Modern developments in general relativity and their historical roots
King’s College London, January 2017

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Gravity at King's - a brief history

- The nineteenth century
- General relativity at King’s 1918-1950
- 1950’s -1971 The Bondi era, gravitational waves and King’s
- 1970-1985 Classical and quantum black holes, quantum gravity

The nineteenth century

- King's College London was inaugurated in 1828 with the suppport of George 1V, various Church of England bishops, clergy and laity and conservative Hanovarian politicians, most notably the Duke of Wellington.

- The first professors were appointed in 1830. The Rev. Thomas G. Hall who was appointed to the chair of mathematics. He had been fifth wrangler in 1824.

- Early in 1831, the first professor of natural and experimental philosophy, including astronomy, was appointed. He was the Rev. Henry Moseley, a thirty year-old Cambridge mathematician who had been seventh wrangler in 1826.

F J C Hearnshaw, *The Centenary History of King's College London*, 1828-1928
G Huelin, *King's College London 1828-1978*

Gravity and nineteenth century King's

- James Clerk Maxwell, appointed at age 29, was the fourth Professor of Natural Philosophy from 1860 to 1865.

(Cyril Domb, *James Clerk Maxwell in London 1860-65*, Notes and Records of the Royal Society of London, 35, 1, 67-103, 1980.)

- From *A Dynamical Theory of the Electromagnetic Field*, Phil. Trans.Roy. Soc., 155, 459-512, 1865

  Gravitation differs from magnetism and electricity in this; that the bodies concerned are all of the same kind, instead of being of opposite signs, like magnetic poles and electrified bodies, and the force between these bodies is an attraction and not a repulsion, as is the case between like electric and magnetic bodies..........The assumption, therefore, that gravitation arises from the action of the surrounding medium in the way pointed out, leads to the conclusion that every part of this medium possesses, when undisturbed, an enormous intrinsic energy, and that the presence of dense bodies influences the medium so as to diminish this energy whenever there is a resultant attraction.
  As I am unable to understand in what way a medium can possess such properties, I cannot go further in this direction in searching for the cause of gravitation."

- William Kingdon Clifford student, Junior Department 1860-63

- From *On the Space-theory of Matter*, Proc.Camb. Phil.Soc.**2**, 157 (1876)

That small portions of space are in fact of a nature analogous to little hills on a surface which is on the average flat; namely, that the ordinary laws of geometry are not valid in them.

That this property of being curved or distorted is continually being passed on from one portion of space to another after the manner of a wave.

That the variation of the curvature of space is what really happens in that phenomenon which we call the motion of matter, whether ponderable or etherial.

That in the physical world nothing else takes place but this variation, subject (possibly) to the law of continuity.

General relativity at King’s 1918-1950

- Albert Einstein’s visit to King’s, June 13, 1921

- In 1921 Viscount Haldane arranged for Einstein to visit England and acted as his host. Einstein spoke at King’s on June 10. Einstein’s London visit is described in *Einstein: The Life and Times*, Ronald W Clark, Hodder & Stoughton London, 1973.

- The Development and the Present Position of the Theory of Relativity

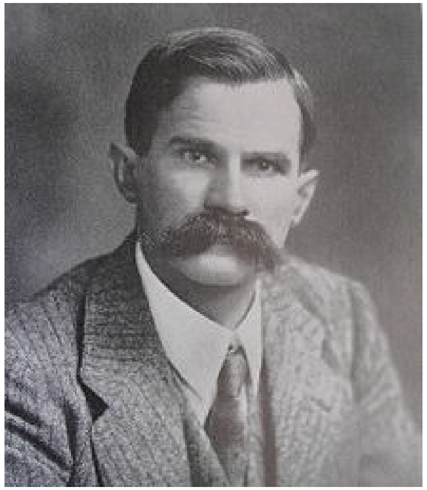
  Einstein spoke in German in a full Great Hall for about an hour. "It is a special joy for me to be able to speak in the capital of the country from where the most important basic ideas of theoretical physics were brought into the world. I think of the theories of the motion of masses and gravitation which Newton gave us, and of the concept of the electromagnetic field by Faraday and Maxwell, which provided physics with a new foundation. One may well say that the theory of relativity brought a kind of conclusion to Maxwell’s and Lorentz’s grand framework of ideas by trying to extend the physics of fields to all of its phenomena, gravitation included."....
  (from Document 58 in *The Collected Papers of Albert Einstein Vol 7*, Princeton University Press)

- In the period 1918-50 a certain amount of research into gravity and general relativity was carried out mainly in the Mathematics Department but also in the Physics Department.

