Forces of nature: Padmanabhan and gravitation

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Plan of the talk

1. Thanu Padmanabhan: Personal and academic history
2. Some personal reminiscences
3. Significant contributions to research
   - Early years ($\sim$ 1978–1992)
   - Intermediate years ($\sim$ 1993–2004)
   - Later years ($\sim$ 2005–2021)
4. Closing remarks

Plan of the talk

Personal history[1]

- Date of birth: March 10, 1957
- Place of birth: Thiruvananthapuram
- Parents: Lakshmi and Thanu Iyer
- Thanu Iyer worked in the forest department of the Government of Kerala

Paddy's parents.

Back

Paddy in September 2021

[1] Photos from Mathrubhumi (Malayalam Weekly), September 19, 2021.

Early education[2]

- 1963–1972, I–X Standard, Government Karamana High School, Thiruvananthapuram
- 1973–1974, Pre-degree, Government Arts College, Thiruvananthapuram
- 1974–1977, B.Sc. Physics, University College, Thiruvananthapuram
- 1977–1979, M.Sc. Physics, University College, Thiruvananthapuram

[2] See J. S. Bagla and S. Engineer, *Prof. Padmanabhan: A personal and professional History*, in *Gravity and the Quantum*, Eds. J. S. Bagla and S. Engineer (Springer, Berlin, 2017).

Influential textbooks

- Berkeley Physics Course, Volumes I–V
- Feynman Lectures on Physics, Volumes I–III
- Landau and Lifshitz's Course of Theoretical Physics, Volumes I–X
- Misner, Thorne and Wheeler's Gravitation

First publication

Solutions of scalar and electromagnetic wave equations in the metric of gravitational and electromagnetic waves

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Address for Correspondence: T.C. 38/130, First Puthan Street, Manacad, Trivandrum 695 009

MS received 23 May 1977

Abstract. The wave equation for a scalar field φ and vector potential A^a are solved in the background metric of a gravitational wave. The corresponding solutions when the metric is generated by a plane electromagnetic wave, is obtained from these solutions. The solution for the scalar wave is discussed in detail. It is found that because of the interaction, two new waves are generated in the lower order approximations. One of them has the same phase dependence as the original wave while the other shows a transient character. There is no interaction when the waves are along the same direction.

Keywords. Gravitational wave; scalar wave; electromagnetic wave; photon-photon interaction; photon graviton interaction.

Paddy's very first paper, written as he was completing his B.Sc. at University College, Thiruvananthapuram[3].

[3] T. Padmanabhan, Pramana **9**, 371 (1977).

Later academic history

- 1979–1980, Doctoral student, Tata Institute of Fundamental Research, Mumbai
- 1980–1983, Research Associate, Tata Institute of Fundamental Research, Mumbai
  Thesis supervisor: Jayant Narlikar
- 1980–1992, Faculty, Tata Institute of Fundamental Research, Mumbai
- 1992–2021, Faculty, Inter-University Centre for Astronomy and Astrophysics, Pune

Primary research interests[4]

- Quantum Theory
- Gravitation
- Cosmology and Structure Formation in the Universe

[4] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Doctoral students[5]

1. T. R. Seshadri (University of Delhi)
2. T. P. Singh (TIFR, Mumbai)
3. J. S. Bagla (IISER, Mohali)
4. L. Sriramkumar (IIT Madras)
5. K. Srinivasan (CFL, Bengaluru)
6. S. Shankaranarayanan (IIT Bombay)
7. Sunu Engineer (CEO of Embedded Computing Machines, Pune)
8. T. Roy Choudhury (NCRA, Pune)
9. Sudipta Sarkar (IIT, Gandhinagar)
10. Gaurang Mahajan (NCCS, Pune)
11. Dawood Kothawala (IIT Madras)
12. Sanved Kolekar (IIA, Bengaluru)
13. Suprit Singh (IIT, Delhi)
14. Krishna Parattu (IIT Madras)
15. Sumanta Chakraborty (IACS, Kolkata)
16. Karthik Rajeev (IIT Bombay)

