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## Editorial

Well, I don't have much to say, just to to remind everyone that suggestions and ideas for contributions are **especially** welcome. I also wish to thank the editors and contributors who made this issue possible. The next newsletter is due September 1st.

If everything goes well this newsletter should be available in the gr-qc Los Alamos bulletin board under number gr-qc/9402007. To retrieve it send email to gr-qc@xxx.lanl.gov (or gr-qc@babbage.sissa.it in Europe) with Subject: get 9402007 (number 2 is available as 9309003, number 3 as 9402002 and number 4 as 9409004). All issues are available as postscript or TeX files in the WWW http://vishnu.nirvana.phys.psu.edu

Or email me. Have fun.

Jorge Pullin

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## LISA Recommended to ESA as Possible New Cornerstone Mission

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In May, 1993, two proposals for laser gravitational wave antennas in space were submitted to the European Space Agency (ESA) as candidates for the Third Medium-sized Mission (M3) under their Horizon 2000 program. The Laser Interferometer Space Antenna (LISA) proposal was for laser heterodyne measurements between four spacecraft in a cluster located well behind the Earth, in orbit around the Sun. The spacecraft in this heliocentric antenna are located at the corners of an equilateral triangle 5 million km on a side, with two spacecraft at one of the corners, and the plane of the triangle is tipped at 60 deg to the ecliptic. The diameter of the transmit/receive telescopes that send the laser beams between the different spacecraft is 30 cm. The frequency range of interest is from somewhat below 0.1 millihertz to about 1 Hz. Thus LISA and ground-based gravitational wave detectors will complement each other by looking at different frequency ranges.

The other proposed mission, named SAGITTARIUS, has six spacecraft in retrograde geocentric orbits with 0.6 million km radial distance. Two spacecraft are at each corner of an equilateral triangle with 1.0 million km sides, which lies in the ecliptic. The telescopes used have 15 cm diameter. Many other features of the two missions are the same. SAGITTARIUS is intended to have lower cost because of smaller spacecraft size and lower propulsion and telemetry requirements. The sensitivity for the SAGITTARIUS antenna is about a factor five worse than for LISA over the frequency range of most interest.

A common Assessment Study for the two missions [1] was carried out by ESA during the period November, 1993, to April, 1994, with Dr. Yusuf Jafry of the European Space Research and Technology Centre as the Study Scientist. The Chairs of the three Working Groups for the Study were as follows: Theory WG - B. Schutz, University of Wales, Cardiff; Accelerometer WG - P. Touboul, Office National d'Etudes et de Recherches Aerospatiales, France; and Interferometry WG - J. Hough, University of Glasgow. The Study Team recommended the LISA mission, mainly because of the factor five higher sensitivity and because the costs assigned by ESA were not much lower for SAGITTARIUS. However, LISA was not chosen by ESA for further study as a candidate for the M3 mission because the cost was roughly a factor two too high for an ESA medium-sized mission, unless a major portion of the cost were to be provided by another agency such as NASA.

In October, 1993, a group led by Prof. Karsten Danzmann of the Universitat Hannover and the Max-Planck-Institut fur Quantenoptik also submitted the LISA concept for consideration by ESA as a new cornerstone mission [2] under the proposed Horizon 2000 Plus program. The concept presented was the heliocentric mission with 5 million km antenna arm lengths, but with six spacecraft instead of four. Cornerstone missions can be nearly a factor two more expensive than medium-sized missions, and require ESA leadership. They must have a scientifically valid "core" that can be carried out by ESA alone, including launch and operations, but might subsequently be enriched by new elements, to be added through international collaboration(s).

The Survey Committee appointed by ESA to make recommendations for the Horizon 2000 Plus program has now recommended [3] the implementation of three additional cornerstones (before the end of 2016) as follows: Cornerstone 5 (or 6) - Mission to Mercury Cornerstone 6 (or 5) - Interferometric Observatory Cornerstone 7 - Gravitational Wave Observatory. The inclusion of the Fundamental Physics discipline (LISA) and the recommended expanded Technological Activities will require a modest increase in the funding of the ESA Scientific Programme beginning in 2001. It is therefore proposed to augment the budget level by 5% each year for the years 2001 -2005.

In the US, the NASA Astrophysics Division issued a Research Announcement in September for proposals to study concepts for new missions which could be flown after the year 2000. If it is decided to fund preliminary mission concept studies for participation in an ESA gravitational wave mission, different possible forms of collaboration with ESA will be considered. However, the question of future NASA participation in a LISA mission and the associated scientific priority for such a mission have not yet been considered by NASA or its advisory groups.

The primary objective of the LISA mission is to search for and study signals from sources involving massive black holes. One possible source is the coalescence of massive black hole binaries formed by mergers of pre-galactic structures or galaxies. The main issue for predicting the number of such events is, at what stage in structure formation are black holes with masses in the range of roughly $10^4$ to $10^7$ solar mass likely to have formed? The LISA sensitivity is sufficient to detect such sources and to study them in detail out to cosmological distances. Another possible source is compact stars orbiting around massive black holes in galactic nuclei.

