INTRODUCTION

This collection of papers reflects the problems that I have worked on over the years. With hindsight, it might appear that there had been a grand and premeditated design to address the outstanding problems concerning the origin and evolution of the universe. But it was not really like that. I did not have a master plan; rather I followed my nose and did whatever looked interesting and possible at the time.

There has been a great change in the status of general relativity and cosmology in the last thirty years. When I began research in the Department of Applied Mathematics and Theoretical Physics (DAMTP) at Cambridge in 1962, general relativity was regarded as a beautiful but impossibly complicated theory that had practically no contact with the real world. Cosmology was thought of as a pseudoscience where wild speculation was unconstrained by any possible observations. That their standing today is very different is partly due to the great expansion in the range of observations made possible by modern technology. But it is also because we have made tremendous progress on the theoretical side, and this is where I can claim to have made a modest contribution.

Before 1960, nearly all work on general relativity had been concerned with solving the Einstein equations in particular coordinate systems. One imposed enough symmetry assumptions to reduce the field equations either to ordinary differential equations or to the Laplacian in three dimensions. It was regarded as a great achievement to find *any* closed form solution of the Einstein equations. Whether it had any physical significance was a secondary consideration. However a more geometric approach began to appear in the early 1960s in the work of Roger Penrose and others. Penrose introduced global concepts and showed how they could be used to establish results about spacetime singularities that did not depend on any exact symmetries or details of the matter content of the universe. I extended Penrose's methods and applied them to cosmology. This phase of work on global properties came to an end in about 1972 when we had solved most of the qualitative problems in classical general relativity. The major problem that remains outstanding is the Cosmic Censorship Conjecture. This is very difficult to prove, but all attempts to find genuine counter-examples have failed, so it is probably true.

This global classical phase of my work is represented by the first three papers in this volume. They deal with the classical properties of the two themes that recur throughout my work: the Big Bang and black holes. Nowadays everyone accepts it as natural that the universe had a beginning about 15 billion years ago and that, before that, time simply was not defined. But opinions were very different in the early 1960s. The Steady State school believed that the universe had existed forever more or less as we see it today. Even among those who thought the universe was evolving with time, there was a general feeling that one could not extrapolate back to the extreme conditions near the initial singularity of the Friedmann models and that it was probably just an artifact of the high degree of symmetry of these solutions. Indeed in 1963 Lifshitz and Khalatnikov claimed to have shown that singularities

would not occur in fully general solutions of the Einstein equations without exact symmetries. Presumably this would have implied that the universe had a contracting phase and some sort of bounce before the present expansion.

The discovery of the microwave background in 1964 ruled out the Steady State Theory and showed that the universe must have been very hot and dense at some time in the past. But the observations themselves did not exclude the possibility that the universe bounced at some fairly large but not extremely high density. This was ruled out on theoretical grounds by the singularity theorems that Penrose and I proved. The first singularity theorems involved the assumption that the universe had a Cauchy surface. Thus they proved *either* that a singularity would occur *or* that a Cauchy horizon would develop. But in 1970 Penrose and I published “The Singularities of Gravitational Collapse and Cosmology” [1]. This was an all purpose singularity theorem that did not assume the existence of a Cauchy horizon. It showed that the classical concept of time must have a beginning at a singularity in the past (the Big Bang) and that time would come to an end for at least part of spacetime when a star collapsed. Most of my work since then has been concerned with the consequences and implications of these results.

Up to 1970, my work had been concerned with cosmology and in particular with the question of whether the universe had a beginning at a singularity in the past. But in that year I realized that one could also apply the global methods that Penrose and I had developed for the singularity theorems to study the black holes that formed around the singularities that the theorems predicted would occur in gravitational collapse. This was what Kip Thorne has called “The Golden Age of Black Holes”, two or three years in which the concept of a black hole as an entity distinct from the collapsing star was established and its main classical properties were deduced. This was a case where theory definitely had the lead over observation. Black holes were predicted theoretically some time before possible black hole candidates were detected observationally.

My two most important contributions to the classical theory of black holes were probably the Area Theorem, which stated that the total area of black hole event horizons can never decrease, and the part I played in proving the No Hair Theorem, which states that black holes settle down to a stationary state that depends only on the mass, angular momentum and charge of the black hole. Most of my work on classical black holes was described in “The Event Horizon” [2], my lectures given at the 1972 Les Houches Summer School on black holes, which was the culmination of the Golden Age. One important part that was not in these lecture notes because it was work carried out actually at Les Houches was a paper on “The Four Laws of Black Hole Mechanics” [3] with J. Bardeen and B. Carter. In it we pointed out that the area of the event horizon and a quantity we called the surface gravity behaved very much like entropy and temperature in thermodynamics. However, they could not be regarded as the actual physical entropy and temperature as Bekenstein had suggested. This was because a black hole could not be in equilibrium with thermal radiation since it would absorb radiation but, as everyone thought at that time, a black hole could not emit anything.