  Most of those who wrote papers about general relativity in this period, Wilson in the Physics Department, Jeffery, Combridge, Temple in the Mathematics Department did so only for a limited time and also engaged on other activities such as research into quantum theory etc. Only one, McVittie, a cosmologist in the Mathematics Department, was primarily engaged in relativistic research.

- The first research paper in general relativity at King's appears to have been written by William Wilson (of the Wilson-Sommerfeld quantization condition in the old quantum theory) who was a member of the Physics Department from 1906 until 1921.

- It was *Relativity and Gravitation*, Proc.Phys.Soc.London, 31, 69-78, (1918). "The motion of a particle in a gravitational field is treated from the point of view of the general theory of relativity." It is shown that the equations of motion can be expressed in Hamiltonian form. "A short outline of the Minkowski theory of Relativity is included in the paper."



- George Jeffery sixth Professor of Mathematics 1922-1924

- Jeffery co-authored the English translation of a collection of important early papers on relativity *The Principle of Relativity*, tr W Perrett & G B Jeffery (first edition 1923). It is still available and used.

- Jeffery (after moving to UCL) co-authored, with O R Baldwin, the first investigation of plane wave solutions of the Einstein-Maxwell equations, *Relativity Theory of Plane Waves*, Proc. Roy. Soc. 111, 757, 95-104, 1926. Metrics of the form

  $$ds^2 = dt^2 - dz^2 - adx^2 - 2bdxdy - cdy^2$$

  where a, b and c are functions of t-z only, were amongst those considered.

  This paper was motivated by results in the linearized theory by Hermann Weyl in *Raum, Zeit , Materie* and Arthur Eddington in *The propogation of gravitational waves,* Proc. Roy. Soc. A 102, 268 (1922), they did not appear to be aware of the papers of H W Brinkman (1923, 1925).

- John Combridge Lecturer in Mathematics1926-1937. Combridge wrote a number of papers in relativity. He went into the College administration in 1937 and eventually became the Registrar until 1962. His contributions included the historically interesting Bibliography of Relativity and Gravitation Theory 1921-1937 (1965)

- George Temple eighth Professor of Mathematics 1932-1953. Temple worked on Alfred North Whitehead's 1922 theory of gravity and various topics in general relativity; also, aerodynamics, quantum mechanics, analysis and the history of mathematics. After retirement he became a monk.

- Geoge McVittie Reader in Mathematics 1936-48. A former student of E Whittaker and A Eddington McVittie had a long and substantial career as a cosmologist both in the UK and in the USA. He had forthright opinions about many of the cosmological controversies of the day e.g. the cosmological constant, the steady state model of the Universe of Bondi, Gold and Hoyle (1948) and so on. He was always concerned to relate theory to observation. During World War two he set up and headed the meteorology division at Bletchley Park.

Two of his notable works were his 1956 book *General Relativity and Cosmology* and the paper *The mass particle in an expanding universe*, Mon.Not.R.Astron.Soc.93, 325 (1933). The latter is of contemporary interest as the solution considered contains a Schwarzschild-de Sitter black hole embedded in an asymptotically ΛCDM cosmology- see e.g. arXiv1106.3666.

The Bondi era 1954 - 1971

Hermann Bondi 1954-1971, Felix Pirani 1955-1983, Clive Kilmister 1950-1983 and many others.