Joint students

17. Nissim Kanekar (NCRA, Pune)
18. Ali Nayeri (Chapman University, California, USA).

[5] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Books I: 1986-2006

1. J. V. Narlikar and T. Padmanabhan, *Gravity, Gauge Theories and Quantum Cosmology* (Reidel, Holland, 1986)
2. T. Padmanabhan, *Structure Formation in the Universe* (Cambridge University Press, Cambridge, England, 1993)
3. T. Padmanabhan, *Cosmology and Astrophysics through Problems* (Cambridge University Press, Cambridge, England, 1996)
4. T. Padmanabhan, *After the First Three Minutes—The Story of our Universe* (Cambridge University Press, Cambridge, England, 1998)
5. T. Padmanabhan, *Theoretical Astrophysics—Volume I: Astrophysical Processes* (Cambridge University Press, Cambridge, England, 2000)
6. T. Padmanabhan, *Theoretical Astrophysics—Volume II: Stars and Stellar Systems* (Cambridge University Press, Cambridge, England, 2001)
7. T. Padmanabhan, *Theoretical Astrophysics—Volume III: Galaxies and Cosmology* (Cambridge University Press, Cambridge, England, 2002)
8. T. Padmanabhan, *An Invitation to Astrophysics* (World Scientific, Singapore, 2006)

Books II: 2007-2019

9. T. Padmanabhan, *Quantum Themes: The Charms of the Microworld* (World Scientific, Singapore, 2009)
10. T. Padmanabhan, *Gravitation: Foundations and Frontiers* (Cambridge University Press, Cambridge, England, 2010)
11. T. Padmanabhan, *Sleeping Beauties in Theoretical Physics* (Springer, Heidelberg, 2015)
12. T. Padmanabhan, *Quantum Field Theory: The Why, What and How*, (Springer, Heidelberg, 2016)
13. T. Padmanabhan and V. Padmanabhan, *The Dawn of Science: Glimpses from History for the Curious Mind* (Springer, Heidelberg, 2019)

Awards and distinctions: 1977–2000[6]

- 1977, Gold medalist, B.Sc., Kerala University
- 1979, Gold Medalist, M.Sc., Kerala University
- 1984–1989, Young Associate of Indian Academy of Sciences
- 1984, INSA Young Scientist Award; Fifth Prize in Gravity Essay Contest (awarded by Gravity Research Foundation, USA)
- 1991, Fellow, Indian Academy of Sciences; Birla Science Prize
- 1993, Fellow, National Academy of Sciences
- 1995, Fellow, Maharashtra Academy of Sciences,
- 1996, Shanti Swarup Bhatnagar Award
- 1997, A. C. Banerji Memorial Lecture Award
- 2000, Millennium Medal (CSIR)

[6] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Awards and distinctions: 2001–2010[7]

- 2001, Fellow, Indian National Science Academy
- 2002, Sackler Distinguished Astronomer, Institute of Astronomy, Cambridge; Al-Khwarizmi International Award; Second Prize in Gravity Essay Contest
- 2003, Homi Bhabha Fellowship; Fifth Prize in Gravity Essay Contest; G. D. Birla Award for Scientific Research
- 2004, Miegunah Fellowship Award, University of Melbourne, Australia
- 2006, Third Prize in Gravity Essay Contest
- 2007, Padma Shri
- 2007, INSA Vainu-Bappu Medal
- 2008, First Prize in Gravity Essay Contest
- 2008, J. C. Bose Fellowship, Department of Science and Technology
- 2009, Infosys Science Prize in Physical Sciences, Infosys Science Foundation

[7] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Awards and distinctions: 2011–2021[8]

- 2011, Third World Academy of Sciences Prize in Physics
- 2012, Fifth Prize in Gravity Essay Contest; Fellow, Third World Academy of Sciences
- 2012–2013, Goyal Prize in Physical Sciences
- 2014, Third Prize in Gravity Essay Contest; Homi Bhabha Lecturer at UK (IoP-IPA award),
- 2018, Fourth Prize in Gravity Essay Contest
- 2019, M. P. Birla Memorial Award
- 2020, Fifth Prize in Gravity Essay Contest
- 2021, Fourth Prize in Gravity Essay Contest
- 2021, Kerala Sasthra Puraskaram (Lifetime Achievement Award of Government of Kerala)

