MATTERS OF GRAVITY

The newsletter of the Topical Group in Gravitation of the American Physical Society
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Editorial

As you probably noticed from the cover, Matters of Gravity is now the official newsletter of the APS's TG on Gravitation. More details about the TG are given in Beverly Berger's article in this newsletter.

From a practical point of view little has changed in the operation of the newsletter. Contributions are still welcome from anyone, the distribution of the newsletter is free to everyone by email and the correspondents are still the same, so keep those articles coming! I want to invite especially those people organizing meetings to send me one or two page reports of what happened after the meeting. Up to the moment I have tried to keep up with the growing number of meetings requesting summaries, but my coverage has been less than adequate.

As usual I wish to thank the correspondents and especially contributors who made this issue possible. The next newsletter is due February 1st.

If everything goes well this newsletter should be available in the gr-qc Los Alamos archives under number gr-qc/yymmnnn. To retrieve it send email to gr-qc@xxx.lanl.gov (or gr-qc@babbage.sissa.it in Europe) with Subject: get yymmnnn (numbers 2-5 are also available in gr-qc). 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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Report from the APS Topical Group in Gravitation

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In April of this year, the Executive Council of the American Physical Society (APS) approved the formation of the Topical Group in Gravitation. This action occurred in response to a petition to form such a group signed by more than 240 APS members (with 200 signatures required). This number included significant support from physicists whose main area of research is not gravitation.

The objective of the Topical Group (TG) is to serve as a focus for research in gravitational physics including experiments and observations related to the detection and interpretation of gravitational waves, experimental tests of gravitational theories, computational general relativity, relativistic astrophysics, solutions to Einstein's equations and their properties, alternative theories of gravity, classical and quantum cosmology, and quantum gravity. In order to function effectively to promote this objective, it is important that the membership of the TG reflect as broad a cross-section of workers in gravitational physics as is possible.

Signing the petition to form the TG is not equivalent to membership in the TG. To join, an APS member must check off the appropriate box on the APS dues payment form. Any APS member who paid dues this year but did not check the TG in Gravitation box should contact the APS Membership Office ((301) 209-3271, membership@aps.org) to rectify this omission. The Membership Office should also be contacted by those wishing to join the APS. (APS welcomes members from all countries.)

Current activities of the TG include planning for two sessions of invited talks at the APS Spring Meeting (May, 1996 in Indianapolis) and conducting an election of the Group's first set of officers. The election will probably occur during October, 1995 with those who have joined the TG before then eligible to vote.

Matters of Gravity is now the official newsletter of the Topical Group in Gravitation and will report on the group's activities in addition to its broader coverage.

With the support of the community of researchers in gravitation, the TG can become an effective organization for promotion of the interests of the field. All gravitational physicists are encouraged to participate in this effort!

Some Remarks on the Passing of S. Chandrasekhar

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Subrahmanyan Chandrasekhar passed away on August 21, 1995, in Chicago, at the age of 84, as a result of a heart attack. He had begun to feel quite ill on the previous night, and, although he managed to drive himself to the hospital on the morning of August 21, his condition could not be stabilized after he arrived.

It should not be necessary for me to explain to the readership of this Newsletter the major role played by Chandra in twentieth century science. Nor do I feel it appropriate even to attempt to summarize here some of the highlights of his extraordinary life and scientific career. Fortunately, the full-length biography by Kameshwar Wali is available to give the reader a good glimpse into his life. However, I do wish here to mark his passing by making a few brief, personal remarks.

To those who had met him but did not get to know him well, Chandra must have seemed an austere and formidable figure. There is some validity to this impression, since he set the highest standards for himself with regard to both intellectual rigor and personal integrity, and he was not tolerant of failings by others in these matters – though much more tolerant of failings by others than of his own failings or potential failings. Chandra was particularly intolerant of scientists motivated primarily by the hope of receiving recognition by others rather than by a deep, inner conviction that their work was of importance and interest, whatever anyone else might think. In order to get to know Chandra, it seemed that a barrier had to be crossed. I believe that all that was needed to cross this barrier was some expression to him of one's inner convictions on research or other intellectual endeavors. It is unfortunate that this barrier had the effect of isolating Chandra from a portion of the scientific community. Once this barrier was crossed, the very sensitive, caring, and, above all, loyal nature of Chandra's personality would become readily apparent. The combination of these very human qualities of Chandra with his almost super-human qualities of discipline, self-sacrifice, and dedication to science had a profound and lasting effect on all those who knew him.

During the last ten years of his life, Chandra's physical stamina declined noticeably, but his interest in science, his discipline, and his fortitude did not. His intellectual efforts in writing his recent book on Newton's Principia were undoubtedly as great as in any of his other major scientific endeavors. It is very fortunate that he was able to bring these efforts to completion this winter, less than six months before his passing. Even while writing this final book, Chandra continued his lifelong pursuit of original scientific research. In my last full-length conversation with him in early August, he described what appeared to me to be a very promising approach to giving a simple derivation of a formula for the gravitational radiation emitted by a nearly Newtonian pulsating star within the perturbation framework he had developed with Valeria Ferrari. His enthusiasm for pursuing this research could not have been very different than the enthusiasm he must have shown when he had begun doing scientific research more than 65 years earlier. By chance, Valeria was passing through Chicago that week on what she thought was going to be a visit of a few days. Chandra lost no time in convincing her to stay an extra week to do some calculations to verify the validity of the approximation he had proposed. It is thus very fitting that Chandra lived the last weeks of his life pursuing science in much the same manner as he had done throughout his extraordinary scientific career.

LIGO Project Status

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Since the last *Matters of Gravity* report on LIGO in March, a number of significant events have occurred. Dedication ceremonies for the Louisiana LIGO site took place on July 6, 1995 at Livingston, Louisiana, exactly one year after a similar ceremony at the Hanford, Washington site. By now the clearing and grubbing activities at the Louisiana site have been completed and rough grading will begin shortly.

Working with our Architect/Engineering contractor (Ralph M. Parsons Co.), LIGO has finalized the conceptual design for the buildings and associated site development. Parsons has now started the full design effort. The large scale demonstration test for the construction of the LIGO beam tubes (which connect the vertex and ends of the two arms) was successfully completed this spring, confirming that the design meets our vacuum and cleanliness requirements. A preliminary design competition for the remainder of the vacuum system was carried out and a contractor selected for the final design and fabrication effort.

