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Homage

# Thanu Padmanabhan - and the Third Revolution in Gravity

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**Abstract.** Prof. Thanu Padmanabhan, affectionately known as Paddy, born and brought up in Thiruvananthapuram, was a renowned Indian theoretical physicist known for his pioneer contribution in understanding gravity as an emergent thermodynamic phenomenon. His research area are general relativity, cosmology, and quantum gravity. In an extraordinary academic career spanning forty-two years, he published more than three hundred research articles, wrote a dozen of highly successful technical and popular books. He mentored about thirty graduate students and postdoctoral fellows. Here I mainly give an overview on his contribution to the emergent gravity paradigm.

## 1. Introduction

Prof. Thanu Padmanabhan, a great Indian theoretical Physicist and a good friend of the Academy of Physics Teachers, passed away on 17th September 2021 at his residence in the Inter University Center for Astronomy and Astrophysics (IUCAA); it was very untimely, occurred at the age of sixty-four and at the height of his research career, while serving as the Distinguished Professor at IUCAA. He is best known for his contribution to understanding gravity as an Emergent Thermodynamic phenomenon.

Padmanabhan was born on March 10, 1957, in Thiruvanathapuram as the son of Mr. Thanu Iyyer and Mrs. Laksmi. He completed the school education in the Govt. School at Karamana, Thiruvananthapuram, and Pre-degree course (equivalent to today's 11 and 12th classes) from Govt. Arts College, Thiruvananthapuram in 1972-74. His B.Sc and M.Sc degrees in Physics were from University College, Thiruvananthapuram during 1974-1977 and 1977-79, under the University of Kerala with first rank and Gold medal. He then joined the Tata Institute of Fundamental Research (TIFR), Mumbai, for Ph.D. under the world-renowned cosmologist and Astrophysicist Prof. Jayant Narlikar, in 1979. Around this time, he got married to Vasanthi, a fellow research scholar in TIFR. In the continued research life of Padmanabhan, the support rendered by Vasanthi was invaluable. He completed his

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Ph.D. in the field of Quantum Cosmology in 1984. He then joined TIFR as a faculty, after a short post-doctoral period at the Institute of Astronomy of Cambridge University, England. Around 1990 he moved to the IUCAA, a research institute started under the leadership of his Ph.D. adviser, Prof. Narlikar. He had a daughter, Dr. Hamsa Padmanabhan, a researcher in Astrophysics. Padmanabhan's passion is theoretical Physics, and he mainly worked in Gravity and cosmology. His significant contribution is understanding Gravity as an emergent phenomenon and is a unique step in understanding Gravity after Newton and Einstein.

## 2. Gravity According to Newton and Einstein

The First theory of gravity was due to Issac Newton in 1965. Newton explained gravity as a force of interaction between massive particles. The theory beautifully explained the laws of planetary motion proposed by Kepler, and it also tells why bodies are falling down. Even though the theory failed to fully explain the shift in Planet Mercury's perihelion, the failure was not noticed adequately because of the relatively small discrepancy. Further, how gravity affects massless particles like light particles is still unknown to this very first law of gravity. With the advent of the special theory of relativity by Albert Einstein in 1905, the handicap of Newton's law of gravity became sky high. Special theory relativity implies a universal limit to the speed (equal to the speed of light in free space, around 3,00,000 km/s) of anything in the universe, whether the massive body, energy, or even interactions like gravity and electromagnetic force, which in turn gives the stunning effect that the time will run differently in different inertial frames. However, on the contrary, Newtonian theory advocate that time is absolute, and gravity influence will propagate with infinite speed. So if the Sun disappears from its location at the center of the solar system, the Earth will change its orbits instantaneously as given by Newtonian gravity. However, as per special relativity, it will take eight minutes for Earth to know the absence of the Sun. This discrepancy motivates Einstein to reformulate gravity

The central principle used by Einstein in formulating the new theory of gravity, known as the General theory of relativity, is the principle of equivalence. This principle states that a uniform gravity is equivalent to a uniformly accelerated frame in a local region of spacetime. Combining this principle with special relativity, Einstein could conclude that gravity will manifest as the curvature of spacetime, produced by the presence of matter. Thus gravity becomes a geometric theory of spacetime and is not a force as envisaged by Newton. So the planet Earth orbiting Sun is not due to any force between them, but the massive Sun will curve the spacetime around it and Earth, even though moving in a straight line through this curved spacetime, its path automatically becomes curved. Einstein immediately solved the discrepancy in the perihelion shift of planet Mercury, using this general theory of relativity. However, the intriguing prediction by this theory is about the bending of light. As the spacetime is curved, like matter, the path of light is also bent naturally, thus resolving the all-time problem about gravity's effect on light. Around 1919, Sir. Arthur Eddington and the team observationally verified this during a solar eclipse. The general theory of relativity predicts many new phenomena alien to the Newtonian theory of gravity. It predicts the existence of exotic objects like a black hole, the existence of gravitational waves, etc. All these things were verified by cosmological observation.