▸ Paddy's photo

[8] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Key visiting positions abroad[9]

- Senior Visiting Fellow, Institute of Astronomy, Cambridge, UK, April–May 1993
- Visiting Faculty, Princeton University, USA, September–November 1994, May 1996
- Visiting Faculty, Pennsylvania State University, USA, May–June 1995
- Visiting Faculty, Caltech, USA, June 1996, April–May 1997, April–May 1998, April-May 1999
- Visiting Faculty, Institute of Astronomy, Cambridge, May 2001
- Sackler Distinguished Astronomer, Institute of Astronomy, Cambridge, July–August 2002, July–September 2003, June–July 2009, June-August 2011
- Visiting Professor, Pauli Center for Theoretical Studies, ETH, Zurich, May–July 2018

[9] Source https://www.iucaa.in/~paddy/biodata/mycv.htm.

Plan of the talk

Paddy's approach to students

Paddy, in 1992, after winning the Birla Science Prize.

If I have a problem and I can solve it, why should I give it to you!

My first glimpse of Paddy's sharpness

Before concluding this section we shall provide an asymptotic formula for the detector response with any smooth window function of the form $W(\tau/T)$. This is a direct generalization of the results in (57)–(61). For such a window function we can write

$$\mathcal{F}(\Omega, T) = \int_{-\infty}^{\infty} \mathrm{d}\tau \int_{-\infty}^{\infty} \mathrm{d}\tau'\, W(\tau, T) W(\tau', T) \mathrm{e}^{-\mathrm{i}\Omega(\tau-\tau')} G^{+}(\tau - \tau')$$

$$= W\left(\mathrm{i}\frac{\partial}{\partial\Omega}, T\right) W\left(-\mathrm{i}\frac{\partial}{\partial\Omega}, T\right) \mathcal{F}(\Omega). \qquad (78)$$

Expanding $W(\tau, T) = W(\tau/T)$ as a Taylor series around $\tau = 0$ and assuming that $W(0) = 1$, $W'(0) = 0$, i.e.

$$W\left(\frac{\tau}{T}\right) \simeq W(0) + W'(0)\left(\frac{\tau}{T}\right) + \tfrac{1}{2} W''(0)\left(\frac{\tau}{T}\right)^{2} \simeq 1 + \tfrac{1}{2} W''(0)\left(\frac{\tau}{T}\right)^{2}, \qquad (79)$$

we obtain that

$$\mathcal{F}(\Omega, T) \simeq \left(1 - \frac{W''(0)}{2T^2}\frac{\partial^2}{\partial\Omega^2}\right)^{2} \mathcal{F}(\Omega) \simeq \mathcal{F}(\Omega) - \frac{W''(0)}{T^2}\frac{\partial^2[\mathcal{F}(\Omega)]}{\partial\Omega^2}. \qquad (80)$$

This gives the rate to be

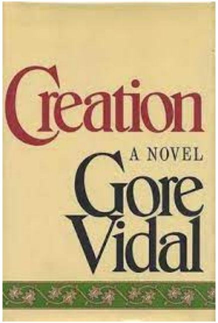
$$\mathcal{R}(\Omega, T) = \mathcal{R}(\Omega) - \frac{W''(0)}{T^2}\frac{\partial^2[\mathcal{R}(\Omega)]}{\partial\Omega^2} + \mathrm{O}\left(\frac{1}{T^4}\right), \qquad (81)$$

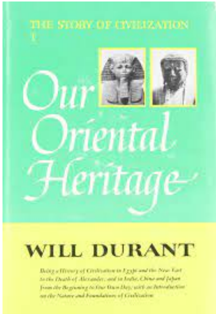
for any window function and trajectory. Note that the response at finite T depends on the derivatives of the window function, e.g. $W''(0)$. Hence, if the detector is switched on abruptly, these derivatives will diverge, thereby leading to divergent responses. We shall discuss this case explicitly in the following section.

Identifying the source of divergences in the response of Unruh-DeWitt detectors that are switched on a finite time interval[10].

[10] L. Sriramkumar and T. Padmanabhan, Class. Quantumy Grav. **13**, 2061 (1996).