Organizationally, a LIGO pre-Program Advisory Committee has been formed, with Peter Saulson(Syracuse) as its chair. The other members are: S. Finn(Northwestern), A. Giazotto(Pisa), J. Hall(JILA), W. Hamilton(LSU), C. Prescott(SLAC), A. Ruediger(MPI-Garching). This committee will exist only for a year or two. During its brief life it will act as both a LIGO Program Advisory Committee(PAC) and as an External Advisory Committee(EAC). Before it goes out of existence it will help design a final PAC and EAC. The first meeting is scheduled for September 8-9, 1995 at Caltech.

Following the very successful Aspen Winter Physics Conference on Gravitational Waves and Their Detection (see *Matters of Gravity*, Number 5, Spring 1995), a second Aspen Winter Physics Conference has been scheduled for January 15-21, 1996. A major theme of the Conference will be the study of advanced interferometers and long range planning. The program will include extensive meetings of the LIGO Research Community, and several sessions on LISA.

In the R&D program, the 40m interferometer at Caltech has been converted to an optically recombined system, as a first step toward operating it as a recycled interferometer. The optical configuration chosen for the optical recombination is modeled after that planned for the full-scale LIGO interferometers and uses a small asymmetry in the arms to produce the required modulation at the point where the difference in arm lengths is sensed. New servosystems required to hold the interferometer at its correct operating points are being testing on the 40 m system, and noise studies to understand the performance in the new configuration are underway

At MIT, a suspended interferometer to investigate optical sources of noise at high phase sensitivity is under development. This interferometer has a simple optical configuration, to emphasize the study of optical sources of noise and to minimize the amount of time needed to debug other noise sources. The initial phase of its fabrication has been completed and it is producing its first data, although still at relatively low power (about 50 mW). Over the next year, the power will be gradually increased, with a goal of achieving shot noise limited sensitivity with 70 W incident on the beamsplitter.

The effort on the LIGO detectors is growing rapidly as projects move from the R&D to the actual detector detailed modeling and hardware design. A recent highlight in this effort was the integration of a stabilized argon ion laser under the control of EPICS. EPICS is the control system planned for the LIGO detectors, and this laser is the first detector subsystem to be fully interfaced to it to provide data logging and operator interfaces appropriate for a facility the scale of LIGO.

Further information about LIGO can be obtained from our WWW home page at

`http://www.ligo.caltech.edu`.

New Hyperbolic forms of the Einstein Equations

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It is well known that the standard form of the 3+1 Einstein equations consisting of evolution equations for the 3-metric and extrinsic curvature, supplemented by prescriptions for determining the kinematical variables the lapse and shift vector, is not manifestly hyperbolic. To produce a d'Alembertian wave equation for the 3-metric it is necessary to specify the harmonic coordinate condition thus eliminating the "undesirable" second derivatives of the 3-metric appearing in the Ricci tensor. The classic hyperbolic systems of Choquet-Bruhat [1] and Fischer and Marsden [2] are based on this harmonic coordinate condition.

In the past year there have been four independent attacks aimed at formulating new hyperbolic versions of general relativity, a common goal being to relax the restrictions of the 4-dimensional harmonic condition. Several of these efforts have been motivated by the "Grand Challenge" effort to simulate the inspiral and coalescence of black hole binaries. Besides for the theoretical advantages for global analysis, it is now widely believed that manifestly hyperbolic evolution systems will be powerful tools for numerical solution of the Einstein equations.

The primary obstacle to long-time simulations of black hole spacetimes is that evolutions using singularity-avoiding foliations (such as maximal slicing) freeze inside the event horizon leading to the oft-discussed "throat stretching". Attempting to numerically resolve the rapidly growing throats for an astrophysically interesting black hole collision scenario while preserving reasonable accuracy is certainly wasteful of computational resources and currently, at least, beyond our capabilities. For this reason, it is now expected that such simulations will excise the interior of the black holes simply by ignoring the spacetime inside the apparent horizon (which, assuming cosmic censorship, lies inside the event horizon). Since there are no general boundary conditions to apply at this surface, one appeals to causal disconnection and ignores the field inside. Thus it is clearly critical to have an evolution system with mathematical characteristics which coincide with the physical lightcone. This same feature greatly simplifies the problems associated with applying *outer* boundary conditions and extracting asymptotic gravitational waveforms; the fields evolved by the code in the strong-field region can be directly matched onto radiative variables in the exterior. Another attractive aspect of such explicitly hyperbolic evolution schemes is that numerical implementations can exploit a wealth of sophisticated computational algorithms developed for the studying the wave equation and the equations of fluid dynamics.

Fritelli and Reula [3] have developed a first-order symmetric hyperbolic formulation of general relativity which allows the Newtonian limit to be taken in a rigorous way. The basic variables in their system are the 3-metric, its momentum, and spatial derivatives of the 3-metric (which obey a new constraint equation). The lapse and shift vector may be chosen arbitrarily – they do not propagate as part of the first-order system. A somewhat similar approach, also starting with the usual form of the 3+1 Einstein equations has been recently published by Bona, Masso, Seidel, and Stela [4] following up on earlier work by Bona and Masso [5]. The basic variables for their system include the 3-metric, extrinsic curvature, the lapse and shift vector as well as spatial derivatives of the lapse, shift, and 3-metric. They write the evolution system in flux-conservative first-order symmetric hyperbolic form which they diagonalize in order to obtain the characteristics. It should be noted that the kinematical variables have characteristic speeds in this system which can be different than the speed of light. Bona et al. have tested their new system with numerical simulations of Schwarzschild black holes using several different slicing conditions. They have already seen substantial improvement over calculations using the standard 3+1 equations.