Other objectives of the LISA mission are to observe signals from galactic binaries and to search for a possible background of gravitational radiation formed at early times. LISA would certainly observe signals from hundreds to thousands of neutron star binaries, and would be able to determine their distribution throughout our galaxy. Comparable numbers of short period white dwarf binaries probably will be seen also, and possibly enough to interfere with the observations of some other types of sources. Cataclysmic variables and binary systems composed of a neutron star and a black hole are also likely to be seen, as well as signals from some known binaries.

**References:**

[1] LISA Study Team, "LISA: Laser Interferometer Space Antenna for gravitational wave measurements", in M3 Selection Process: Presentation of Assessment Study Results, 3 and 4 May, 1994, Paris (European Space Agency SCI(94)9, May, 1994).

[2] K. Danzmann et al, "LISA: Laser Interferometer Space Antenna for Gravitational Wave Measurements (Cornerstone Mission Concept submitted to ESA), Max Planck Institut für Quantenoptik, Garching (October, 1993).

[3] European Space Agency, ESA SP-1180 (November, 1994).

## LIGO Project News

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The Laser Interferometer Gravitational-wave Observatory (LIGO) project was given a major boost in November when the National Science Board met to consider LIGO and approved the new project plans. This approval included a revised construction estimate and subsequent funds for the commissioning and initial operations. The strong backing of the National Science Foundation director and staff and the strengthening of the project management were key elements in gaining the support of the National Science Board.

The pace of work on the Project has increased substantially over the past six months. Site preparation is well underway at the Washington LIGO site and should begin soon at the Louisiana site. The rough grading (the earthwork to level the foundation plane) has been completed in Washington and the site will be allowed to settle while the design of the foundations is finalized. The site in Louisiana has been purchased by Louisiana State University and leased to the NSF for LIGO. The Environmental Assessment has been completed; clearing of the site will begin as soon as the final environmental approval is given.

A test of the beam tube design is now underway. This is a test of the design developed by our contractor (Chicago Bridge and Iron). It involves a full diameter section of beam tube approximately 40 m long, fabricated with the techniques planned for the LIGO field installation. The key aspects of the design to be tested are the leak-tightness of the welds and the outgassing of the fabricated tube. The tube is now under vacuum and a bake-out of the tube (140 C for 30 days) is planned to start in early February.

The Ralph M. Parsons Company was selected as the Achitect-Engineer for the LIGO facilities. They will design the building for the two LIGO sites, including the foundations and covers for the beam tubes. They will also take responsibility for the site planning and eventually provide management oversight for the actual construction. Parsons was selected after a nationwide solicitation and a very rigorous competition.

The final major facilities design contract is for the vacuum system, including the chambers, pumping system, and vacuum instrumentation, but excluding the beam tubes. Proposals for this contract are due in February and we hope to have the design work underway before summer.

The major highlight from the R&D program is another improvement in the sensitivity of the LIGO 40 m interferometer. New test masses were installed in the interferometer. These new test masses are of a monolithic design with the mirror surface an integral part of the test mass; the earlier test masses had a compound construction with mirrors optically contacted onto a fused silica body. The compound design appears to have been a source of noise. The interferometer now has a peak sensitivity (near 450 Hz) of $2.5 \times 10^{-19}\mathrm{m/Hz}^{1/2}$, expressed as an equivalent differential arm length.

The LIGO Project is now operating a World Wide Web server which will provide access to general information about LIGO, latest news and results, preprints and technical reports, and other relevant information. You can access our home page (our URL is "http://www.ligo.caltech.edu") using Mosaic or another WWW browser. We expect that this will become one of the principal channels of communication with the interested scientific community.

**Some Recent Work in General Relativistic Astrophysics**

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This will be a short summary highlighting aspects of work on three different topics: numerical models of coalescing neutron stars; an update on work that sharply restricts the role that nonaxisymmetric instability could play in rotating neutron stars; and an announcement of a public-domain code and some other accurate recent codes for modeling rotating relativistic stars.

• Several groups have begun detailed studies of the late stages of coalescing neutron-star binaries, elucidating much more of physics immediately preceding merger. An orbital instability known from work on Newtonian ellipsoids appears to dominate the final part of the inspiral, and it can be found analytically as well as by the numerical hydrodynamics that has been implemented. For a $r^{-1}$ potential, circular orbits are, of course, always stable. In general relativity an effective potential that rises more quickly leads to unstable circular orbits within $r = 6M$ for small particles orbiting larger masses; one expected that the same instability for a system of with components of roughly equal mass would limit the smooth inspiral of two black holes or possibly even two neutron stars if the equation of state is soft enough that unstable orbits lie outside the stars' surfaces. But there is a surprise. The *Newtonian* gravitational force between two stars in a binary system already has a tidal contribution that rises more quickly than $1/r^2$, fast enough that the effective potential can have a maximum. For incompressible ellipsoids in a binary system, this leads to an unstable orbit before the ellipsoids coalesce, and Rasio and Shapiro and coworkers have shown that the same dynamical instability arises for models as compressible as neutron stars.