Examples of Paddy's outlook





Gore Vidal: . . . I was obliged yesterday to listen for nearly six hours to a self-styled historian whose account of what the Athenians like to call "the Persian Wars" was nonsense. . . . But then, I know the origin of the *Greek* wars.

Will Durant: Perhaps, in return for conquest, arrogance and spoliation, India, will teach us the tolerance and gentleness of the mature mind, the quiet content of the unacquisitive soul, the calm of the understanding spirit and a unifying, pacifying love for all living things.

Plan of the talk

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Plan of the talk

Avoiding singularities in quantum cosmology

QUANTUM COSMOLOGY VIA PATH INTEGRALS

Jayant V. NARLIKAR and T. PADMANABHAN
Tata Institute of Fundamental Research, Bombay-400005, India

Received May 1983

Contents:

By quantizing the conformal degrees of freedom associated with the gravitational field, Paddy was able to show that singularities such as the big bang can be circumvented[11].

[11] J. V. Narlikar and T. Padmanabhan, Phys. Rept. **100**, 151 (1983).

Role of Planck length in quantum field theories

Physical Significance of Planck Length

T. PADMANABHAN

Astrophysics Group,
Tata Institute of Fundamental Research,
Homi Bhabha Road, Bombay 400 005, India

Received August 14, 1984

The significance of Planck length in a quantum gravity model is investigated by concentrating on the conformal degree of freedom. It is shown that Planck length is a lower bound to physical proper length in any space-time. It is impossible to construct an apparatus which will measure length scales smaller than Planck length. These effects exist even in flat space-time because of vacuum fluctuations of gravity. It is shown that these fluctuations lead to a high energy cut-off in flat space field theories, thereby removing the divergence problem. The one-loop corrections to a self interacting scalar field is computed and shown to be finite.

By integrating out the conformal fluctuations, Paddy had shown that the propagator of quantum fields will be regulated by the Planck length at short distances[12]. Back to PID

[12] T. Padmanabhan, Ann. Phys. **165**, 38 (1985).

Non-inertial frames and the Unruh effect

GENERAL COVARIANCE, ACCELARATED FRAMES AND THE PARTICLE CONCEPT

T. PADMANABHAN
Tata Institute of Fundamental Research, Bombay, India

(Received 11 September, 1981)

Abstract. The definition of particle states in various accelerated frames is considered. It is shown that in any realistically accelerated system, quantum field theory can be formulated without any ambiguity. We further show that the definition of a particle based on Green's function techniques does not always agree with the definition based on explicit quantization. We analyse the standard accelerated detector results from this point of view and show that the uncertainty principle imposes a rigorous bound on these detection processes.

In this work, Paddy had examined the behavior of quantum fields in different non-inertial frames in flat spacetime with the aim of understanding whether the notion of a particle is a generally covariant concept[13].

[13] T. Padmanabhan, Astrophys. Space. Sci. **83**, 247 (1982).

Statistical mechanics of gravitating systems

STATISTICAL MECHANICS OF GRAVITATING SYSTEMS

T. PADMANABHAN

Theoretical Astrophysics Group, Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India

Received August 1989

Contents:

In this work, Paddy discusses the statistical description of a system containing a large number of particles which interact via Newtonian gravity[14].

[14] T. Padmanabhan, Phys. Rept. **188**, 285 (1988).

Plan of the talk

Path integral duality and zero-point length

Duality and Zero-Point Length of Spacetime

T. Padmanabhan*

IUCAA, Post Bag 4, Ganeshkhind, Pune 411 007, India

(Received 27 August 1996)

The action for a relativistic free particle of mass m receives a contribution $-mds$ from a path of infinitesimal length ds. Using this action in a path integral, one can obtain the Feynman propagator for a spinless particle of mass m. Assuming that the path integral amplitude is invariant under the "duality" transformation $ds \to L_P^2/ds$, one can calculate the modified Feynman propagator. I show that this propagator is the same as the one obtained by assuming that quantum effects of gravity lead to modification of the spacetime interval $(x-y)^2$ to $(x-y)^2 + L_P^2$. The implications of this result are discussed. [S0031-9007(97)02531-3]

PACS numbers: 04.60.–m, 03.65.Db

Paddy, using a method of 'path integral duality', had shown that propagators in quantum field theories are regulated at small length scales[15].