The situation was completely changed however when I discovered that quantum mechanics would cause a black hole to emit thermal radiation with a temperature proportional to the surface gravity. I announced this first in a letter in *Nature* and then wrote a longer paper, “Particle Creation by Black Holes” [4], which I submitted to *Communications in Mathematical Physics* in March 1974. I did not hear anything from them for a year, so I wrote to enquire what was happening. They confessed they had lost the paper and asked me to send another copy. They then added insult to injury by publishing it with a submission date of April 1975, which would have made it later than some of the great flood of papers my discovery led to on the quantum mechanics of black holes. I myself have written a number of further papers on the subject, the most significant of which are “Action Integrals and Partition Functions in Quantum Gravity” [5] with G. W. Gibbons in which we derived the temperature and entropy of a black hole from a Euclidean path integral, and “Breakdown of Predictability in Gravitational Collapse” [6] in which I showed that the evaporation of black holes seemed to introduce a loss of quantum coherence in that an initial pure quantum state would appear to decay into a mixed state. Interest in this possibility of a non-unitary evolution from initial to final quantum states has recently been reinvigorated by the study of gravitational collapse in two-dimensional field theories in which one can consistently take into account the back reaction to the particle creation. I have therefore included a recent paper of mine, “Evaporation of Two Dimensional Black Holes” [7], as an example.

Event horizons occur in exponentially expanding universes as well as in black holes. G. W. Gibbons and I used Euclidean methods in “Cosmological Event Horizons, Thermodynamics and Particle Creation” [8] to show that de Sitter space had a temperature and entropy like a black hole. The physical significance of this temperature was realized a few years later when the inflationary model of the universe was introduced. It led to the prediction that small density perturbations would be generated in the expanding universe; see “The Development of Irregularities in a Single Bubble Inflationary Universe” [9]. This was the first paper on the subject but it was soon followed by a number of others, all predicting an almost-scale-free spectrum of density perturbations. The detection of fluctuations in the cosmic microwave background by the COBE satellite has confirmed these predictions and can claim to be the first observation of a quantum gravitational process.

In “Zeta Function Regularization of Path Integrals in Curved Spacetime” [10], I introduced to physics what was then a new technique for regularizing determinants of differential operators on a curved background. This was used in “The Path Integral Approach to Quantum Gravity” [11] to develop a Euclidean approach to quantum gravity. This in turn led to a possible answer to the problem that my early work on singularities had raised: How can physics predict how the universe will begin because all the laws will break down in the Big Bang? In “Wave Function of the Universe” [12], J. B. Hartle and I put forward the No Boundary Proposal: The quantum state of the universe is determined by a path integral over all compact positive definite (Euclidean) metrics. In other words, even though spacetime has boundaries at singularities in real Lorentzian time, it has no boundaries in the imaginary direction

of time. The action of spacetime is therefore well defined, so the path integral can predict the expectation values of physical quantities without any assumption about initial conditions. In “Quantum Cosmology” [13], another set of Les Houches lectures, I showed that the No Boundary Proposal would imply that the universe would expand in an inflationary manner and in “Origin of Structure in the Universe” [14], J. J. Halliwell and I showed that it would imply that the universe would contain gravitational and density perturbations with an almost-scale-free spectrum. These density perturbations are just what is required to explain the formation of galaxies and other structures in the universe and they agree with the COBE observations. Thus the No Boundary Proposal can explain why the universe is the way it is.

In “Arrow of Time in Cosmology” [15], I pointed out that the results of the “Origin of Structure” paper implied that the universe would have started out in a smooth and ordered state, and would have evolved to a more irregular and disordered state as it expanded. Thus the No Boundary Proposal would explain the existence of a Thermodynamic Arrow of Time that pointed in the direction in which the universe was expanding. However I also claimed that if the universe were to reach a point of maximum size and start to recontract, the Thermodynamic Arrow would reverse. Shortly after writing this paper, I realized that the Thermodynamic Arrow would not in fact reverse in a contracting phase. I added a note to the proofs of the “Arrow of Time” paper but did not get round to writing a fuller explanation until “The No Boundary Proposal and the Arrow of Time” [16].