The systems of van Putten and Eardley [6] and Choquet-Bruhat and York [7,8] each involve going up one time-derivative from the usual form of the Einstein equations and producing explicit wave equations for the dynamical parts of the field. van Putten and Eardley, using a tetrad formulation, start from the Bianchi identity and form Yang Mills-like wave equations for the connection 1-forms. The Choquet-Bruhat and York system is derived by taking a time-derivative of the usual evolution equation for the extrinsic curvature in a manner proposed by Choquet-Bruhat and Ruggeri [9]. (Related ideas were pursued by Friedrich [10].) By employing the momentum constraints, a quasi-linear wave equation for the extrinsic curvature is formed for either harmonic slicing or slicings where the trace of the extrinsic curvature is specified in advance. The main difference between these approaches is the choice of variables, tetrad vs. standard 3+1. In both of these formulations wave equations are produced which are spatially gauge-covariant. It is also apparent that the 3-metric evolves but does not, in general, propagate in a wavelike manner; it does not directly carry the dynamical degrees of freedom but rather provides an arena for the wave propagation. This physically intuitive feature can be seen explicitly in the Choquet-Bruhat/York system by choosing the harmonic time-slicing, reducing the formally third-order system to first-order symmetric hyperbolic form, and reading off the characteristic speeds of the fields. The 3-metric, extrinsic curvature, lapse and acceleration all propagate with zero speed; they are dragged along in a direction normal to the foliation. Only the time-dependent tidal forces have characteristic speeds equal to the speed of light.

It is already clear that these systems will be fruitful for analytic approximation schemes and perturbation theory. As far as numerical relativity is concerned, formal and aesthetic differences may not be adequate to identify the best scheme. The proof of successful numerical implementation will be in the non-linear gravitational pudding resulting from the violent coalescence of two black holes.

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Massless Black Holes

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The idea of a massless black hole almost sounds like a contradiction in terms. A black hole is supposed to be a massive object which has undergone gravitational collapse. What could it mean for a black hole to be massless? Surprisingly, it has recently been shown that 'massless black holes' play an important role in string theory. They have appeared in at least two different contexts, and in each case were instrumental in resolving long standing problems. The first problem concerned the strong coupling limit of string theory in ten dimensions, and the second involved some troubling singularities in the low energy description of string theory in four dimensions.

One example of a massless black hole was discussed by Witten [1], who made the following argument (see also [2]). We usually think of an extremal black hole as having a mass equal to its charge $M = |Q|$. However, if one is careful about coupling constants, one finds that (for a certain ten dimensional string theory called Type IIA) the relation is really

$$M = |Q|/g$$

where g is the coupling constant. These extremal black holes are supersymmetric, and one can use this fact to argue that this formula does not receive any quantum corrections even in the limit of strong coupling. In the extreme limit where $g \to \infty$, the mass of these extreme black holes goes to zero. This suggests that these black hole solitons become light degrees of freedom in the strong coupling limit of the theory. In fact, if one assumes that the charge is quantized and that different charges correspond to distinct states, one is lead to a tower of states with $M = c|n|$ for some small constant c. This is exactly the same spectrum that one obtains from Kaluza-Klein compactification of one dimension on a circle. As the radius of the circle becomes large, the massive Kaluza-Klein states become light just like the black holes at strong coupling. Using this connection, it has been conjectured that the low energy dynamics of the strongly coupled ten dimensional string theory is, in fact, *eleven dimensional* supergravity.

A second example of massless black holes in string theory was provided by Strominger [2]. A standard method of reducing string theory to four dimensions is to compactify it on a six dimensional manifold called a Calabi-Yau space. However, it has been known for some time that this approach suffers from the following difficulty. There are continuous deformations of the Calabi-Yau space which give rise to scalar 'moduli' fields in four dimensions. In particular, there is a deformation which corresponds to a three-surface in the Calabi-Yau space shrinking down to zero size. At this point, the effective four dimensional lagrangian becomes singular, since the kinetic energy term for one of the moduli fields acquires a diverging coefficient. (Notice that this is a singularity in the action itself, and not a particular solution.) Strominger resolved this singularity as follows. The ten dimensional theory contains three dimensional extended objects surrounded by an event horizon [4] .

One can think of them as 'black three-branes'. These objects carry a mass per unit three-volume M/V and charge Q, and there is an extremal limit in which $M = |Q|V$. Now, when one compactifies on a Calabi-Yau space, this black three-brane can wrap around a nontrivial three-surface in the compact space. From the four dimensional viewpoint, the three-brane now looks like an ordinary black hole. However, when the volume of the three-surface shrinks to zero, the mass of this black hole goes to zero. Near this point, the black hole can no longer be treated classically, but instead acts like another light 'particle' which should be included in the low energy lagrangian. Strominger has shown that the singularity in the standard four dimensional action is exactly what one would get if one views this as an effective action obtained by starting with a nonsingular action with one additional massless charged scalar field, and integrating it out. Perhaps even more striking is the fact [5] that one can use these massless black holes to give an apparently nonsingular description of a transition from one Calabi-Yau space to a topologically different one.

To summarize, in the above examples, extremal black holes act just like elementary particles (or in string theory, just like other states of the string). The main difference is that they can carry certain charges which are not carried by ordinary particles. This clearly suggests that there may be no fundamental distinction between extremal black holes and elementary particles.

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A plea for theoretical help from the gravity wave co-op

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With the most recent successes in operating cryogenic gravity wave detectors at LSU, Rome and Perth and with the recent discovery of the TIGA configuration for an omnidirectional detector we see very great advantages to operating resonant TIGA detectors in coincidence with the upcoming LIGO and VIRGO detectors. Carl Zhou's paper in the last PRD shows that such a configuration will be very powerful in determining a source's location in the sky. The gravity wave co-op has started to design TIGA detectors to run in coincidence with the interferometers. As shown by Johnson and Merkowitz we expect such detectors to be more sensitive than the interferometers in their higher and narrower frequency range. There are problems, however.

The gravity wave co-op has been told the only way that a new detector can possibly be built is if there is a guaranteed source for it to go after. It probably is not sufficient, we are told, to depend on supernova sources since most recent models have a much softer collapse and much less GW emission than we expected several years ago.

Thomas Stevenson at the University of Maryland did an estimate of the detectability of a NS-NS inspiral and merger, based on the recent work of Centrella et al. His conclusion was that, for a source at 15 Mpc, the signal to noise ratio in a nearly quantum limited TIGA would be about 4 in the largest TIGA that we can consider practical, a 60 tonne detector at 870 Hz. That's too low for a detection with only one detector and even too low for a two detector coincidence. Most of the energy that would be detected would come from the final few revolutions of the inspiral with very little coming from the actual merger. Warren Johnson and I had separately done a very cursory look at Centrella's results and came to a similar discouraging conclusion.