- Hermann Bondi was appointed as the 10th Professor of Mathematics in 1954. He brought in Felix Pirani, his former student at Cambridge, over from the Dublin Institute for Advanced Studies as a Lecturer in Mathematics in 1955 and together with Clive Kilmister, a former student of McVittie, they formed the core of a highly productive and influential general relativity group. Its major contribution in the 1950's and 60's was to the study of gravitational radiation.

- The group was a major centre of activity in significant part because of the hefty financial support provided by the USAF. This enabled the appointment of post-docs and many short-term and long term visitors some of whom made major contributions while at King's. In addition it enabled the wide distribution of notes series of lectures given by visitors and collections of papers.

  J N Goldberg *US Airforce support of general relativity 1956-1972* in Eisenstaedt & Kox A J (eds) Studies in the history of general relativity (Einstein studies, volume 3) pp89-102. Birkhauser (1992).

Gravitational Waves and King's

Background

- In 1916 Einstein solved the linearized equations (as suggested by de Sitter) and found (plane) wave solutions. In 1918 Einstein corrected a calculational error in his plane wave calculation and in 1922 Eddington corrected Einstein's quadrupole formula. In 1936 Einstein and Rosen publish a cylindrical wave solution of the full theory and in 1937 Nathan Rosen claimed there were no gravitational (plane) waves. Doubts about gravitational waves continued to be expressed e.g. by Einstein, Rosen, Leopold Infeld......

- Earlier work of Beck, Brinkman, Baldwin & Jeffery on exact wave solutions appears to have been forgotten.

- The consequence was CONFUSION and uncertainty about the existence of physically significant gravitational wave solutions of Einstein's equations, see - Daniel Kennefick in *Travelling at the speed of thought*, Princeton University Press (2007)

The King's contribution

- In 1955 The Berne conference celebrating the fiftieth anniversary of Einstein's special relativity was attended by Bondi and Pirani. Marcus Fierz told Bondi he was the man to sort out the confusion. Bondi was looking for a suitable topic for a small group in a small department of about 10 people.

- During1954-5 Pirani, in Dublin on a post-doc, with J L Synge and others, started working on research related to gravitational radiation. Pirani never doubted the existence of gravitational waves and thought that an understanding of the radiation field would be important for the quantization of the theory.

- Pirani in *On the physical significance of the Riemann tensor* Acta.Phys. Polon. 15, 389-403 (1956)

  "A difficulty in general relativity theory is the lack of what might be called a theory of measurement. One learns that all coordinate systems are equivalent to one another, but one does not learn systematically how to choose the appropriate coordinate system in which to calculate this or that quantity. Coordinate systems are usually chosen for mathematical convenience, not for physical appropriateness. This would not matter if calculations were always carried out in a manner independent of the coordinate system, but this is not the case. The result is fruitless controversy, like that over the harmonic coordinate system."

  In this paper Pirani assigned orthonormal tetrads to observers to make physically significant measurements and showed that by using the equation of geodesic deviation and a cloud of test particles an observer can determine the full curvature tensor in the vicinity of its world line. He compared this with the measurement of relative accelerations (tidal forces) in Newtonian theory. (He also considered spinning test particles and discontinuities of the Riemann tensor).

- In 1957 the Chapel Hill workshop took place at the University of North Carolina. The lectures and discussions were edited and widely circulated. Pirani's talk dealt with the use of the equation of geodesic deviation as above.

- Peter Saulson, a long-time member of the Ligo consortium has written*, "Nowhere in this one page presentation are gravitational waves mentioned specifically, but it must have been clear to everyone that applying this idea to the gravitational wave question would be one of its most important results. The discussion immediately following this paper makes this obvious."

*Peter Saulson *Josh Goldberg and the physical reality of gravitational waves,* Gen. Relativ. Gravit. 43, 3289-3299 (2011).

- In the discussion following Pirani's talk Bondi asked, "Can one construct in this way an absorber for gravitational energy by inserting an (absorption) term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves." Pirani replied, "I have not put in an absorption term, but I have put in a "spring". You can invent a system with such a term quite easily."

