CONTEMPORARY MATHEMATICS

Mathematics and General Relativity

Proceedings of a Summer Research Conference held June 22–28, 1986

AMERICAN MATHEMATICAL SOCIETY

VOLUME 71

http://dx.doi.org/10.1090/conm/071

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Volume 71

Mathematics and General Relativity

Proceedings of the AMS-IMS-SIAM Joint Summer Research Conference held June 22—28, 1986 with support from the National Science Foundation

James A. Isenberg, Editor

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The AMS-IMS-SIAM Joint Summer Research Conference in the Mathematical Sciences on Mathematics in General Relativity was held at the University of California, Santa Cruz on June 22–28, 1986, with support from the National Science Foundation, Grant DMS-8415201.

1980 *Mathematics Subject Classification*. (1985 *Revision*). Primary 83C, 35J, 35K, 35L, 53B, 53C, 32-XX.

Library of Congress Cataloging-in-Publication Data

AMS-IMS-SIAM Joint Summer Research Conference in the Mathematical Sciences on Mathematics in General Relativity (1986 : University of California, Santa Cruz)
Mathematics and general relativity : proceedings of the AMS-IMS-SIAM joint summer research conference held June 22-28,1986 with support from the National Science Foundation / James A. Isenberg, editor.
p. cm. -- (Contemporary mathematics, ISSN 0271-4132 ; v. 71)
Includes bibliographies.
ISBN 0-8218-5079-2
1. General relativity (Physics)--Mathematics--Congresses.
2. Mathematical physics--Congresses. I. Isenberg, James A.
II. Title. III. Series.
QC173.6.A47 1986
530.1'1--dc19 88-9685
CIP

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PREFACE

General relativity is an exquisite marriage joining the mathematics of differential geometry to the physics of gravitation. Since its beginnings over seventy years ago in the work of Einstein, Hilbert, and others, it has been a very successful and prosperous alliance for both partners. From the physical point of view, its success may be measured by the accurate agreement of Einstein's classical theory with all gravitational experimentation and astrophysical observation done thus far, and by the theory's prediction of new and interesting effects for which there is much evidence (e.g., black holes, cosmological expansion, gravitational waves, and gravitational lenses.) Mathematically, general relativity has stimulated the fertile study of pseudo-Riemannian as well as Riemannian geometry, and it has motivated important work in complex geometry, in topology, and in the study of both hyperbolic and elliptic PDE systems. In addition to the direct benefits, very important advances for both mathematics and physics have developed from some of general relativity's legacies: Yang-Mills theory, supersymmetry-supergravity theory, and superstring theory.

Reflecting the very wide range of directions in which general relativity research is currently proceeding, the discussions at our Santa Cruz conference (held in June, 1986) involved a large number of topics. The common feature in most was a concentration on questions with serious mathematical content. The intent of those discussions, as well as of this volume of the proceedings, is to keep the mathematical side of general relativity fresh by acquainting

more mathematicians and physicists with such questions and the progress that has been made in answering them.

One of the most important recent advances in general relativity has been the proof of the Positive Mass Theorem by Schoen and Yau, and independently by Witten. This success led to a revival in interest in one of the classic questions in general relativity: Is there an expression which provides a local measure of energy density in a general spacetime? The first three articles in this volume discuss attempts to find such an expression. Penrose gives a status report on his twistorial version – what he calls "Quasi-Local Mass," or more generally "Quasi-Local Angular Momentum-Energy-Momentum." (One can calculate all these quantities using his approach). Christodoulou and Yau (§2) focus on another version, first proposed by Hawking. They also discuss the general features one should look for in the desired quantity, as well as some of the analytical problems which arise in trying to nail down a good definition. One of the necessary features of any good definition of localized mass is that if one calculates the mass enclosed in a sphere in an asymptotically flat spacetime and then lets the radius of the sphere approach infinity, the limit must (exist, and) agree with the (well-defined) total mass of the spacetime. Shaw (in §3) discusses this requirement, as well as what happens for large but finite spheres, in the Penrose version, the Hawking version, and certain other versions of localized mass. Note that although there is one unique total mass for any well-behaved asymptotically flat spacetime, there are a number of alternative formulas for calculating it. Sorkin (in §4) presents a new one here, derived from a variational principle, which has a number of virtues.