▸ Zero-point length

[15] T. Padmanabhan, Phys. Rev. Letts. **78**, 1854 (1997)).

Method of complex paths

Particle production and complex path analysis

K. Srinivasan* and T. Padmanabhan†
IUCAA, Post Bag 4, Ganeshkhind, Pune 411 007, India
(Received 11 December 1998; published 14 June 1999)

This paper discusses particle production in Schwarzschild-like spacetimes and in a uniform electric field. Both problems are approached using the method of complex path analysis which is used to describe tunnelling processes in semiclassical quantum mechanics. Particle production in Schwarzschild-like spacetimes with a horizon is obtained here by a new and simple semiclassical method based on the method of complex paths. Hawking radiation is obtained in the (t,r) coordinate system of the standard Schwarzschild metric *without* requiring the Kruskal extension. The coordinate singularity present at the horizon manifests itself as a singularity in the expression for the semiclassical propagator for a scalar field. We give a prescription whereby this singularity is regularized with Hawking's result being recovered. The equation satisfied by a scalar field is also reduced to solving a one-dimensional effective Schrödinger equation with a potential $(-1/x^2)$ near the horizon. Constructing the action for a fictitious nonrelativistic particle moving in this potential and applying the above mentioned prescription, one again recovers Hawking radiation. In the case of the electric field, standard quantum field theoretic methods can be used to obtain particle production in a purely time-dependent gauge. In a purely space-dependent gauge, however, the tunnelling interpretation has to be resorted to in order to recover the previous result. We attempt, in this paper, to provide a tunnelling description using the formal method of complex paths for both the time and space dependent gauges. The usefulness of such a common description becomes evident when "mixed" gauges, which are functions of both space and time variables, are analyzed. We report, in this paper, certain mixed gauges which have the interesting property that mode functions in these gauges are found to be a combination of *elementary* functions unlike the standard modes which are transcendental parabolic cylinder functions. Finally, we present an attempt to interpret particle production by the electric field as a tunnelling process between the two sectors of the Rindler spacetime.
[S0556-2821(99)07012-5]

PACS number(s): 04.70.Dy, 04.62.+v, 12.20.−m

Paddy's work with his doctoral student K. Srinivasan wherein they had determined the extent of particle production in external fields by adopting a novel method of considering integrals over complex paths[16].

[16] K. Srinivasan and T. Padmanabhan, Phys. Rev. D **60**, 24007 (1999).

Can dark energy and dark matter be attributed to a common source?

Can the clustered dark matter and the smooth dark energy arise from the same scalar field?

T. Padmanabhan* and T. Roy Choudhury
IUCAA, Ganeshkhind, Pune 411 007, India

(Received 8 May 2002; published 29 October 2002)

Cosmological observations suggest the existence of two different kinds of energy densities dominating at small ($\lesssim$500 Mpc) and large ($\gtrsim$1000 Mpc) scales. The dark matter component, which dominates at small scales, contributes $\Omega_m \approx 0.35$ and has an equation of state $p=0$, while the dark energy component, which dominates at large scales, contributes $\Omega_V \approx 0.65$ and has an equation of state $p \simeq -\rho$. It is usual to postulate weakly interacting massive particles (WIMPs) for the first component and some form of scalar field or cosmological constant for the second component. We explore the possibility of a scalar field with a Lagrangian $L=-V(\phi)\sqrt{1-\partial^i\phi\partial_i\phi}$ acting as *both* clustered dark matter and smoother dark energy and having a scale-dependent equation of state. This model predicts a relation between the ratio $r=\rho_V/\rho_{\rm DM}$ of the energy densities of the two dark components and an expansion rate n of the universe [with $a(t) \propto t^n$] in the form $n=(2/3)(1+r)$. For $r \approx 2$, we get $n \approx 2$ which is consistent with observations.

DOI: 10.1103/PhysRevD.66.081301 PACS number(s): 98.80.Cq, 95.35.+d

Paddy's work with his doctoral student Tirthankar Roy Choudhury on examining if there can be a common source for dark energy and dark matter[17].

[17] T. Padmanabhan and T. Roy Choudhury, Phys. Rev. D 66, 081301 (2002).