  Richard Feynman, at the workshop, also developed a thought experiment to show the physical effects of such waves . A formulation of the so-called sticky bead argument by Feynman is contained in the report,*The role of gravitation in physics,* now online at: http://www.edition-open-sources.org/sources/5/index.html.

- In 1957 Pirani, having reviewed a paper by McVittie, seen a review of a paper by the Soviet physicist A. Petrov on the algebraic classification of the Weyl tensor, and having helped proof read J L Synge's book *Relativity: the special theory* where he read Synge's geometric and algebraic approach to electromagnetic waves, published the paper *Invariant formulation of Gravitational Radiation theory* Physical Review 105, 1089-1099 (1957). He wrote:

  "The investigation of gravitational radiation in general relativity theory is hampered by the lack of an invariant definition of that concept.....An invariant definition is proposed in this paper. This definition is given in terms of the Riemann tensor.

- Pirani used, and introduced English-speaking readers to, the classification of the Weyl tensor into canonical types by Petrov. (Subsequently this classification was used in the proof of many interesting new mathematical results and in the finding of new exact solutions - including the Kerr metric).

- He proposed that gravitational radiation was present if the Riemann tensor was algebraically special.

- 1957 H Bondi *Plane Gravitational Waves in General Relativity* Nature **179**, 1072-1073

- In this letter Bondi wrote: "Polarized plane gravitational waves were first discovered by N.Rosen, who, however, came to the conclusion that such waves could not exist because the metric would have to contain certain physical singularities. More recent work by Taub and McVittie showed that there were no unpolarized plane waves, and this result has tended to confirm the view that true plane gravitational waves do not exist in empty space in general relativity. Partly owing to this, Scheidegger and I have both expressed the opinion that there might be no energy-carrying gravitational waves at all in the theory. It is of interest to point out, as was first shown by (Ivor) Robinson (footnote: to be published shortly) and has now been independently proved by me that Rosen's arguement is invalid and that true gravitational waves do exist. Moreover it is shown here that these waves carry energy, (the so called sticky bead argument) although it has not yet been possible to relate the intensity of the wave to the amount of energy carried."

- Plane wave metrics were, in fact, first published by the mathematician H W Brinkman in *On Riemann spaces conformal to Euclidean space* Proc. Nat. Acad. Sci. USA 9, 1-3 (1923)

- In 1958 Andrzej Trautman, then a doctoral student being supervised by Leopold Infeld in Warsaw, was invited to visit London by Felix Pirani. He gave five lectures. These were mimeographed, widely circulated, and very influential.

- *Lectures on general relativity* by Andrzej Trautman, Mathematics Department, KCL, May-June 1958:

  1. Boundary conditions in gravitational wave theory
  2 & 3. Equations of motion and gravitational radiation
  4. Three problems of general relativity
  (i) Propogation of gravitational disturbances (ii) Conservation laws and symmetry properties of space-time (iii) The fast approximation method
  5.Equations of motion of rotating bodies.

- C Denson Hill and Pawel Nurowski, *How the green light was given for gravitational research*, arXiv 1608.08637

- Lecture1. Boundary conditions in gravitational wave theory

- This lecture had a direct influence on the King's group. Trautman imposed conditions on the metric at great distances from an isolated system, strong enough so the system could be regarded as having finite total energy but weak enough so that he could regard it as emitting gravitational radiation.

- Using asymptotically Minkowskian coordinates he generalized the Sommerfeld radiation conditions for scalar fields in Minkowski space-time to electromagnetism and general relativity. In his far field analysis of gravitational radiation from bounded sources he evaluated the energy-momentum integral of such systems at infinity and showed that energy could only be radiated away. He also showed that asymptotically the Riemann tensor was of Petrov type N.