On the other hand, there are those who argue that Centrella's work is just the first cut in a very difficult problem and that a different model for the star could give vastly different results. Williams and Tohline, for instance, used a fluid model code to investigate inspiraling normal binary stars. They found a bar like central region after the merger which resulted in a very large time dependent quadrupole moment. Tohline suspects that his code would give a similar result in the NS-NS case. Some of us naively hope that the formation of rapidly spinning black holes, perhaps at the end of a merger, will prove to be an efficient source.

Those of us who build detectors are simple plumbers who don't have access to the latest information about sources or the insight to understand what is good and what is bad about various numerical approaches to the problem. We need good input about possible sources, the type of statistics that we might expect from these sources, and the character of the gravitational wave signal that might be expected. The frequencies of interest to the resonant detectors are those above 1 kHz. The detectors that we know how to build will probably be pretty noisy above 3 or 4 kHz so that is probably the upper limit of what we should consider building.

This letter then is an urgent request for any input about possible high frequency sources. We need to have a good plausible source to look for with reasonable statistics. We need to get the search underway as soon as possible because it will take at least a couple of years to design and build the detector and it will probably take some time to work out the details of the sources that we think we can detect.

With LIGO now well underway some may believe that its great sensitivity will eliminate the need for resonant burst detectors. Our experience is that confidence in any detection will be enormously enhanced if there are more detectors involved. It will certainly be more convincing if a gravitational wave detection is made with one technology and confirmed by another.

To build the omni-directional TIGA we need sources. We cannot just improve technology in the hope that we will see something. Please give serious thought to possible high frequency gravitational wave sources. It is important for all of us if we are to begin to do gravitational wave astronomy.

Why Quantum Cosmologists are Interested in Quantum Mechanics

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The objectives of quantum cosmology are a description of the universe in quantum mechanical terms, and, within that description, a theory of the universe's initial condition that makes testable predictions about observations today. Early work on this subject concentrated on the predictions of particular theories of the initial condition using semiclassical approximations to quantum mechanics. More recently there has been interest on the part of some quantum cosmologists, and others in quantum gravity, in generalizing the usual framework of quantum mechanics and in clarifying its interpretation when applied to closed systems such as the universe. A somewhat representative (but not exhaustive!) list of recent papers in this vein is given below.

The first reason that quantum cosmologists are interested in quantum mechanics is that a generalization of the usual theory may be needed to deal with quantum spacetime geometry. A fixed spacetime geometry is central to the usual formulations of quantum mechanics, for instance, to give meaning to the time which enters so basically. But, in a quantum theory of gravity, spacetime geometry is not fixed. It is rather a quantum dynamical variable, fluctuating and without definite value. This conflict is called the "problem of time" in quantum gravity. (For lucid reviews see refs [9,10].) A long investigated route to a resolution of this question has been to keep quantum mechanics as is, but find preferred time(s) in general relativity [9,10,11]. Recently, however, there has been interest in the opposite contrast – keep general relativity as is, but generalize quantum theory, so that it does not require a fixed background spacetime, but yields the usual theory in situations where spacetime geometry is approximately fixed and can supply a fixed notion of time [12,13].

A second reason that quantum cosmologists are interested in quantum mechanics is that, in applying quantum mechanics to the universe as a whole, the interpretive difficulties of the subject are encountered in an unavoidable manner. To utilize the probabilities of density fluctuations at the time the observed universe was the size of an elementary particle one needs to be clear about what these probabilities mean! Phenomena such as classical behavior, that in the familiar frameworks might be posited or taken for granted, now require explanation in a wholly quantum universe. The range of ideas that have been put forward for quantum frameworks for the universe as a whole are well beyond what could be described or critically analyzed in this small compass. One contrast that emerges is between those who would put observers, measurement, and even consciousness in a central position in quantum theory [1,2], and those who, with the aim of precision, would expel these elements from so fundamental a role [3-8].

How are we to evaluate generalizations of quantum mechanics that have been proposed? How are we to distinguish between the various interpretive ideas? The methods for doing this are standard in physics. In cosmology we may ask: Are the proposed frameworks general enough to calculate the probabilities for alternative behaviors of the universe – its large scale behavior and that of everything inside it including quantum spacetime? Are the frameworks logically consistent and conceptually and mathematically precise? Do they allow the assumptions of quantum theory to be stated more precisely and clarify long standing issues of interpretation? Do they lead to calculations of observable quantities that can be carried out in the near term? Do they correctly and easily reproduce what is already well tested in quantum mechanics and field theory? Do they differ one from another in testable predictions? Do they further the research program of understanding quantum gravity and the quantum origin of the universe?

More important than the differences between the ideas under discussion is the common thread that links them. By focusing on a program of predicting the observable features of this largest of physical systems from a theory of its quantum initial condition, we may be led to a clearer and more general form of quantum theory – perhaps even with implications for the laboratory.

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Probing the Early Universe with the Cosmic Microwave Background

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The cosmic microwave background (CMB), first discovered by Penzias and Wilson in 1964, provides a critical test of the big bang model and provocative ideas that go beyond the big bang to explain the origin and evolution of large scale structure in the universe [1] The CMB may also be used to constrain the values of cosmological parameters such as the Hubble expansion rate and the matter density of the universe.

According to the big bang model, the CMB is radiation emitted some 100,000 years after the big bang. Prior to that time, the universe consisted of a hot, dense gas of free electrons and nuclei in equilibrium with photons. After 100,000 years or so, the universe had cooled enough for the free electrons and nuclei to combine into neutral atoms. From that time onwards, the photons, which interacted only very weakly with the newly neutralized medium, began to freely stream in all directions. Initially, the spectrum was perfectly black body with a temperature of nearly 10,000 K. Over the subsequent 10 billion years, the photon distribution red shifted due to the expansion of the universe. The spectrum remains black body today but now the average energy lies in the microwave regime.

Recently, the Far Infra-Red Absolute Spectrophotometer (FIRAS) experiment on board the COsmic Background Explorer (COBE) satellite measured the spectrum of the radiation and confirmed the big bang predictions. With exquisite experimental precision, the spectrum was shown to be perfect black-body with a temperature of $T_0 = 2.726 \pm 0.010$ K [2].