Tachyons as dark energy

Cosmology with tachyon field as dark energy

J. S. Bagla*
Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad-211 019, India

H. K. Jassal† and T. Padmanabhan‡
Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune-411 007, India
(Received 10 December 2002; published 14 March 2003)

We present a detailed study of cosmological effects of homogeneous tachyon matter coexisting with non-relativistic matter and radiation, concentrating on the inverse square potential and the exponential potential for the tachyonic scalar field. A distinguishing feature of these models (compared to other cosmological models) is that the matter density parameter and the density parameter for tachyons remain comparable even in the matter dominated phase. For the exponential potential, the solutions have an accelerating phase, *followed by* a phase with $a(t) \propto t^{2/3}$ as $t \rightarrow \infty$. This eliminates the future event horizon present in cold dark matter models with a cosmological constant (ΛCDM) and is an attractive feature from the string theory perspective. A comparison with supernova type Ia data shows that for both the potentials there exists a range of models in which the universe undergoes an accelerated expansion at low redshifts which are also consistent with the requirements of structure formation. They do require fine-tuning of parameters but not any more than in the case of Λ CDM models or quintessence models.

DOI: 10.1103/PhysRevD.67.063504 PACS number(s): 98.80.Cq, 95.35.+d

Paddy's work with his former doctoral student Jasjeet Bagla and postdoctoral fellow Harvinder Jassal on examining tachyons as a candidate for dark energy [18].

[18] J. S. Bagla, H. K. Jassal and T. Padmanabhan, Phys. Rev. D **67**, 063504 (2003).

Nature of the cosmological constant

Cosmological constant—the weight of the vacuum

T. Padmanabhan

IUCAA, Pune University Campus, Ganeshkhind, Pune 411 007, India

Accepted 1 March 2003
editor: M.P. Kamionkowski

Abstract

Recent cosmological observations suggest the existence of a positive cosmological constant Λ with the magnitude $\Lambda(G\hbar/c^3) \approx 10^{-123}$. This review discusses several aspects of the cosmological constant both from the cosmological (Sections 1–6) and field theoretical (Sections 7–11) perspectives. After a brief introduction to the key issues related to cosmological constant and a historical overview, a summary of the kinematics and dynamics of the standard Friedmann model of the universe is provided. The observational evidence for cosmological constant, especially from the supernova results, and the constraints from the age of the universe, structure formation, Cosmic Microwave Background Radiation (CMBR) anisotropies and a few others are described in detail, followed by a discussion of the theoretical models (quintessence, tachyonic scalar field, ...) from different perspectives. The latter part of the review (Sections 7–11) concentrates on more conceptual and fundamental aspects of the cosmological constant like some alternative interpretations of the cosmological constant, relaxation mechanisms to reduce the cosmological constant to the currently observed value, the geometrical structure of the de Sitter spacetime, thermodynamics of the de Sitter universe and the role of string theory in the cosmological constant problem.

PACS: 98.80.−k; 98.80.Es; 98.80.Cq; 98.80.Qc; 04.60.−m

Keywords: Cosmological constant; Dark energy; Cosmology; CMBR; Quintessence; de Sitter spacetime; Horizon; Tachyon; String theory

Paddy's review on the cosmological constant[19].

[19] T. Padmanabhan, Phys. Rept. **380**, 235 (2003).

Plan of the talk

Gravitation and the thermodynamics of horizons

Gravity and the thermodynamics of horizons

T. Padmanabhan

IUCAA, Post Bag 4, Ganeshkhind, Pune 411 007, India

Accepted 13 October 2004
editor: M.P. Kamionkowski
Available online 8 December 2004

Abstract

Spacetimes with horizons show a resemblance to thermodynamic systems and it is possible to associate the notions of temperature and entropy with them. Several aspects of this connection are reviewed in a manner appropriate for broad readership. The approach uses two essential principles: (a) the physical theories must be formulated for each observer entirely in terms of variables any given observer can access and (b) consistent formulation of quantum field theory requires analytic continuation to the complex plane. These two principles, when used together in spacetimes with horizons, are powerful enough to provide several results in a unified manner. Since spacetimes with horizons have a generic behaviour under analytic continuation, standard results of quantum field theory in curved spacetimes with horizons can be obtained directly (Sections 3–7). The requirements (a) and (b) also put strong constraints on the action principle describing the gravity and, in fact, one can obtain the Einstein–Hilbert action from the thermodynamic considerations (Section 8). The review emphasises the thermodynamic aspects of horizons, which could be obtained from general principles and is expected to remain valid, independent of the microscopic description ('statistical mechanics') of horizons.