The published studies of binary coalescence of neutron stars have used Newtonian gravity, generally corrected by a quadrupole gravitational radiation-reaction term. Shibata, Nakamura and Oohara used an Eulerian code to look at synchronously rotating binaries and at binaries with nonrotating stars. The viscosity of neutron stars is probably too small to synchronize their spins in the time it takes them to spiral together (Kochanek; Bildsten and Cutler), and three groups (Davies, Benz, Piran and Thielmann; Colpi, Rasio, Shapiro, and Teukolsky; Zhuge, Centrella and McMillan) have used smoothed particle hydrodynamics to study binaries without synchronized spins. For stars of $1.4 M_\odot$ and radius 10 km, orbital instability at a 30 km separation leads to rapid merging, with 20% of the total mass ejected from the central region to form dramatic, if short-lived, spiral arms. Now neutron stars near the maximum *and minimum* mass configurations are unstable to radial oscillations, and Clarke, Eardley and Blinnikov had suggested that tidal stripping of matter in coalescence could lead to an explosion of the less massive member of a coalescing binary system when it nears its minimum mass. Orbital instability and merger is the picture given by the current simulations, but Colpi and Rasio suggest that the spiral arms quickly fragment into lumps smaller than the minimum mass which then explode.

• Millisecond pulsars are being detected at an accelerating rate. A dozen are now known with periods less than 3 ms, although the shortest known period (1.6 ms) is still that of the first fast pulsar. The upper limit on the angular velocity of a neutron star is sensitive to the equation of state of matter above nuclear density, and there is a reasonable chance that within the next decade we will have confidence in an observational value of that limit. For neutron stars with sufficiently weak magnetic fields, the upper limit on rotation is set by gravity, but there has been a question of whether a nonaxisymmetric instability driven by gravitational radiation will limit the rotation before the equator of the star rotates at the Kepler frequency. Lindblom and Mendell have completed an analysis of the damping of normal modes of neutron stars by an effective viscosity arising from a superfluid dissipation mechanism called 'mutual friction'.

In rotating neutron-star matter mutual friction is caused by the scattering of electrons off the cores of the neutron vortices. This scattering is greatly enhanced by nuclear interactions between the neutrons and protons that induce proton supercurrents and hence strong magnetic fields within the neutron vortices. Lindblom and Mendell have spent several years on a careful treatment of the superfluid interior of neutron stars, and the application of their formalism to the nonaxisymmetric instability appears to be unambiguous and striking: Mutual friction completely suppresses the gravitational-radiation instability in all neutron stars cooler than the superfluid-transition temperature. They take pains to enumerate caveats to the conclusion, but the work seems to leave little doubt that the nonaxisymmetric instability plays no role in limiting the rotation of old neutron stars spun-up by accretion. The paragraph itself needs a caveat: Even with a weak magnetic field, and without the gravitational instability, a medium-to-soft equation of state might mean that a neutron star will be spun up by accretion to a limit shy of the Kepler frequency, because the innermost stable circular orbit (and hence the inner edge of the accretion disk) can lie outside the star.

If rapidly rotating neutron stars form from the accretion-induced collapse of white dwarfs, there may still be a time during the cooling, at temperatures between $1 \times 10^{10}$ K and the superfluid transition temperature of about $10^9$ K during which the nonaxisymmetric instability could play a role. But earlier work of Ipser and Lindblom (see Lindblom 1995 and references therein, and Hashimoto et. al. for updated and corrected calculations) together with the damping of the instability at $10^9$ K means that the deviation from the Kepler frequency would be small.

• Responding to rapidly growing class of fast pulsars, a number of different groups have written codes to construct models of rapidly rotating neutron stars. (The methods in use are due to Butterworth and Ipser (BI); to Komatsu, Eriguchi and Hachisu (KEH), who use the Butterworth-Ipser set of equations but a somewhat different algorithm; Cook, Shapiro and Teukolsky with a modification of KEH; Neugebauer and Herlt, a finite-element method; and Salgado et al, with a alternative algorithm and an alternative set of equations of state.) An ongoing comparison of substantially different codes so far shows agreement limited only by grid size and accuracy that is easily better than 1all quantities (vastly better than the uncertainty in the equation of state from which the models are constructed). A public-domain code, written by Stergioulas, is now available, and may make models of rotating stars nearly as accessible as spherical models. The Stergioulas code is automated to construct sequences of constant angular momentum and constant baryon number and to locate configurations with maximum angular velocity. It implements the KEH method as modified by Cook et al., and agrees to better than 0.1% on with a recent code accurate code constructed by Gourgoulhon et al. and based on a substantially different method and a different choice of independent field equations.

As Cook et al. have found, there is often a slight difference between the models of maximum $M$ and $\Omega$ for models of neutron stars corresponding to a proposed equation of state. In fact there are two classes of equations of state, depending on whether the model with maximum mass among all equilibrium configurations is unstable (Stergioulas and Friedman). If it is, the *stable* models with maximum mass, baryon mass, angular velocity, and angular momentum coincide. Otherwise they are all distinct, although in general close enough that a dense set of models is needed to resolve them.

**References** (Only one reference by the same set of authors is listed.):


Butterworth, E. M., & Ipser, J. R. ApJ, 204, 200 (1976).

Colpi, M. and Rasio, F., "Explosions of neutron star fragments ejected during binary coalescence," preprint (1994).

Cook, G. B., Shapiro, S. L., & Teukolsky, S. A. ApJ, 424, 823 (1994).