Another interesting outgrowth of the work on the Positive Mass Theorem (especially in Witten's formulation) is the "New Variables" Program for canonical quantization recently initiated by Ashtekar. This approach replaces the familiar canonical variables (i.e., Cauchy data) for general relativity – the intrinsic three-metric and the extrinsic curvature of a Cauchy hypersurface – by certain

spinorial ones which are closely tied to self-duality conditions on the spacetime curvature. In §5, Ashtekar introduces his program, and discusses its utility for the study of the "half-flat Einstein equations." Then in the following two contributions, Smolin and Jacobson discuss the progress that they and others have made in setting up a canonical quantization of Einstein's theory using Ashtekar's formalism. Though still far from achieving this goal, their work is promising.

Self-duality (and anti self-duality) is the focus of §§8-9. Boyer, in §8, considers the problem of determining which compact orientable four-dimensional manifolds admit metrics with self-dual or anti-self-dual Weyl curvature. Then in §9, Flaherty shifts attention to Yang-Mills theory. He sketches a method for constructing Yang-Mills instantons (i.e., self-dual connections) on certain complex surfaces (quaternionic Siegel spaces) which he describes. In both Boyer's and Flaherty's contributions, complex geometry plays an important role.

In Wald's article, as well as in most of the remaining ones in this volume, one is back to working with real Lorentz signature spacetimes. Wald, after giving general definitions of "gauge theory" and "spin-one" or "spin-two" field theories, looks for examples of spin-one and spin-two gauge theories other than the familiar Yang-Mills and Einstein theories. In the spin-two case, he uncovers interesting new possibilities.

One of the outstanding problems in classical (i.e., nonquantum) general relativity at present is that of determining the relationship between initial data for a given spacetime and the global properties of that spacetime. Mathematically, this is essentially the problem of long time existence and stability of the Einstein partial differential equations. [In the jargon of general relativity, at least part of this issue is referred to as the Strong Cosmic Censorship question.] Klainerman and Christodoulou have recently made considerable progress in studying certain aspects of this problem. They focus on the conjecture that any set of sufficiently small Cauchy data (i.e., sufficiently close to Cauchy data for flat space-

time) leads to a globally complete (singularity free) spacetime solution of Einstein's equations. In §11, Klainerman reports on preliminary results related to their efforts to prove this conjecture.

Any study of the relationship between spacetime initial data and global properties relies on the premise that the Cauchy problem is well-posed. For the vacuum Einstein equations, for the Einstein-Maxwell and Einstein-Yang-Mills theories, and for certain others, well-posedness has long been established. In §12, Knill and Whitman show that Rosen's bimetric theory is also well-posed; and the work of Szczyrba (§13) sets up the analysis of this property for one of the quadratic curvature Lagrangian theories. When one considers fluid fields, however, problems can arise. These are made vivid in the contribution of Hiscock and Lindblom (§14), where it is found that certain seemingly natural field theories for fluids with dissipation can have disastrous instabilities and noncausal behavior. On the other hand, they find that certain other field theories for dissipative fluids may be able to avoid these problems.

One way to better understand what happens in complicated field theories, such as those with fluids, might be to carry out a systematic canonical analysis, complete with reduction by the gauge group of the theory. Marsden's contribution (§15) discusses some aspects of this approach, including what to do if one does not have a complete symplectic formulation of the theory, but rather must work with a looser formulation involving a Poisson manifold.

Einstein's theory, as well as most of the others examined in §§10-15, is based on a PDE system which is roughly hyperbolic in nature. Hamilton, however, looks at a rather different system of PDEs in studying "Ricci flow" on various two, three, and four dimensional manifolds. His system is $(\partial/\partial\tau)g = -2\mathrm{Ric}[g] + 2/n\langle R\rangle g$, where g is a Riemannian metric on a compact n-dimensional manifold, $\mathrm{Ric}[g]$ is its Ricci curvature, and $\langle R\rangle$ is the average of the scalar curvature over the manifold. This system is parabolic, and in studying its longtime existence and convergence properties, one learns much about Riemannian manifolds. Results for three and

four dimensional manifolds are discussed elsewhere; here, in §16, the analysis on two-dimensional manifolds is studied.

