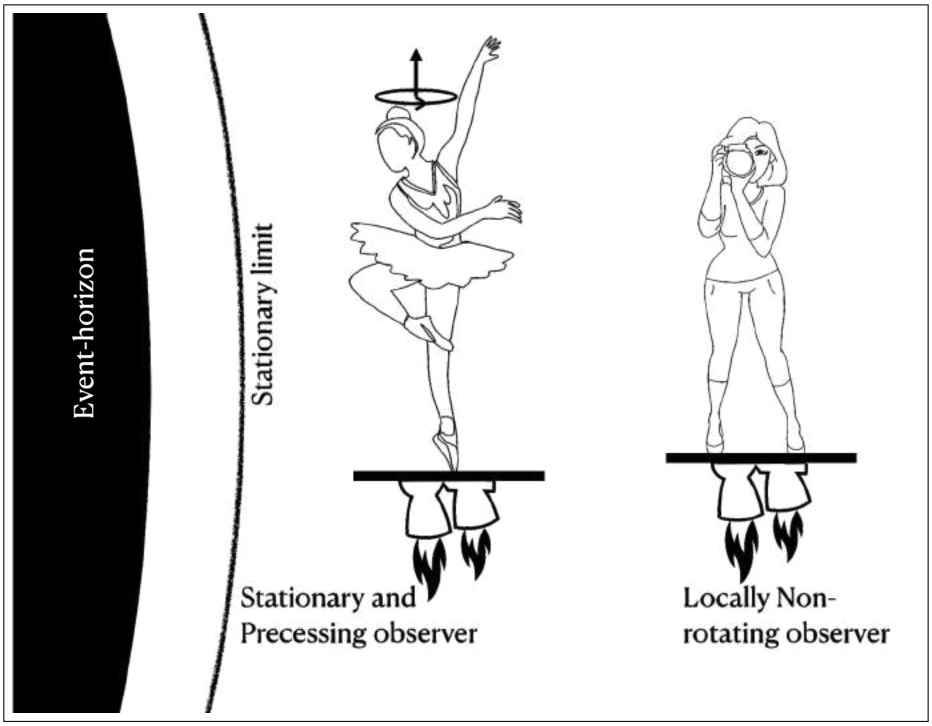

Figure 8. Stationary and locally non-rotating observer around Kerr black hole.

servers who co-rotate with the frame-dragging angular velocity ω at the given location and remain stationary with $R = const.$, but rotating. They are well-defined everywhere outside the horizon. If they carry a gyroscope, it will not process because the observer and gyroscope share the same angular velocity ω.

Vishu and his co-workers generalised the non-rotating observers to general axially symmetric space times (*Figure* 8).

Gyroscopes are vital in understanding the rotational effects in black hole spacetimes. Precession of the gyroscope can pin down the footprints of phenomena such as the dragging of inertial frames. Gravity Probe B indeed verified that the Earth's rotational field is consistent with general relativity. Vishu and his long-time collaborator, Bala Iyer, formulated gyroscopic precession [12] in the framework of Frenet–Serret formalism. The Frenet–Serret formalism describes the geometry of curves and is fundamental to a set of trajectories. This formalism relates the precession frequency of a gyroscope directly to the geometry of the path.

In the End

Vishu's outstanding and impactful scientific work provided one of the most effective and powerful tools in quasinormal modes for black hole and gravitational wave physics; he set the ball rolling for probing the stability of black holes, which kept the likes of Chandrasekhar engaged for nearly a decade.

Vishu's outstanding and impactful scientific work provided one of the most effective and powerful tools in quasinormal modes for black hole and gravitational wave physics; he set the ball rolling for probing the stability of black holes, which kept the likes of Chandrasekhar engaged for nearly a decade. On the other hand, he has left a glorious legacy in science outreach and education. At the planetarium, he initiated and promoted several innovative and interesting programmes such as SEED (Science Education in Early Development), SOW (Science Over Weekends), REAP (Research Education Advancement Programme in Physical Sciences) and BASE (Bangalore Association of Science Education).

He was a man full of zeal and enthusiasm for knowing and learning everything around him and equally keen on sharing it with others. He had a very pleasant and welcoming disposition with a great sense of subtle and tickling humour that sometimes turned sublime. It was Antonio Machado, who famously said, "*Traveller there is no path, Paths are made by walking*", in the same vein we would like to say, "*There was no path, he made the one by walking.*" That's how we would like to remember him with affection and fondness.

Acknowledgement

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Suggested Reading

[1] J. R Oppenheimer and H. Snyder, On continued gravitational contraction, *Physical Review*, Vol.56, No.5, pp.455–459, 1939.

[2] B. Datt, On a class of solutions of the gravitation equations of relativity, (Über eine Klasse von Lösungen der Gravitationsgleichungen der Relativität), (1938). B. Datt, On a class of solutions of the gravitation equations of relativity, *General Relativity and Gravitation*, Vol.31,, pp.1619–1627, 1999.

[3] S. Chandrasekhar, Stellar configurations with degenerate cores, *The Observatory*, Vol.57, No.727, pp.373–377, 1934.

[4] Amalkumar Raychaudhuri, Relativistic cosmology. I, *Phys. Rev*., Vol.98, No.4, pp.1123–1126, 1955.

[5] R. Penrose, Gravitational collapse and space-time singularities, *Phys. Rev. Lett*., Vol.14, No.3, pp.57–59, 1965.

[6] S. W Hawking, Occurrence of singularities in open universes, *Phys. Rev. Lett*., Vol.15, No.17, pp.689–690, 1965.

[7] M. D Kruskal, Maximal extension of Schwarzschild metric, *Phys. Rev*., Vol.119, No.5, pp.1743–1745, 1960.

[8] R. P Kerr, Gravitational field of a spinning mass as an example of algebraically special metrics, *Phys. Rev. Lett*., Vol.11, No.5, pp.237–238, 1963.

[9] N. Dadhich, Einstein is Newton with space curved, *Current Science*, Vol.109, No.2, pp.260–264, 2015; arxiv:1206.0635.

[10] R. Penrose, Gravitational collapse: The role of general relativity, *Nuovo C. Riv. Ser*., 1, pp.252–276, 1969.

[11] James M. Bardeen, William H. Press, Saul A. Teukolsky, Rotating black holes: Locally nonrotating frames, energy extraction, and scalar synchrotron radiation, *Astrophysical Journal*, Vol.178, pp.347–370, 1972.

[12] B. R Iyer and C. V Vishveshwara, Frenet–Serret description of gyroscopic precession, *Phys. Rev. D*., Vol.48, No.12, pp.5706–5720, 1993.

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