Bildsten, L. & Cutler, C. ApJ, 400, 175 (1992).

Davies, M, Benz, W., Piran, T., & Thielmann, F., Ap J 431, 742 (1994).

Hashimoto, M., Oyamatsu, K., & Eriguchi, Y. "Upper limit of the angular velocity of neutron stars", preprint 1994.

Kochanek, C. Ap J 398, 234 (1992).

Komatsu, H., Eriguchi, Y., & Hachisu, I. MNRAS, 237, 355 (1988).

Lai, D., Rasio, F. & shapiro, S. Ap. J. Suppl. 88, 205 (1993).

Lindblom, L. ApJ 438, 265 (1995).

Neugebauer, G., & Herlt, E. Class. Quant. Grav., 1, 695 (1984).

Salgado, M., Bonazzola, S., Gourgoulhon, E., and Haensel, P., Astron. and Ap., in press.

Stergioulas, N. and Friedman, J.L., ApJ in press.

Lindblom, L, & Mendell, G. Ap. J. in press.

Shibata, M. Nakamura, T. and Oohara, K. Prog. Theor. Phys 88, 1079 (1992).

Rasio, F. and Shapiro, S. Ap J 432, 242 (1994).

Zhuge, X., Centrella, J., and McMillan, S. L. W. "Gravitational radiation from coalescing binary neutron stars," preprint 1994.

**Pair Creation of Black Holes**

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Hawking's prediction of thermal radiation from a black hole remains one of the most important results to emerge from the union of quantum mechanics and gravity. There are good arguments that this prediction is independent of unknown Planck scale physics for black holes much larger than the Planck mass. However there is another prediction that can be made which combines quantum mechanics and gravity, and appears to be independent of Planck scale physics. This is the fact that charged black holes will be pair created in a background electric or magnetic field. This process is the direct analog of the creation of electron-positron pairs or monopole-antimonopole pairs which have been studied previously. Over the past few years, the pair creation of black holes has attracted considerable attention. A key motivation is that, in addition to being an apparently unambiguous consequence of quantum gravity, this process is likely to shed light on the nature of black hole entropy. Since a black hole should be equally likely to be pair created in any of its available states, by comparing the rate for black hole creation to the rate of e.g. monopole creation, one can effectively count the number of internal states of a black hole.

In direct analogy to tunneling phenomena in ordinary field theory, black hole pair creation can be described in a semi-classical approximation using an instanton. As Gibbons first pointed out [1] , the exact instanton describing this pair creation event can be constructed by analytically continuing a solution found by Ernst in the mid 1970's. This instanton was first studied by Garfinkle and Strominger [2] who argued that regularity of the instanton fixed the charge to mass ratio of the black holes so that they were always nonextremal. They also found that the black holes were created with their horizons identified, so that they formed a wormhole in space. The rate of pair creation (in the semi-classical approximation) is directly related to the action of the instanton. Garfinkle and Strominger computed this action in the limit of weak fields (i.e. $qB << 1$) and found that it agreed with the rate of pair creating monopoles with the same mass and charge. Of course, the most likely black holes to be produced have the Planck mass, and for these, the semiclassical approximation breaks down. However, this approximation should be valid for the pair creation of larger black holes, which is predicted to occur with a nonzero (although small) probability.

The next step forward was taken by Garfinkle, Giddings, and Strominger [3] who computed the instanton action exactly and found that it was smaller than the the corresponding monopole case by precisely a factor of the Bekenstein-Hawking entropy $S = A/4$. In other words, the pair creation of black holes is enhanced over the pair creation of monopoles by a factor of $e^S$, exactly what one would expect if black holes had $e^S$ internal states.

This simple state of affairs did not last long. Dowker et. al. [4] soon found that there was another regular Ernst instanton which described the pair creation of extremal black holes. When they computed its action, they found that the extremal pair creation rate was NOT enhanced over that of monopoles. This puzzle was clarified in a recent paper by Hawking et. al. [5] who gave independent arguments that the entropy of an extreme Reissner-Nordstrom black hole is zero. The discontinuity between nonextreme black holes (which have $S = A/4$) and extreme black holes was related to the change in topology of the euclidean solutions. Thus pair creation arguments provide evidence that black hole entropy is indeed related to the number of internal states of a black hole.

An important qualification needs to be made at this point. The above statements about the rate of pair creation are based solely on the leading order semiclassical approximation. Higher order terms (e.g. fluctuations about the instanton) have not been included and may be large (especially in the extremal case). It is important to understand these corrections because for ordinary field theory instantons, the density of states factor comes from the one loop fluctuations. For black hole pair creation, it appears to be present in the instanton action. Although this is unusual from the field theory standpoint, it is not unprecedented. It is well known that one can derive the Bekenstein-Hawking entropy for a single black hole from just the black hole instanton, without including the fluctuations.

In related work, Dowker et. al. [6] found a generalization of the Ernst instanton which includes an arbitrary coupling to a dilaton and discussed the pair creation of charged dilatonic black holes. For a particular value of the dilaton coupling, the extremal limit describes the pair creation of Kaluza-Klein monopoles [4]. Hawking et. al. [5] also pointed out that if black holes can be pair created, it should be possible for them to annihilate, and discussed some consequences of black hole annihilation.