PACS: 04.70.−s; 04.70.Dy

Keywords: Black hole; Quantum theory; Entropy; Horizon; Einstein–Hilbert action

Paddy's initial review highlighting the resemblance of spacetimes with horizons to thermodynamic systems, which allow association of notions of temperature and entropy[20].

[20] T. Padmanabhan, Phys. Rept. **406**, 49 (2005).

Extension to modified theories of gravitation

Thermodynamical aspects of gravity: new insights

T Padmanabhan

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Received 25 November 2009
Published 25 March 2010
Online at stacks.iop.org/RoPP/73/046901

Abstract
The fact that one can associate thermodynamic properties with horizons brings together principles of quantum theory, gravitation and thermodynamics and possibly offers a window to the nature of quantum geometry. This review discusses certain aspects of this topic, concentrating on new insights gained from some recent work. After a brief introduction of the overall perspective, sections 2 and 3 provide the pedagogical background on the geometrical features of bifurcation horizons, path integral derivation of horizon temperature, black hole evaporation, structure of Lanczos–Lovelock models, the concept of Noether charge and its relation to horizon entropy. Section 4 discusses several conceptual issues introduced by the existence of temperature and entropy of the horizons. In section 5 we take up the connection between horizon thermodynamics and gravitational dynamics and describe several peculiar features which have no simple interpretation in the conventional approach. The next two sections describe the recent progress achieved in an alternative perspective of gravity. In section 6 we provide a thermodynamic interpretation of the field equations of gravity in any diffeomorphism invariant theory and in section 7 we obtain the field equations of gravity from an entropy maximization principle. The last section provides a summary.

(Some figures in this article are in colour only in the electronic version)

This article was invited by G Gillies.

Paddy's review extending the relation between horizon thermodynamics and gravitational dynamics to modified theories[21].

[21] T. Padmanabhan, Rept. Prog. Phys. **73**, 046901 (2010).

Gravitation as an emergent phenomenon

Lanczos–Lovelock models of gravity

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[b] Department of Physics, IIT Madras, Chennai - 600 036, India

A R T I C L E I N F O

Article history:
Accepted 23 May 2013
Available online 3 June 2013
editor: Marc Kamionkowski

A B S T R A C T

Lanczos–Lovelock models of gravity represent a natural and elegant generalization of Einstein's theory of gravity to higher dimensions. They are characterized by the fact that the field equations only contain up to second derivatives of the metric even though the action functional can be a quadratic or higher degree polynomial in the curvature tensor. Because these models share several key properties of Einstein's theory they serve as a useful set of candidate models for testing the emergent paradigm for gravity. This review highlights several geometrical and thermodynamical aspects of Lanczos–Lovelock models which have attracted recent attention.

Paddy's review with his former doctoral student Dawood Kothawala wherein the so-called paradigm of emergent gravity is discussed in specific modified theories[22].

[22] T. Padmanabhan and D. Kothawala, Phys. Rept. **531**, 115 (2013).

Paradigm of emergent gravity paradigm in other theories

Eddington gravity with matter: An emergent perspective

Sumanta Chakraborty[1,*] and T. Padmanabhan[2,†]

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[2]*Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411007, India*

(Received 25 December 2020; accepted 24 February 2021; published 19 March 2021)

We describe an action principle, within the framework of the Eddington gravity, which incorporates the matter fields in a simple manner. Interestingly, the gravitational field equations derived from this action is identical to Einstein's equations, in contrast with the earlier attempts in the literature. The cosmological constant arises as an integration constant in this approach. In fact, the derivation of the field equations *demands* the existence of a nonzero cosmological constant, thereby providing the *raison d'être* for a nonzero cosmological constant, implied by the current observations. Several features of our approach strongly support the paradigm that gravity is an emergent phenomenon and, in this perspective, our action principle could have a possible origin in the microstructure of the spacetime. We also discuss several extensions of the action principle, including the one which can incorporate torsion into the spacetime. We also show that an Eddington-like action can be constructed to obtain the field equations of the Lanczos-Lovelock gravity.