The focus of cosmologists has recently turned to what can be learned from the CMB anisotropy, the difference in blackbody temperature along different lines of sight on the sky. The anisotropy can be used to test ideas about the very early evolution of the universe and the origin of large-scale structure. It was nearly 30 years after the discovery of the CMB before any non-uniformity in the CMB temperature across the sky was detected. The temperature variation is so tiny that instruments with microKelvin sensitivity had to be developed. The first successful detection was by the Differential Microwave Radiometer experiment aboard the COBE satellite (1992) [3].

The root-mean-square fluctuation in temperature, found to be roughly 0.001%, is an important cosmological parameter for understanding the formation of galaxies. How did the universe evolved from being highly homogeneous at the 100,000 year mark, as imaged by the CMB, to being highly inhomogeneous today, as shown in recent maps of the distribution of galaxies? The favored explanation has been "gravitational instability", the amplification of inhomogeneity caused by gravity drawing additional matter into overdense regions and away from underdense ones. A straight-forward calculation shows that the inhomogeneity must have been $0.001\%/\Omega$ at the 100,000 year mark in order for gravitational instability alone to explain the inhomogeneity seen today. Here Ω is the ratio of total energy density of the universe to the critical density, the threshold that separates an open, ever-expanding universe from a closed universe that ultimately recollapses. The COBE observation has provided important support for the gravitational instability concept provided Ω is not much smaller than one.

The key, unresolved issue is: What created the anisotropy in the first place? A leading explanation is the inflationary [4] model of the universe. In this model, the seeds of large-scale structure are quantum fluctuations in the energy density generated when the observable universe occupied a sub-nucleonic size just instants after the big bang. There then followed a brief burst of extraordinary superluminal expansion (*inflation*) in which the microscopic quantum fluctuations were stretched into a spectrum of energy density perturbations that span cosmic dimensions.

The fluctuation spectrum is predicted to be nearly scale-invariant. If one expands the energy density field $\rho(\mathbf{x})$ in a sum of fourier modes with amplitude $\delta(\lambda)$, then the amplitude of a mode is nearly independent its wavelength λ. If the spectrum is parameterized by a spectral index, n, defined by $\delta(\lambda) \sim \lambda^{(1-n)/2}$, then a precisely scale-invariant spectrum corresponds to $n = 1$ (See [1] for more precise definitions and discussion). In inflationary models this index can be in the range $0.7 \leq n \leq 1.2$.

Given a map showing the temperature variation of the CMB across the sky, the best test of inflation or competing models is the temperature auto-correlation function, defined as

$$C(\alpha) \equiv \langle \frac{\delta T}{T_0}(\mathbf{x}) \frac{\delta T}{T_0}(\mathbf{x}') \rangle_{\mathbf{x}.\mathbf{x}'=\cos\alpha} \equiv \sum_l \frac{2l+1}{4\pi} C_l P_l(\cos\alpha)$$

where $\langle \ldots \rangle$ is an all-sky average over every pair of directions separated by anlge α. The values of the C_l's, called *multipole moments*, depend on the average temperature variation between two directions separated by $100/l$ degrees (π/l radians). A plot of $l(l+1)C_l$ vs. l is called the CMB power spectrum (see Fig. 1, which is normalized by the COBE value of the power spectrum at $l = 9$).

The power spectrum is a tell-tale fingerprint that can be used to distinguish competing cosmological models. The characteristic power spectrum predicted by inflation (Fig. 1) has a plateau for $l < 100$ (large angular scales) and a series of peaks for $l > 100$. Variations in the energy density result in varying gravitational potentials that red shift or blue shift the CMB photons by different amounts across the sky, producing apparent CMB temperature differences across the sky. If the energy density fluctuations are scale-invariant, the variations they induce on the CMB temperature are too, resulting in a power spectrum independent of l. This is true for those energy density fluctuations that have not evolved since inflation, which are the fourier modes relevant to $l < 100$. These modes have wavelengths $\lambda \gg 100,000$ light-years, and so no redistribution of matter could have happened across them by the time the CMB radiation first began free-streaming.

The COBE experiment, which was sensitive only to the long-wavelength modes affecting multipoles with $l < 30$, constrained the spectral index n to be 0.91 ± 0.36 [5]. This value is consistent with the inflationary prediction, although some other models of large-scale structure formation, such as cosmic strings and textures, make a similar prediction. As shown in Fig. 1, i ndependent experiments sensitive to $l < 100$ have yielded consistent results.

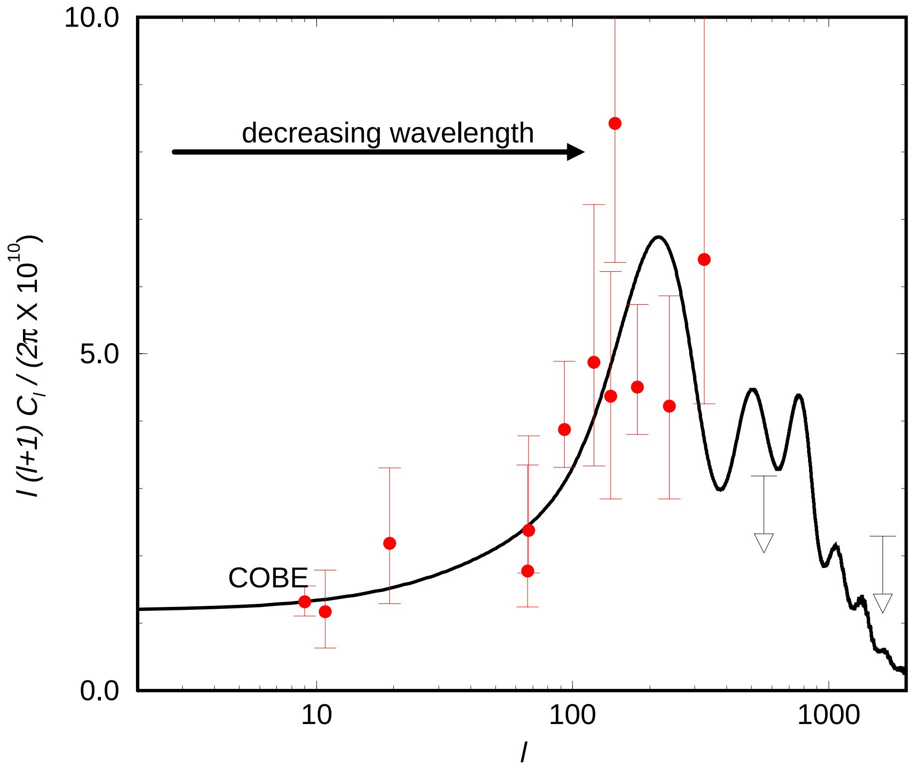

Figure 1 *A plot of the CMB power spectrum vs. multipoles for a flat universe with Hubble expansion rate 50 km/s/Mpc, and composition 5% baryons with the rest Cold Dark Matter. The power spectrum is normalized to COBE. Results from experiments are overlaid. As we move from left to right in* l*, we probe anisotropies created by fluctuations of decreasing wavelength. The key features (described in the text) are the plateau for* $l < 100$ *and the oscillations beginning at* $l \sim 220$*.*