Before the experimentalists get too hopeful, I should perhaps point out that it would take a magnetic field of approximately $10^{50}$ gauss to have a reasonable probability of pair creating magnetically charged black holes. Unfortunately, electric fields are even less promising, since they would decay through electron-positron pair creation long before black holes were produced.

## References

[1] G. Gibbons in *Fields and Geometry* ed. A. Jadczyk (World Scientific, 1986).

[2] D. Garfinkle and A. Strominger, Phys. Lett., B256, 146, 1991.

[3] D. Garfinkle, S. Giddings and A. Strominger, Phys. Rev., D49, 958, 1994.

[4] F. Dowker, J. Gauntlett, S. Giddings and G. Horowitz, Phys. Rev., D50, 2662, 1994.

[5] S. Hawking, G. Horowitz, and S. Ross, 'Entropy, Area, and Black Hole Pairs", submitted to Phys. Rev., gr-qc/9409013.

[6] H.F. Dowker, J.P. Gauntlett, D.A. Kastor and J. Traschen, Phys. Rev., D49, 2909, 1994.

## The Conformal Field Equations and Global Properties of Spacetimes

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H. Friedrich's method of "regular conformal field equations" has shown to be very useful to establish existence and asymptotic properties of solutions of Einstein's field equations

$$\tilde{R}_{ab} = \Lambda \tilde{g}_{ab} \; . \tag{1}$$

I shall try to outline this method and some results achieved by it. References can be found in [1].

Motivated by Penrose's treatment of null infinity via a conformal rescaling of the spacetime metric $\tilde{g}_{ab}$ the aim is to use the "unphysical metric"

$$g_{ab} = \Omega^2 \tilde{g}_{ab} \tag{2}$$

together with the conformal factor $\Omega$ as the unknown fields. Rewriting of (1) in terms of the unphysical metric and $\Omega$ leads to the equation

$$\tilde{R}_{ab} = R_{ab} + 2\Omega^{-1}\nabla_a \nabla_b \Omega + g_{ab} g^{cd} \left( \Omega^{-1} \nabla_c \nabla_d \Omega - 3\Omega^{-2} \nabla_c \Omega \nabla_d \Omega \right) = \Lambda \Omega^{-2} g_{ab} \; . \tag{3}$$

This equation is singular for $\Omega = 0$, that is precisely at those points (at infinity) where we want to understand its consequences.

The "regular conformal field equations" are a system of equations (for the conformal factor, the rescaled metric, the non–physical Ricci tensor and the rescaled Weyl tensor $d^a{}_{bcd} := \Omega^{-1} C^a{}_{bcd}$) which are equivalent to (3) and regular in the sense that no factor of $\Omega^{-1}$ occurs in the equations and that $\Omega$ does not appear in the principle part of the differential operator associated with the equations (the terms with the highest derivatives). The Bianchi identities are part of the equations.

These equations are not only regular, but can furthermore be split into a system of symmetric hyperbolic evolution equations and constraints which are compatible with the evolution. This allows to study various Cauchy and characteristic initial value problems with an initial hypersurface on which $\Omega$ vanishes, hence to prescribe data at points which are at infinity of the physical spacetime.

It is worthwhile to note that the evolution equations are in a certain sense hyperbolic in any coordinate system.

I shall now consider the three cases $\Lambda > 0$, $\Lambda < 0$, and $\Lambda = 0$ and describe some of the results obtained.

The de Sitter solution has a positive cosmological constant and is geodesically complete. It can be conformally embedded into the Einstein universe and its boundary consists of two spacelike hypersurfaces $scri^+$ and $scri^-$ on which $\Omega$ vanishes. Therefore this embedding defines a solution of the conformal field equations. One can now analyze the Cauchy problem to find out which data can be given on a spacelike hypersurface on which $\Omega = 0, d\Omega \neq 0$. The result is that a positive definite metric is freely specifiable together with the electric part of the rescaled conformal Weyl tensor. De Sitter data determine uniquely the de Sitter solution. If we take data sufficiently near these data, general theorems on the stability of solutions of symmetric hyperbolic systems on compact domains imply that these solutions exist on a sufficiently large domain and reach a second hypersurface on which $\Omega$ vanishes. Translating this result to physical spacetime, we have constructed a solution which is geodesically complete and asymptotically de Sitter in the past as well as in the future.

Suppose we would like to prove the same theorem working in physical spacetime. Changing the data from de Sitter data on some Cauchy surface would by general theorems only give a solution on some compact part of the de Sitter spacetime. To obtain a solution which is geodesically complete special estimates would be needed, and no general method is known to obtain such estimates. Thanks to the conformal equations no such estimates are needed. “The geometry is worked out of the equations”.

Recently H. Friedrich, [1], considered the anti–de Sitter spacetime ($\Lambda < 0$). Again it can be conformally embedded into the Einstein universe. Its boundary is timelike with the topology $S^2 \times R$. To prove existence of solutions which are asymptotically anti–de Sitter Friedrich solved a boundary initial value problem for the conformal field equations with a timelike boundary. This is the first general initial boundary value problem in the context of Einstein's equations which found complete treatment. Translating again to physical spacetime the solution behaves asymptotically anti–de Sitter near $scri^+$ which is timelike.