- The Bondi group's work included the *Gravitational waves in General Relativity I-XIV* series in the Proceedings of the Royal Society, 12 papers until 1969, one in 1989 by Bondi & Pirani and finally a non KCL paper in 1995. The first nine are

L.Marder *I The cylindrical waves* Proc.Roy.Soc. A 244, 524 (1958)

L.Marder *II The reflexion of cylindrical waves* Proc.Roy.Soc.. A 246, 133 (1958)

H Bondi, F.Pirani & I.Robinson III Exact plane waves Proc.Roy.Soc. A 251, 519 (1959)

F.Pirani *IV The gravitational field of a fast moving particle* Proc.Roy.Soc. A 252, 519 (1959)

L.Marder *V An exact spherical wave* Proc.Roy.Soc. A 261, 91 (1961)

R K Sachs *VI The outgoing radiation condition* Proc.Roy.Soc. A 264,309 (1961)

H.Bondi, M.G.J.van der Burg & A.W.K.Metzner *VII Waves from axi-symmetric isolated systems* Proc.Roy.Soc. A 269,21 (1962)

R.K.Sachs *VIII Waves in asymptotically flat space-time* Proc.Roy.Soc. A 270,103 (1962)

M.G.J.van der Burg *IX Conserved quantities* Proc.Roy.Soc. A 294,112 (1966)

- H Bondi, F.Pirani & I.Robinson *III Exact plane waves* Proc.Roy.Soc. A 251, 519 (1959)

- This paper expanded Bondi's letter above. Working by analogy with electromagnetism, they defined a plane gravitational wave to be a solution of Einstein's vacuum field equations which admits a 5-dimensional group of symmetries. From Petrov's list of solutions with high symmetry they obtained the unique class with these symmetries. It was Petrov type N.

- They considered in detail the simple special case of metrics of the form,

$$ds^2 = (\exp 2\varphi)(d\tau^2 - d\xi^2) - u^2\{\exp(2\beta)d\eta^2 + (\exp -2\beta)d\zeta^2\},$$
$$u = \tau - \xi,\ \beta = \beta(u), \varphi = \varphi(u),\ 2\varphi' = u\beta'^2.$$

  and studied sandwich waves (plane waves joined to flat spaces either side of some range of *u*, and matched by using the A. Lichnerowicz conditions) falling on test particles. They showed that plane waves carry energy.

- The paper ended the long standing controversy about the nature of the singularities by showing that such waves are devoid of any real ones.

- H.Bondi *Gravitational Waves in General Relativity* Nature, **186**, 535 (1960), announced some of the results in

- H.Bondi, M.G.J.van der Burg & A.W.K.Metzner *VII Waves from axi-symmetric isolated systems* Proc.Roy.Soc. A 269,21 (1962). For calculational convenience this paper dealt with axially and reflection symmetric systems.

- These symmetry assumptions were dropped in R.K.Sachs *VIII Waves in asymptotically flat space-time* Proc.Roy.Soc.A270,103(1962).

- "Bondi was the first to give a systematic treatment of quite general metrics describing the radiation from a bounded source" - A.Trautman.

- The Bondi, van der Burg, Metzner paper

  Part A. GENERAL CONSIDERATIONS by H.Bondi F.R.S. 1. Introduction, 2. Causality 3. The loss of mass 4. Huygen's Principle and the change of wave form 5. Method of treatment

  Part B. A SUITABLE COORDINATE SYSTEM by H. Bondi and M.G.J. van der Burg 1. The character of the metric

$$ds^2 = (Vr^{-1}e^{2\beta} - U^2 r^2 e^{2\gamma})du^2 + 2e^{2\beta}dudr$$
$$+2Ur^2 e^{2\gamma}dud\theta - r^2(e^{2\gamma}d\theta^2 + e^{-2\gamma}\sin^2\theta d\phi^2)$$

  2. The structure of the field equations 3. The main equations 4. The outgoing wave condition
  5. The supplementary conditions 6. The static case 7. The curvature tensor

  Part C. PERMISSABLE COORDINATE TRANSFORMATIONS by A.W.K.Metzner
  1. Evaluation of the transformations by power series 2. Rigorous transformations of Minkowski space

  Part D. THE NATURE OF THE SOLUTIONS by H.Bondi F.R.S. 1. News (news function $c_{,u}$ where $\gamma \sim c/r + ..$) and mass loss 2. Linearized form of the equations 3. Non-radiative motions
  4. construction of solutions
  5. The reception of gravitational waves 6. The classification of time variation

Some of the other work on radiation at KCL in the 1960's

- Ray Sachs, mentioned above, came to KCL as a post-doc in 1961 and also derived the peeling theorem and investigated the structure of the Bondi-Metzner-Sachs asymptotic symmetry group. He and Josh Goldberg, on leave for a year at King's on an NSF Senior Fellowship, obtained the Goldberg-Sachs theorem *A theorem on Petrov types* Acta. Phy. Polon. suppl. **22**, 13 (1962).