## 3. Is Einstein's Gravity Theory Complete?

During the later part of the 20th century, many have suspected that even Einstein's theory has some very serious drawbacks. The First among them is the existence of singularity, in which Einstein's theory breaks down completely in the situation of intense gravitation field. It is impossible to predict the ultimate fate of black holes and the events that occurred in the very initial epoch of our universe because, in these situations, Einstein's theory loses its predictive power due to the occurrence of singularity. It was expected that such problems could be eliminated once this theory was combined with the quantum theory. Here comes the second most crucial failure, that so far, there is no successful theory of quantum gravity. From its proposal, attempts were made to unify the general theory with the second significant contribution of the 20th century, the quantum theory. Unfortunately, no success till today. Another problem is that the gravity theory by Einstein does not respect one of the symmetries possessed by the matter world. This symmetry is in the freedom to fix the zero-level of potential of energy. If one redefine the zero level of the potential energy, the equation of motion does not change in the dynamics of the matter world. But since in Einstein's theory, the curvature of spacetime is very much related to the energy associated with the matter, when one changes the zero level of the energy, the curvature will change. As a result, the symmetry in the matter sector in fixing the zero level is not there in the gravity described by General relativity. Due to these reasons, one may speculate that Einstein's theory of gravity may not be the correct theory of gravity.

## 4. Padmanabhan's View on Gravity - Emergent Gravity Paradigm

Around 2000, in an article submitted to the Gravity Research Foundation, USA, which won the third prize, Padmanabhan restructured the Einstein equation of gravity as a fundamental thermodynamic law. Through this, it was shown that gravity is the thermodynamics of spacetime. Thermodynamics is the science of hot bodies. So if gravity is the thermodynamics of spacetime, it immediately implies that like matter or fluids, the spacetime can carry heat; that is, it can be hot.

To understand the consequence of this idea, it is needed to go back two centuries back when the scientists were trying to understand heat?. It was thought that heat was some fluid called calorie, having no mass, color, or weight, which flows from hot to cold bodies. Around 1865, Ludwig Boltzmann stated that heat is a form of energy. Moreover, he speculated that the matter should be made of microscopic particles for carrying heat. This remarkable proposal was made when the scientific world had no idea about atoms or molecules, which rendered the idea of Boltzmann revolutionary. Following the speculation of Boltzmann, Padmanabhan postulated that, since spacetime can carry heat, it must also have microscopic structures, say atoms of spacetime, technically called microscopic degrees of freedom. In the case of matter, Boltzmann obtained that there contain about $10^{23}$ atoms in one mole of any substance, which was later confirmed by observations. Correspondingly, Padmanabhan calculated that in $cm^2$ of spacetime area, there exists around $10^{66}$ number of spacetime atoms. This implies that the spacetime atoms are so tiny compared to the atoms of matter. This makes the direct observation of the spacetime atoms a Gedaken effort, which may not be feasible in the coming decades.

Padmanabhan moved further in this direction. Standard thermodynamic parameters like temperature, pressure, volume, density, etc., were the properties of matter as a whole or termed macroscopic properties. For instance, when one says that the temperature of a glass of water is 30 0 C, it refers to the temperature of water in the glass as a whole and not the molecule's temperature. As a matter of fact, water molecules have only kinetic energy, and the average of the kinetic energies of all the molecules is what is experienced as the temperature. Hence the macroscopic property, like temperature, has no significance in the microscopic level of molecules or atoms. Such properties like temperature, pressure, density, etc come into existence when molecules come together to form a continuum substance. In short, thermodynamics is a property of the macroscopic world only or can be called an emergent property. This gives an essential turn in the idea of gravity due to Padmanabhan. When you understand that gravity is the thermodynamics of spacetime, then like the thermodynamics of matter, gravity too is an emergent property, which does not exist in the microscopic world of spacetime atoms. This gave the name of the proposal of Padmanabhan's concept on gravity as Emergent Gravity. If so, gravity cannot be considered a fundamental property since it does not exist at the microscopic level of the spacetime but is only an emergent property of the macroscopic spacetime continuum.

## 5. Conclusion

In 1665, Issac Newton speculated that gravity is the force between massive particles. However, in 1905, it came to understand that the Newtonian theory is incompatible with the special theory of relativity. In 1915, Einstein formulated a modified theory of gravity, known as the General relativity theory, which led to the revolutionary idea on gravity that it could be the curvature on the spacetime produced due to the presence of matter, thus removing the misconception that gravity can be a force. In around 2000, Prof. Padmanabhan argued that gravity could be an emergent phenomenon, and thus properties like spacetime curvature, geometry, etc., have meaning only at the macroscopic level. Genuinely speaking, gravity is the thermodynamics of spacetime and may not be a fundamental property. So in a way, Einstein's idea that gravity is the spacetime curvature can be a misconception. The new concept is that gravity could be the thermodynamics of spacetime; if so, it may not be a fundamental thing as we thought. This is a revolutionary development towards our understanding of gravity.

## Notes and References

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