For de Sitter and anti–de Sitter space the boundaries of the conformal imbeddings into the Einstein universe are smooth hypersurfaces, and it is possible to pose regular initial or boundary value problems. This is different for the conformal embedding of Minkowski space into the Einstein universe. Besides the smooth null hypersurfaces at infinity, $scri^+$ and $scri^-$, there are the vertices of these null cones, $I^0$ and $I^\pm$ where $\Omega$ vanishes. Examples like the Schwarzschild spacetime show that in general the conformal structure will be singular at spacelike infinity $I^0$.

Postponing the problem of spacelike infinity the hyperboloidal Cauchy problem was studied. Prescribing almost Minkowski data on a hypersurface intersecting $scri^+$, H. Friedrich showed the existence of solutions which are geodesically future–complete and have a regular point $I^+$ as future timelike infinity. So far no such a result has been obtained by working with the equations in spacetime.

Numerical investigations of a hyperboloidal Cauchy problem by P.Hübner, [2], using conformal field equations coupled to a scalar field in the case of spherical symmetry, demonstrated that one can calculate numerically global properties (horizon, $scri^+$, singularities) of the spacetime on a compact grid with regular equations.

To treat the usual Cauchy problem by conformal techniques one has to analyze the singularity at spacelike infinity enforced by positive ADM–mass. Investigations are under way to decide which class of data will evolve into spacetimes with smooth $scri^+$, and will finally resolve the general structure of spatial infinity.


[1] Helmut Friedrich; Einstein Equations and Conformal Structures: Existence of Anti–de Sitter Space–Times; MPA 808 June 1994; to appear in Journal of Geometry and Physics

[2] Peter Hübner; A Method for Calculating the Structure of (Singular) Spacetimes in the Large; GR–QC–940929

## Aspen workshop on numerical investigations of singularities in general relativity

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This workshop was organized by Jorge Pullin, Bernd Schmidt, Susan Scott and took place in the Aspen Center for Physics from August 22 to September 11 1994. Activity at the workshop was mainly concentrated in the following three areas:

- The new type of singularity structure discovered by Choptuik in gravitational collapse.
- The status of theoretical developments in singularity theory.
- The interpretation of numerically observed singular space-times.

The first week of the workshop focussed mainly on the study of the phenomena discovered by Choptuik. In brief, Choptuik considers the collapse of a spherically symmetric scalar field. The final outcome can either be a black hole or empty space; in both cases the scalar field radiates to infinity. Choptuik concentrates on the space-times in the boundary between the two behaviors cited above. He finds that the mass of the final black hole created has a universal law as a function of the initial data that closely resembles the power laws observed in critical phenomena in statistical mechanics. Choptuik also observes that these space-times present a unique universal pattern of oscillations with a discrete self-symmetry.

The workshop opened with a talk by Charles Evans who presented a model similar to that of Choptuik, but where the scalar field was replaced by a perfect fluid. He has been able to find exactly a critical self similar solution and expects to be able to find the critical exponent by using perturbation theory. Richard Price talked about a very different approach in which analytic approximations were studied taking Choptuik's data as "experimental data". Douglas Eardley presented yet another model, with a complex scalar field, where again an exact critical solution can be found. This led to a lot of discussion concerning the possible relationship with Evans' model. In the background of all these discussions were several connections with the empirical observations of Price on Choptuik's data.

Carsten Gundlach presented a completely different approach where the discrete self-similarity observed by Choptuik is taken as exact and the equations are integrated as a boundary-value problem within a single self-similar region. The expectation is that by requiring regularity at the origin and at a "sonic horizon", the critical Choptuik solution will appear as a unique solution. John Stewart described an approach to the Choptuik space-time based on the Newman-Penrose formalism and the characteristic initial value problem. He also described some preliminary calculations that show that an approach similar to the one Price presented in his lecture can be taken in the Newman-Penrose language. It was an example of a piece of research directly motivated by the communication fostered by the workshop.

The phenomena discovered by Choptuik have been the source of a lot of discussion and excitement in the general relativity community worldwide in recent times. This was the first workshop partly devoted to this topic. It led to much discussion and comparison of notes among a number of the experts who are trying to understand this problem.

There was a series of three talks given by Chris Clarke, Bernd Schmidt and Susan Scott which gave an overview of the theoretical developments in singularity theory for relativity during the past three decades. These included the main topics of the classification of singularities, boundary constructions for space-time and the possibility of performing extensions of space-times. This series provided a very useful and timely background for many of the numerical relativists present.

A number of interesting theoretical investigations were either started or undertaken during the workshop. Chris Clarke and Susan Scott developed four different ways of topologising a manifold together with its abstract boundary — the abstract boundary is a boundary construction recently developed by Scott and Szekeres which is applicable to any $n$-dimensional manifold. Steven Harris and Susan Scott considered how causal structure could be included in the abstract boundary construction for space-time. Steven Harris also made some progress in his attempt to prove that compactness is a property of the Busemann boundary of a general Riemannian manifold.