Another important outcome of the Euclidean approach to quantum gravity was “The Cosmological Constant is Probably Zero” [17]. In it I showed that if the cosmological constant could take a range of values, then zero would be overwhelmingly the most probable. In my opinion this is the only plausible mechanism that has been advanced to account for the extremely low observational upper limits on the cosmological constant. This explanation received fresh impetus when, in “Wormholes in Spacetime” [18], I put forward the idea that there might be thin tubes or wormholes connecting different regions of spacetime. Sydney Coleman showed that such wormholes would change the values of physical constants and could therefore implement this mechanism to make the cosmological constant zero. Coleman went on to suggest that it might determine all the other constants of physics as well. My doubts on this latter claim were expressed in “Do Wormholes Fix the Constants of Nature?” [19].

Recently my interest in the global structure of the universe led me to consider whether the macroscopic topology of spacetime could change. In “Selection Rules for Topology Change” [20], G. W. Gibbons and I showed that there was an important restriction if there was to be a Lorentz metric which allowed spinors to be defined consistently. Roughly speaking, wormholes or handles could be added to the topology of spatial sections only in pairs. However, any topology change necessarily requires the existence of closed time-like curves which in turn implies that one might be able to go back into the past and change it with all the paradoxes that this could lead to. In “Chronology Protection Conjecture” [21], I examined how closed time-like curves might appear in spacetimes that did not contain them initially and

I presented evidence that the laws of physics would conspire to prevent them. This would seem to rule out time machines.

I can claim that my work so far has shed light (maybe an unfortunate metaphor) on the Big Bang and black holes. But there are many problems remaining, like the formulation of a consistent theory of quantum gravity and understanding what happens in black hole evaporation. Still, that is all to the good: the really satisfying feeling is when you find the answer to part of Nature's puzzle. There is plenty left to be discovered.

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REFERENCES

- [1] The Singularities of Gravitational Collapse and Cosmology (with R. Penrose), *Proc. Roy. Soc.* **A314**, 529 (1970).
- [2] The Event Horizon, in *Black Holes* (eds. DeWitt & DeWitt), Gordon and Breach (1973).
- [3] The Four Laws of Black Hole Mechanics (with J. M. Bardeen & B. Carter), *Commun. Math. Phys.* **31**, 161 (1973).
- [4] Particle Creation by Black Holes, *Commun. Math. Phys.* **33**, 323 (1973).
- [5] Action Integrals and Partition Functions in Quantum Gravity (with G. Gibbons), *Phys. Rev.* **D15**, 2725 (1977).
- [6] Breakdown of Predictability in Gravitational Collapse, *Phys. Rev.* **D14**, 2460 (1976).
- [7] Evaporation of Two-Dimensional Black Holes, *Phys. Rev. Lett.* **69**, 406–409 (1992).
- [8] Cosmological Event Horizons, Thermodynamics, and Particle Creation (with G. Gibbons), *Phys. Rev.* **D15**, 2738 (1977).
- [9] The Development of Irregularities in a Single Bubble Inflationary Universe, *Phys. Lett.* **B115**, 295–297 (1982).
- [10] Zeta Function Regularization of Path Integrals in Curved Spacetime, *Commun. Math. Phys.* **56**, 133 (1977).
- [11] The Path-Integral Approach to Quantum Gravity, in *General Relativity: An Einstein Centenary Survey* (ed. with W. Israel), Cambridge University Press (1979).
- [12] Wave Function of the Universe (with J. B. Hartle), *Phys. Rev.* **D28**, 2960–2975 (1983).
- [13] Quantum Cosmology, Les Houches Lectures, in *Relativity Groups and Topology* (eds. B. Dewitt & R. Stora), North-Holland (1984).
- [14] Origin of Structure in the Universe (with J. J. Halliwell), *Phys. Rev.* **D31**, 8 (1985).
- [15] Arrow of Time in Cosmology, *Phys. Rev.* **D32**, 2489 (1985).
- [16] The No-Boundary Proposal and the Arrow of Time, in *Physical Origins of Time Asymmetry* (eds. J. J. Halliwell, J. Perez-Mercader & W. H. Zurek) Cambridge Univ. Press (1992).
- [17] The Cosmological Constant is Probably Zero, *Phys. Lett.* **B134**, 403 (1984).
- [18] Wormholes in Spacetime, *Phys. Rev.* **D37**, 904 (1988).
- [19] Do Wormholes Fix the Constants of Nature? *Nucl. Phys.* **B335**, 155–165 (1990).
- [20] Selection Rules for Topology Change (with G. Gibbons), *Commun. Math. Phys.* **148**, 345–352 (1992).
- [21] Chronology Protection Conjecture, *Phys. Rev.* **D46**, 603–611 (1992).