DOI: 10.1103/PhysRevD.103.064033

Paddy's work with his former doctoral student Sumanta Chakraborty on gravitation as an emergent phenomenon in Eddington gravity[23].

[23] S. Chakraborty and T. Padmanabhan, Phys. Rev. D **103**, 064033 (2021).

Plan of the talk

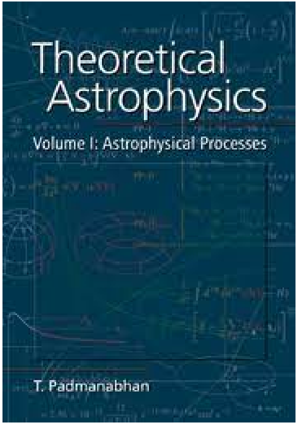
Pursuit of physics

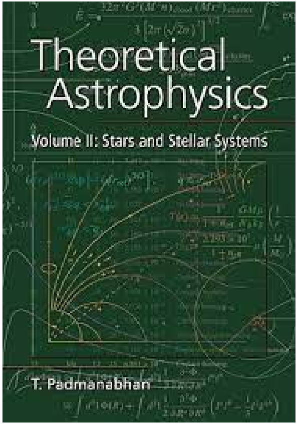
From the preface of *Sleeping Beauties in Theoretical Physics*

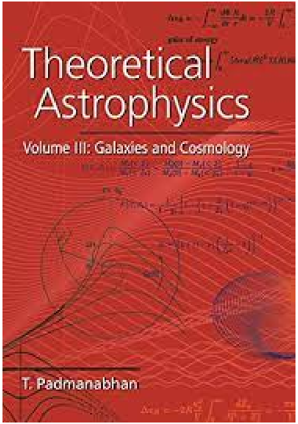
Theoretical physics is fun. Most of us indulge in it for the same reason a painter paints or a dancer dances—the process itself is so enjoyable! Occasionally, there are additional benefits like fame and glory and even practical uses; but most good theoretical physicists will agree that these are not the primary reasons why they are doing it. The fun in figuring out the solutions to Nature's brain teasers is a reward in itself[a].

[a] T. Padmanabhan, *Sleeping Beauties in Theoretical Physics* (Springer, Heidelberg, 2015).

A course on theoretical astrophysics







Paddy's comments from the Preface

The approach used in these three volumes is similar to that used by Gengis Khan, namely, (1) cover as much area as possible, (2) capture the important points, and (3) be utterly ruthless!

Clarity in writing and mastery of the subject

From a review of *Theoretical Astrophysics—Volume I: Astrophysical Processes*

It is written with exceptional clarity, which is the hallmark of Padmanabhan's work, but the reader should be clear that in needing to conquer vast tracks of astrophysical real-estate, prisoners are not taken and the pace is fast. To do this, whilst still providing a book which is understandable and illuminating is a considerable achievement. The approach is rigorous and unashamedly mathematical—surely necessary to obtain proper understanding, and this volume will appeal to, and challenge, astrophysicists who wish to cement their knowledge through mathematics. . . . it is a magnificent achievement and a superb book.[a].

[a] A. Heavens, The Observatory **121**, 197 (2001).

From a review of *Gravitation: Foundations and Frontiers*

There is immense erudition, and mastery of both formal tools and calculational details; it is really impressive that one individual can understand so much, so deeply[a].

[a] J. Peacock, The Observatory **130**, 378 (2010).

With family

Paddy, with wife Vasanthi Padmanabhan, and their daughter Hamsa Padmanabhan[24]

[24] Photo from Mathrubhumi (Malayalam Weekly), September 19, 2021.

With students and grand-students

Paddy with students and grand-students.

Paddy at IIT Madras.

Paddy: A force of nature

Paddy was a *force of nature*, ‘full of energy, unstoppable, unchallengeable, and unforget-table’, much like gravitation that he strived all his life to understand.

Thank you for your attention