Numerical investigations by Beverly Berger, David Garfinkle and Vince Moncrief of vacuum cosmological models with compact space sections with two Killing vectors reveal a surprisingly simple singularity structure. It is "velocity-dominated" which implies, in particular, that the asymptotic geometry is known analytically. A code for the case with just one Killing vector is about to bring results in the coming months. If it turns out the singularities are also velocity-dominated in this quite general case, numerical relativity has produced a challenge for mathematicians to prove the existence and understand the basic mechanisms that give rise to these singularities. For this topic the workshop was again a unique opportunity, since it brought together the people doing the actual numerical work with several mathematical experts on singularity theory.

Finally, there was a series of talks dealing with subjects somewhat related to singularities. Jorge Pullin, Jim Wilson and Jeff Winicour spoke about collisions of stars and black holes from different points of view, and Hans-Peter Nollert described his recent work that tends to suggest that new normal modes exist in the formation and distortion of black holes.

**Second Annual Penn State Conference: Quantum Geometry**

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This series of conferences was inaugurated in '93 and the first meeting, held in October of that year, was devoted to numerical relativity. The second conference was held during the first three days of September '94 and its theme was quite different. It was motivated by the fact that, over the last few years, several distinct approaches have been developed to explore the nature of quantum geometry. Some come from advances in quantum gravity, some from the mathematical developments on low dimensional manifolds and some from recent advances in computational physics. The aim of this conference was to bring together experts in these different areas to discuss recent results and to enhance the dialog between these three communities. It was a "discussion conference" with approximately 80 participants from US, Canada, Mexico and Europe.

There were relatively few, long talks with ample time for questions, discussion and long comments. The exchanges that followed the main talks were generally lively and led to a deeper understanding of the state of the art. Indeed to non-experts, these discussions were sometimes more illuminating than the talks themselves. There was a healthy mix of physicists and mathematicians although, unfortunately, the computational physicists were under-represented.

The conference program can be divided into five broad categories. The first of these dealt with recent mathematical developments and their applications. It included talks by John Baez on "Higher dimensional algebras and topological quantum field theories," John Barrett on "Quantum gravity as a topological field theory,", Roger Brooks on "Quantum gravity and equivariant cohomology" and Daniel Kastler on "Non-commutative geometry and its applications to the standard model of particle physics". Baez's beautiful synthesis of the interplay between algebras and TQFTs in two, three and four dimensions is briefly summarized in the introduction to his contribution to the Marcel Grossmann Proceedings and is available on the network. Similarly, the tantalizing ideas on "geometrizing" the Higgs mechanism using Alain Connes framework are discussed in Kastler's Luminy lecture notes, also available electronically. The second set of talks concerned computational physics. Here, Jan Ambjorn provided a broad review entitled "Computer simulations of quantum gravity: A viable approach?" and Bernd Brügmann discussed subtle issues related to the choice of measures in his talk "Dynamical triangulations of four dimensional quantum gravity." The third set of talks discussed the insights that have been gained into the nature of quantum geometry through two approaches to quantum gravity, string theory and non-perturbative quantum general relativity. Jorge Pullin presented a general review in "Recent mathematical developments in non-perturbative quantum gravity;" Carlo Rovelli presented recent results on the spectra of geometric operators and on quantum dynamics in a talk entitled "In search of topological Feynman rules for quantum gravity" and Brian Greene, in his talk "Mirror symmetry and space-time topology change," explained how differential geometry is 'transcended' in string theory.

The last two sets of talks was related to quantum geometry only indirectly. However, the areas they covered are fertile and just of the sort that may lead to new insights into this subject. The first dealt with the issue black hole entropy and the number of microstates. Ted Jacobson summarized the new developments and shared his understanding of the subject as a whole in his talks "Black hole entropy and vacuum fluctuations" and Steve Carlip, in his talk "Statistical mechanics of the 3-d black hole," presented some very tantalizing ideas about the degrees of freedom residing on the black hole horizon. The last set of talks was devoted to mathematical and conceptual issues in classical and quantum general relativity and Yang-Mills theory. Viqar Husain discussed his recent work on "Self-dual gravity and the chiral model;" Charles Torre provided an elegant summary of his work in "Hidden symmetries, observables and symplectic structures for the Einstein equations: just say NO;" Ranjeet Tate discussed the "Singularities in quantum minisuperspace models;" Arlen Anderson sketched his recent ideas on "The issue of time in quantum gravity" and Ingemar Bengtsson pointed out subtleties in quantizing constrained systems in his talk "Yang-Mills on a circle –Non compact gauge groups." There was also a thought provoking after dinner talk by Roger Penrose entitled "Shadows of the mind" which provided a preview of his book which has since been published. While this was a general talk, it was most fitting for the subject of the conference because of Penrose's long held view that it is some aspect of quantum gravity that would be responsible for the non-computability inherent in the functioning of the human mind.

This series of conferences does not normally publish proceedings. However, detailed reviews based on most of the main talks at this specific conference (together with a few invited articles) will be published as a special issue of the Journal of Mathematical Physics in the fall of 1995. The issue will be entitled "Quantum geometry and diffeomorphism invariant quantum field theory" and will be edited by Lee Smolin and Carlo Rovelli.