- Roger Penrose, who while at Cambridge had used two component spinor techniques to dramatically simplify and make transparent many of the calculations that people were doing (including correcting Petrov's classification), was at King's as a post-doc between 1961 and 1963. In the summer of 1961, at Syracuse, he and Ezra (Ted) Newman had constructed the much used Newman Penrose formalism. His landmark papers at King's, e.g. *Asymptotic Properties of Fields and Space-times* Phys. Rev. Lett. **10**, 66-68 (1963), on the use of conformal techniques put past work into a precise geometrical framework and marked the beginning of a period of new insights into horizons and global causal structures. With Ted Newman, on sabbatical leave from Pittsburgh at King's in 1965-66, he discovered the Newman-Penrose constants (which are zero for the Kerr family of solutions).

- Andrzej Trautman, Felix Pirani & Hermann Bondi, *Lectures on General Relativity*, Brandeis Summer Institute in Theoretical Physics 1964, volume one, eds. S.Deser & K.W.Ford (Prentice - Hall Inc, New Jersey 1965)

- Ray d'Inverno *Introducing Einstein's relativity* (Clarendon Press Oxford 1992)

1970-1980 Black holes and quantum theory

Three new people whose main research in this period was related to gravitation joined the Mathematics Department staff, David Robinson (1970-2001), Paul Davies (1972-1980) and Chris Isham (1973-76). A distinctive quantum field theory presence was introduced with the appointment of John G. Taylor (1971-1996) and Peter West (1979-present). Three main areas of research were

- Classical black holes- uniqueness theorems for black holes
- Quantum field theory in non-Minkowski space-times
- Other classical and quantum gravity, geometric quantization, quantum field theory and supergravity. For this conference talk I shall focus on the first two areas.

- Outside the King’s Building entrance 1976

Classical black holes - uniqueness of equilibrium black holes

Background

- After the 1930's there was a hiatus in the development of what became known as relativistic astrophysics until the 1960's. Then new observational and theoretical results led to the serious study of black holes.

- At a meeting here at King's in 1967 Werner Israel, on leave in Dublin from the University of Alberta, announced the remarkable first black hole uniqueness theorem. It was for static vacuum metrics,

$$ds^2 = -V^2 dt^2 + g_{ab} dx^a dx^b,$$

- A chronologically ordered account of black hole uniqueness results, from the 1960's until about 2005 is in my review, *Four decades of black hole uniqueness theorems*, pp115-143 in *The Kerr Spacetime: Rotating Black Holes in General Relativity*, eds. D L Wiltshire, M Visser & S M Scott, (Cambridge University Press, 2009).

The King's contribution

- The static problem

  Israel had investigated an interesting, but restricted class of static asymptotically flat solutions of Einstein's vacuum field equations whose metrics could be written in the form

$$ds^2 = -V^2 dt^2 + W^{-1} dV^2 + g_{AB} dx^A dx^B,$$

  The solutions were required to have regular, connected event horizons (at $V = 0$) and singularity free geometry external to the event horizon ($0 < V < 1$) such as a single non-rotating equilibrium black hole metric might plausibly be expected to satisfy. His striking conclusion was that the class was exhausted by the positive mass Schwarzschild family of metrics

$$ds^2 = -(1 - 2mr^{-1})dt^2 + (1 - 2mr^{-1})^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2).$$

- In 1971-72 Henning Muller Zum Hagen, at King's a NATO visiting fellowship from Hamburg, Hans Jurgen Seifert in Hamburg and I generalized Israel's result so that it applied without his restrictive assumptions - see *Black holes in static vacuum space-times*, Gen.Relativ.Grav.4, 53-78, (1973). Later I was able to give a much simpler proof.