The behavior for $l > 100$ is different because the energy density fluctuation modes that perturb the CMB have wavelengths much shorter than 100,000 light-years. Matter and radiation have had time to redistribute across the wavelength before the CMB was emitted. In particular, there are a series of acoustic oscillations in which the matter and photons are drawn together by gravity and then bounce back due to the radiation pressure. The effect of the acoustic oscillations on the CMB photons is to produce the series of peaks shown in the figure.

The discovery of CMB anisotropy peaks would be extremely significant since it would be an unmistakable verification of inflation. The location of the left-most peak along the l-axis is a sensitive test of Ω; a peak at $l \sim 200$ is support for the inflationary predictions $\Omega = 1$. This method for measuring Ω is extremely powerful compared to present methods because it probes the universe over greater distances and counts all forms of energy density including baryonic matter, dark matter, unclustered matter and cosmological constant.

The detailed shape of the first and subsequent peaks depend sensitively on cosmological parameters. Precise measurements, especially when combined with more conventional astronomical observations, will determine the energy densities in baryons and various species of dark matter, the vacuum energy density or cosmological constant, and the Hubble expansion rate.

A number of ongoing experiments are attempting to measure the CMB anisotropy with half-degree resolution or better to determine the existence and shape of any peaks. Whereas the COBE experiment is aboard a space platform, the others are performed at remote, high, and dry locations such as Saskatoon and the South Pole or are launched in high-altitude balloons. Fig. 1 shows the present experimental situation. It can be seen that, while the error bars on present experiments are too large to make the results conclusive, there seems to be reasonable agreement with the inflationary predictions.

There have been rapid improvements in observational strategy and technology. The detectors on most experiments launched today are more than an order of magnitude more sensitive than those aboard COBE. Several groups are now pioneering long-duration balloon experiments in which a balloon-based apparatus circumnavigates Antartica for several weeks. There are also an international efforts underway to launch a second satellite experiment with high angular resolution instruments. There is a much improved understanding of how to remove foreground signals from the data and how to use the CMB anisotropy to test cosmological models. Thus, there is every hope that a precise, high resolution map of CMB temperature variations across the sky will be available within the next decade and that this snapshot of the early universe will be a historic contribution to our understanding of the origin and evolution of the universe.

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G Measurements

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The highly discrepant results of G measurements which I reviewed in Newsletters 3 and 4 have attracted public attention upon their presentation at the spring APS meeting in Washington this year. Values of G presented there by the German PTB group and by the New Zealand group were those reported earlier (Newsletter #4). The group at Wuppertal University in Germany had previously reported a G with 117 ppm accuracy in good agreement with the CODATA value (0.6σ), but now report 6.6685 (± 140 ppm), 3.2σ below CODATA: 6.6726 (± 128 ppm), and 2.6σ above New Zealand: 6.6656 (± 95 ppm). The big puzzle remains the PTB result: 6.7154 (± 83 ppm), 42σ above CODATA and even further from the other new values. This result, the product of many years of carefully repeated measurements by the German NIST equivalent laboratory, is not to be lightly dismissed.

Gabe Luther continues his G measurement at Los Alamos. I have lost email contact with the Russian group that has been measuring G. Not surprisingly, several new G measurements are under way or planned; I am aware of the following:

Jim Faller's group at JILA is using its free fall g measurement instruments with a movable local mass to measure G, initially at a level of about a percent to explore the feasibility of a more accurate measurement. Jens Gundlach of the University of Washington "EötWash" group plans a measurement using their rotating torsion balance in a novel fashion: the turntable rotation speed will be servoed to null the $\sin(2\theta)$ acceleration signal from a torsion pendulum due to a pair of attracting masses. The measured acceleration of the turntable then reflects the acceleration of the pendulum, while the fiber never twists. This nicely avoids troublesome issues of fiber deflection calibration and possible fiber nonlinearities. The pendulum is to be a thin plate suspended vertically; thus its quadrupole moment (which largely determines the gravitational torque) is nearly proportional to its moment of inertia I. The measured angular acceleration which determines G is then highly insensitive to the mass distribution and geometry of the pendulum. By also rotating the source masses and averaging over turntable orientations, the effects of turntable readout nonlinearities and ambient fixed gravitational fields are averaged out. Jens finds measured turntable acceleration noise levels should allow a 100 ppm G determination in less than a day.

At UCI we plan a G measurement using a cryogenic torsion pendulum, using the now classic method of measuring the pendulum's oscillation frequency as a function of source mass orientation. We too will use a thin vertical plate for the pendulum. The source masses will be a pair of rings positioned so that their multipole couplings to the pendulum ideally vanish for $\ell = 1, 3, 4$, and 5, leaving an essentially pure quadrupole coupling. The pendulum will oscillate at one of five amplitudes between 2 and 9 radians at which the frequency shift as a function of amplitude is an extremum and hence insensitive to error in amplitude determination. Large amplitude operation raises concerns of fiber nonlinear effects, which have often been viewed as a possible source of systematic error in such experiments; however our measurements of nonlinearities in an aluminum 5056 fiber at 4.2K, as reflected in the harmonic content and frequency amplitude dependence of a symmetric pendulum operating at large amplitudes, indicate that fiber nonlinearities should affect a G measurement at a (correctable) level of only a few ppm. Comparison of G values determined at a variety of oscillation amplitudes will provide a powerful consistency check for systematic effects. We aim for 20-50 ppm accuracy in an initial experiment, with a goal of 1-5 ppm accuracy in a second phase using fused silica source mass rings.