## First Samos Meeting on Cosmology, Geometry and Relativity

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Ten years ago a new university was founded in the Aegean Archipelago. In the 1990's general relativity research was begun in its Department of Mathematics, which is located on the island of Samos in the east Aegean sea. Samos will be known to many relativists as the birthplace of Pythagoras; this year it has firmly established its place on every relativist's world map through an international relativity conference that promises to be the first in a series. This year's meeting was held at Karlovassi on September 5-7 1994, preceded by the 2nd Summer School on Analysis, Geometry and Mathematical Physics in the Department of Mathematics (Organizers: M. Anoussis, S. Cotsakis and N. Hadjisavvas), which focused on Geometry and Cosmology. It was intended for Greek undergraduate and graduate students of mathematics, physics and related fields. The plan is to have these Schools every year as a forum and bridge for entering research in these fields.

The First Samos Meeting on Cosmology, Geometry and Relativity was organized by S. Cotsakis (Aegean) and G. W. Gibbons (Cambridge). It was attended by about 30 participants, half from Greece and the remainder from countries as diverse as Europe, India, South Africa, and the US. The aim of the meeting was to show the close interplay between rigorous mathematics and its use in relativity and cosmology. Rather than featuring a great variety of topics, a smaller number of invited speakers were given the opportunity to develop their subjects in depth and detail by allotting two hours for each lecturer.

The main speakers and their topics were:

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| Y. Choquet-Bruhat | Global existence for ultrarelativistic Yang-Mills fluids |
| D. Brill | Black hole collisions, analytic continuation and cosmic censorship |
| G. W. Gibbons | Gravitating solitons |
| D. Christodoulou | Relativistic fluids and gravitational collapse |
| R. Beig | The Einstein vacuum constraints and trapped surfaces |
| V. Moncrief | Hamiltonian reduction of Einstein's equations. |

The intensive pace of the lectures and contributed papers was relieved by social hours and a banquet. The fine weather allowed these to be held in the open air, symbolizing to us the open and friendly nature of the meeting and its location. We also had welcome opportunity to appreciate the beauty and long cultural tradition of this island. In accordance with local customs, the lunch breaks lasted four hours, allowing us to explore the town of Karlovassi, its beaches, and the nearby countryside. The conference ended with an afternoon excursion to the principal archeological sites, such as the Vathi Museum and the Temple of Hera, and a tour around the island with lunch in a traditional Greek tavern by the beach.

During the Meeting it became clear that all participants were very positive about the idea of a 2nd Samos Meeting on Geometry, Cosmology and Relativity. Accordingly it was decided to have the second meeting sometime around the summer of 1996. As plans develop details will be posted on MacCallum's gr-list. The Proceedings of the conference will be published in the Springer series *Lecture Notes in Physics.*

## 1995 Aspen Winter Conference on Gravitational Waves and Their Detection

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The Conference was held in Aspen, Colorado, Jan.22 - 28, 1995 with fifty-three participants. The conference had three aims, each of which was achieved as detailed below. One aim was to hold an organizational meeting of the LIGO users community during the conference in order to formulate a users charter and organizational structure. To this end, a nearly day long set of open meetings on Wednesday, Jan. 25, discussed organizational structures and modes of communication for the gravitational wave research community in the era of LIGO, VIRGO and the other planned interferometric detectors as well as a new generation of resonant mass detectors. The overarching goal that emerged during the discussion was the need to define the means by which the future gravitational wave research community might communicate data between detectors for coordinated analysis, the modes of collaboration in new research proposals for LIGO and other detectors, and ways in which the scientific opportunities offered by the new detectors might be maximized.

A second aim was to involve physicists from other fields. To implement this, the program started with a day of overviews by acknowledged leaders in the field. In addition, Kip Thorne gave an outstanding public lecture, entitled "Black Holes and Gravitational Waves: The Dark Side of the Universe." About a quarter of the participants were from other areas such as Elementary Particle Physics, Quantum Optics, and Precision Frequency Measurement.

The third aim was to bring together gravitational physicists with varying perspectives on how to best detect gravitational waves. The first day of overviews by Schutz, Cutler, Matzner, Thorne, Shoemaker, Hamilton, and Bender, was followed by a session on Acoustic Detectors at which Weber, Blair, Johnson and Pizzella discussed the history and present status of the field. Brief descriptions of all of the present and planned interferometric detectors were given by Sanders, Flaminio, Ward, Kawabe, and Blair. The LIGO Users discussion described above started with remarks by Sanders and Berley, followed by extensive comments by many participants. An entire day was devoted to detailed discussions of Interferometer Subsystems and Technologies, with every interesting area covered by Shoemaker( he did yeoman duty because Rai Weiss couldn't attend), Flaminio, Mizuno, Kawashima, Whitcomb, Shine, Saulson, D. Robertson, and Moriwaki. A session on Ideas for Future Detectors was a platform for the clever suggestions of Ruediger, Drever, Kimble and Braginsky. This was followed by a series of talks on Data Analysis and Observation Planning given by Schutz, Finn, Nicholson, Compton and Allen, which discussed the strategy and methodology involved. The final session considered Space Based Gravitational Wave Detectors. Wahlquist and Jafry described how this is done with American and European spacecraft. Stebbins, Newell and Richman discussed their work on Active Vibration Isolation Systems. The Conference summary, a tour de force, by David Shoemaker, concluded a most enjoyable and exciting conference.