- The stationary problem
- In 1971 Brandon Carter, Cambridge: asymptotically flat, pseudo-stationary axisymmetric black hole solutions consist of a discrete set of continuous families, each depending on at least one and at most two independent parameters; the Kerr black hole solutions with non-degenerate horizons are the only family that can admit zero angular momentum.
- Carter showed that the uniqueness problem could be globally formulated in terms of boundary conditions for a metric in the Weyl-Papapetrou form

  $$ds^2 = -Pdt^2 + 2Qd\phi dt + Hd\phi^2 + W(d\rho^2 + dz^2)$$

  and a pair of second order partial differential equations for H and (following Ernst) a potential for W, both functions of the two non-ignorable coordinates ρ and z. His calculation used the linearized version of these equations.
- In 1974 I was able to prove an analogous result for the more complicated Einstein-Maxwell equations and in 1975 recover Carter's result within a Lagrangian framework. Working in Carter's framework I was able to prove the uniqueness result for the full non-linear equations in *Uniqueness of the Kerr black hole*, Phys. Rev.Lett.34, 905-906 (1975).

Quantum field theory in non-Minkowski space-times

Background

Although a small number of investigations of quantum field theory in curved space-time backgounds had been carried out recently, for example by Leonard Parker, Stephen Fulling and Yakov Zel'dovich and Alexei Starobinsky it was Stephen Hawking's work, *Black hole explosions?,* published in Nature in 1974 that led to an explosion of research in this area.

The King's contributions

- This was another period when not only the people at King's permanently but also a significant number of post-docs, students and visitors made important contributions to a subject. In particular, but not only, Paul Davies, Stephen Fulling,1974-76, Steve Christensen, 1975-76, Larry Ford 1977-79, Paul's students Tim Bunch and Nick Birrell were centrally involved in this area. Important contibutions also came from Chris Isham, Mike Duff 1974-76 and, during a whirlwind visit in 1976, Stanley Deser.

- Some of the best known results found at KCL included: scalar particle production in Schwarzschild & Rindler metrics (Fulling-Davies -Unruh effect, the prediction that an accelerating observer will observe a thermal bath including black-body radiation where an inertial observer would see none), radiation from a moving mirror in 2D and conformal anomaly (Davies & Fulling) and qft in de Sitter space (Bunch-Davies vacuum). In addition there was a considerable amount of other work done on qft in Robertson-Walker backgrounds, point-splitting regularization of $\langle T_{\mu\nu} \rangle$, and conformal anomalies - more from Larry Ford next.

- Detailed discussions are in the book, largely written at King's - N.D. Birrell & P.C.W.Davies *Quantum fields in curved spaces* (Cambridge University Press 1982); see also the later book S.A.Fulling *Aspects of Quantum Field theory in Curved Space-time* (Cambridge University Press 1989).

A miscellany from King's 1954-1985

- Hermann Bondi *Cosmology* second edition (Cambridge University Press 1962)
- Chris Isham *An introduction to quantum gravity* Mike Duff *Covariant quantization,* Chapters I and II respectively in *Quantum Gravity*, eds. C J Isham, R Penrose & D W Sciama, (Clarendon Press Oxford 1975)
- Andrew Hodges *Alan Turing: the enigma* (Burnett Books & Hutchinson 1983)
- Stephen Huggett & Paul Tod *An Introduction to Twistor Theory* (Cambridge University Press 1985)
- Hermann Bondi's 1966 report led to the building of the Thames barrier. He became Director-General of the European Space Organisation in 1967 and, resigning his KCL appointment in 1971, became Chief Scientific Advisor to the Department if Defence. In 1983 and 1984 respectively Felix Pirani and Clive Kilmister retired and in1985 KCL merged with a number of other Colleges of the University of London and, for a while, became KQC.