At the APS meeting, Craig Spaniol (West Virginia State College) and John Sutton (Goddard Space Flight Center) announced their hope to organize a multi-institutional program for a new G measurement. Spaniol may be contacted at 304-766-4123.

Several proposals have been made for G measurements in space (outside my province as reporter on "laboratory gravitation experiments"). A discussion of several of these proposals appears in a paper to be published by Alvin Sanders and George Gillies.

Is general relativity about null surfaces ?

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What has Ted Newman been doing during the last decade? Some papers of him appeared, but too few for Ted's volcanic creativity. Indeed, for over a decade Ted Newman's main activity has been to pursue a strange and ambitious program with by a small band of faithful collaborators, primarily Carlos Kozameh and Simonetta Frittelli. Now the three are emerging from the long search with a stream of papers presenting a surprising new rabbit in the hat: a reformulation of general relativity as a theory of evolving surfaces, whose dynamics is determined by an equation in six dimensions.

The group has gone through a long sequence of twists and shifts, during which it has been talking of light-cone cuts on Scri, holonomies of the self- dual connection along light rays, sphere-worth sets of coordinate transformations, and so on. Most of this language has now been left behind, and the formulation of GR finally discovered is simple and tidy; and surprisingly different from the way we use to think of GR or any other field theory.

Let me try to summarize this reformulation, at the cost of much vagueness and much simplification. Consider an open region M of a four dimensional manifold, and a foliation s of M. (A foliation is a family of non-intersecting surfaces filling M. The surfaces are determined as level surfaces of a suitably regular function $s : M \rightarrow R$). Clearly, there exists (locally) a metric tensor g on M –determined up to a conformal rescaling– such that each surface of the foliation s is null. Let us next consider several (overlying) foliations of M, or, more precisely, a one-(complex-)parameter family $s(\zeta)$ of such foliations; ζ is a complex parameter. In general, there will not be a metric g such that each surface in each foliation is null. Frittelli, Kozameh and Newman have found the conditions on the family of foliations $s(\zeta)$, such that g exist, plus an extra equation for the undetermined conformal factor which implies that g is an Einstein metric.

Since the theory is generally covariant, the physical content of the family of foliation s(ζ) is given by the position of the overlying foliations with respect to each others. This fact can be used as follows. The family of foliations s(ζ) determines a preferred coordinate system x for every z –essentially by posing $x^1 = s$, $x^2 = \frac{\partial s}{\partial \zeta}$, $x^3 = \frac{\partial s}{\partial \bar{\zeta}}$, $x^4 = \frac{\partial^2 s}{\partial \zeta \partial \bar{\zeta}}$. The other second derivatives, namely $\Lambda = \frac{\partial^2 s}{\partial \zeta \partial \zeta}$ contain physical information. These can be expressed in the preferred coordinate system as $\Lambda(x;\zeta)$. Newman and collaborators have found a partial differential equation for the complex function of six real variables $\Lambda(x;\zeta)$, which implies the existence of the metric g. Once such equation is solved, the explicit form of g can be found from $\Lambda(x;\zeta)$ by derivation. The magic is then that the equation for the conformal factor that implies that g solves the Einstein equations is just a differential equation (an ODE, not a PDE !).

This strange way of looking at GR reveals a new side of the theory, and emphasizes the peculiarity of general relativity. As Ted Newman puts it, a conventional field theory describes propagation along characteristics of certain operators; but general relativity is a theory determining its own characteristics. He suggests that this result indicates that GR has such a peculiar structure that no known form of quantum mechanics could be merged with it. Certainly this beautiful result indicates that general relativity is still capable of surprising us, and emphasizes how deeply GR is a relational theory: the theory can be viewed as a theory of the relative position –the position with respect to each others– of overlaying foliations.

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ITP program solicitation

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The Institute for Theoretical Physics is an NSF funded institute located on the Santa Barbara campus of the University of California. Its purpose is to foster the progress of theoretical physics, especially in areas where the traditional subfields overlap. It does this chiefly by organizing 4-6 month research programs in which groups of scientists in residence at the ITP explore specific problem areas. *

Input from the scientific community is central to determining the programs the ITP runs. I am writing to encourage relativists to submit proposals for research programs in areas where you believe that ITP activities can make significant contributions. The main emphasis is on full, multi-month programs, but ideas for workshops or mini-programs lasting a few weeks or longer are also welcome. Criteria for the selection of programs include intellectual significance, timeliness, suitability for the ITP, experimental or observational significance, and availability of outstanding participants.

The cycle for selecting programs for 1997-1998 year will begin with the Advisory Board's steering committee meeting at the very end of this September. At this early stage of program development, proposals need not be elaborate — a title, a paragraph or two explaining the idea, and some suggestions for organizers and program participants will be sufficient. For maximum utility suggestions should be made several weeks in advance of the end of September so that they can be distributed to the steering committee. Program suggestions can be sent to Prof. James Langer, Director, Institute of Theoretical Physics, University of California, Santa Barbara, CA 93106, or to langer@itp.ucsb.edu, or to me at the same address, or at hartle@itp.ucsb.edu.

Please do not hesitate to get in touch with me at 805-893-2725 or hartle@itp.ucsb.edu if you have questions.

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* More information about the ITP can be found from its homepage: http://www.itp.ucsb.edu.

7th Gregynog workshop in general relativity

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The 7th Gregynog Workshop on General Relativity focused on Numerical Relativity and took place from Monday August the 21th to Thursday August the 24th, 1995. It was attended by some 40 researchers from the following countries: Austria, Brazil, France, Germany, Greece, India, Japan, Mexico, Russia, South Africa, Spain, the United Kingdom and the United States.

Gregynog is a beautiful stately home surrounded by woods in the middle of Wales. Its relaxed atmosphere is ideal for workshops of this type, since it allows for extensive interaction among the participants after the conference sessions.

The programme for the workshop included many different aspects of numerical relativity: critical phenomena in gravitational collapse, relativistic stars, black-hole collisions, quasi-normal modes, Cauchy-Characteristic matching, connection approaches to numerical relativity, cosmology, numerical and visualization techniques, etc.