Although some spacetime solutions of the Einstein equations (e.g. those of "small Cauchy data" as in the Christodoulou-Klainerman conjecture) may avoid singularities, the Hawking-Penrose theorem shows that most do not. Therefore, the study of singularities in spacetimes – what forms they might take and where they will occur – has been an important branch of general relativity at least for the last twenty years. A key issue is whether or not the singularities that form will involve infinite curvature invariants, corresponding physically to infinite tidal forces. The Hawking-Penrose theorems do not say. In §17, Kupeli uses the relatively virgin tool of the "shape function" on Cauchy hypersurfaces to study this problem. In §18, Schoen addresses a more specific question: Does a localized, highly compressed, concentration of matter always generate sufficiently strong gravitational effects to cause the local spacetime to collapse into a black hole? He reports on recent work (with Yau) which gives sufficient (mathematical) conditions for the collapse to occur.

Kossowski also discusses singularities in his contribution (§19), but his emphasis is not on those involving spacetime curvature blowups. Rather, he focuses on examining null hypersurfaces immersed in pseudo-Riemannian manifolds, and looks at incompleteness of geometric structures intrinsic and extrinsic to the immersion. In doing so, he introduces an interesting tensor which serves as a connection of sorts for the intrinsic (degenerate!) metric of the null hypersurface.

While general relativity as a theory of classical physics and as a mathematical system works very well, attempts to make it in some way compatible with the quantum principle have met with little success. Admittedly there are no experimental results to serve as a guide, but still there is much theoretical, mathematical, and aesthetic incentive to find a gravitational theory which is compatible with quantum physics and has Einstein's theory as a classical limit. With confidence in the prospects for a standard (particle

theory type) perturbation method of quantization of Einstein's theory largely gone, there is renewed interest in canonical quantization techniques, among others. Ashtekar's spinor variable approach (§§4-6) has heightened this interest. In §20, Kuchar addresses one of the long standing problems of the canonical quantization approach as applied to Einstein's equations: how to factor order the operators so that the constraint algebra is (in an appropriate sense) preserved. He studies some model finite-dimensional systems and is able to find an appropriate factor ordering, which in addition is covariant under all relevant transformations. The relevant transformations for general relativity are parametrized by the diffeomorphism group Diff(M) of the spacetime manifold M and are known to be especially tricky to handle in quantization. Friedman and Witt, in §21, discuss some of the mathematical properties of Diff(M), especially concentrating on the analysis of the fundamental group π_0[Diff(M)] and consider the relevance of these properties for the canonical quantization of general relativity as well as for the rest of physics (e.g., for the existence of fermions). Yasskin's contribution (§22) discusses a different aspect of the mathematics of Diff(M). He considers how the diffeomorphism group of a spacetime manifold M relates to the diffeomorphism groups of the leaves of a spatial hypersurface foliation (codimension one) on the one hand and of the curves of a timelike congruence on the other. This could be useful in understanding the dynamical analysis of general relativity and perhaps ultimately it could be useful in quantization.

Another approach attempting to tie together general relativity and quantum ideas has been initiated by Hartle and Hawking. Conceptually based on Feynman path integration, the Hartle-Hawking program calculates a "ground state wave function for the universe" via action-weighted integration over all metrics on compact four dimensional manifolds bounded by a single three-dimensional hypersurface. Ultimately, one ends up working with solutions to a form of the Wheeler-DeWitt equation. In §23, D'Eath and Halliwell try to add fermionic fields to the game. They can

do so if the fermion fields are dealt with as a perturbation on a background geometry.

A much more radical scheme for finding a quantum theory of gravity is to look for it as part of a superstring theory. Currently this is perhaps the most widely supported approach among theoretical physicists, if not among general relativists. Peskin (in §24) discusses recent work in superstring field theory, focussing on how to achieve a gauge invariant and covariant formulation. Then in §25, Shaw describes how twistor space constructions can be useful in finding complete solutions of the constraints of string theory without having to impose the light cone gauge conditions.

While a wide range of topics is discussed in the contributions to this volume, it should be noted that this book does *not* purport to provide a comprehensive look at current research in general relativity. Little is said about astrophysics, cosmology, experimental tests, or numerical modeling. Even in mathematical general relativity, our focus, only a portion of current research is covered. Still, we hope this book provides a good representative look at some of the mathematical issues being studied in general relativity.

We wish to thank the NSF, the AMS, and SIAM for their generous support of our conference. We also thank Ms. Marcia Almeida and her staff for their help in preparing the typed copy of the manuscript in this volume.

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ISBN 978-0-8218-5079-4

9 780821 850794

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