Since it would be impossible to summarize all the talks in this space, I will concentrate my attention on those subjects that I consider to have been the highlights of the meeting:

1) Critical phenomena and self-similarity in gravitational collapse.

Charles R. Evans presented a review of this exciting field. Other related talks where given by R. Hamade, C. Gundlach and T.P. Singh.

It is clear that the field has greatly developed since Choptuik's original discovery of critical phenomena in scalar field collapse. Many other physical systems have now been shown to have a similar behavior (gravitational wave collapse, radiation field collapse, relativistic fluid collapse), and studies have been performed both in spherical and axial symmetry.

The phenomena seems to be relatively well understood numerically. Great progress has also been made analytically making use of renormalisation group techniques.

The critical exponents found for near critical collapse seem to be truly universal for a given physical system. However, they are now known not to be universal across different physical systems.

2) Black-hole collisions.

The head-on collision of two black holes seems to be very well understood. The numerical work of the NCSA-Washington University collaboration has provided us with beautiful pictures of the evolution of both apparent and event horizons. Of particular interest has been the study of the dynamical oscillations of the horizon geometry, as well as the caustic structure of the horizon merger. This calculations where originally done in 2D and have recently been repeated in 3D showing a very close agreement.

One of the most important results to emerge form the study of this problem has been the remarkable agreement between full numerical evolutions and linearized approximations. The work of J. Pullin and R. Price has shown that the linear approximation works surprisingly well in a strong field regime.

3) Cauchy-characteristic matching.

A technique that finally seems to be giving its first fruits is that of Cauchy-characteristic matching. The work presented at the workshop by R. d'Inverno shows that the technique works very well for 1D problems. Its application to more than one dimension is also being developed, as was shown to us in the work of N. Bishop.

This technique, with its promise of eliminating arbitrary boundary conditions and allowing calculations to go out all the way to Scri+, will be essential for numerical relativity in the future.

4) Hyperbolic relativity.

Over the last few years the need to understand the characteristic structure of the evolution equations of general relativity has become apparent. Writing the evolution equations in a fully hyperbolic form is a fundamental step both from the analytical and numerical points of view.

The works presented by C. Bona and J. Masso have shown how it is indeed possible to write the evolution equations in hyperbolic form in a way that allows the use of very powerful numerical techniques.

Hyperbolic relativity is one of the most fundamental developments of the last few years and will surely have a great impact in numerical relativity in the near future.

5) 3D numerical relativity.

During the workshop it became clear that 3D numerical relativity is finally here. There are now several groups working on 3D codes on both sides of the Atlantic.

3rd Annual Penn State Conference: Astrophysical Sources of Gravitational Waves

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This conference was organized by C. Cutler and K. Thorne, and took place at Penn State during July 7–11, 1995. It was the third gravity conference in an annual series at Penn State, the first two having focused on numerical relativity and quantum geometry, respectively. The Conference was divided into two parts: 2 days of invited and contributed talks intended to give a broad overview of the field to people who might be new to it, followed by a 2-day workshop concerned more narrowly with coalescing neutron star and black hole binaries. This workshop was the follow-up to a similar workshop held at Caltech in Jan., 1994. Roughly 85 people attended part I of the Conference, with the great majority also staying on for part II, the workshop. In part I, the invited speakers and their titles were:

Albert Lazzarini "LIGO and the Users Community"

Mark Bocko "Overview of TIGA and other Spherical, Resonant Bar Detectors"

Vincent Loriette "VIRGO Status Report"

Adam Burrows "Supernovae"

Ewald Mueller "The Gravitational Wave Signature of Rotational Core Collapse"

Dong Lai "Hydrodynamical Processes in Newborn,

Spinning NS's and in Merging NS binaries, and their Gravitational Wave Signatures"

Bruce Allen "Gravitational Waves from the Early Universe"

Peter Bender "LISA Overview and Target Sources for LISA"

Clifford Will "Coalescing Compact Binaries"

Misao Sasaki "Black Hole Perturbation Approach to Gravitational Radiation from Compact Binary Systems"

Bernard Schutz "Gravitational Waves from Rotating Neutron Stars"

There were also contributed talks by G. Quinlan, F. Ryan, S. Chakrabarti, W. Suen, E. Seidel, and K. New, and D. Nicholson contributed an especially stimulating talk on non-linear filtering and adaptive line enhancement.

The somewhat unusual format chosen for the workshop seemed to work rather well. Ten sets of scientific issues relating to binary coalescence were identified, and then for each set one or two experts in that area were chosen to moderate a (roughly) one-hour discussion. The hour generally began with a short presentation by the expert(s) that outlined the basic problems, which was followed by a few 5-minute talks in which people described their latest (and often unpublished) results in these areas, and ended with a group discussion. The group discussions were often lively. One resulted in a bet between

R. Price and K. Thorne on the question of whether or not, in the final coalescence of two spinning black holes with non-aligned spin axes, most of the gravitational wave energy emitted after the inspiral phase will essentially take the form of a simple, quasi-normal mode ringdown. This question was related to an extended discussion on the proper role of the BH Grand Challenge Project vis-a-vis LIGO.

Pleasantly, it was clear that a lot of progress had been made since the previous workshop, especially in the areas of PN calculations of inspiral templates (by the groups of Will and Wiseman and Blanchet, Damour, and Iyer), and in estimating the computing power required to do a real-time time search of LIGO data for coalescing binaries (< 300 Megaflops, according to B. Owen). Especially interesting was the re-formulation by Will and Wiseman of the Epstein-Wagoner approach to doing PN calculations, in such a way as to remove, at all orders, the infinities that had muddied the Epstein-Wagoner approach.

The meeting ended with a general discussion in which it was agreed that a formal organization of theorists interested in LIGO-related research should be created, in order to represent their concerns to LIGO Management, to be a body to which LIGO Management can turn for theoretical input, and to sponsor more meetings. A self-destructing committee was appointed to write a charter and oversee the first election of a Steering Committee for that organization.

General news from GR14

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•**Elections** During the general assembly the following election results were announced. Jürgen Ehlers, director of the newly founded Max Planck Institute for Gravitational Physics in Potsdam, Germany, is the new President. He succeeds Sir Roger Penrose of Oxford and Penn State Universities. According to the rules of the Society, Professor Penrose will now serve as the Vice-President. Professor Malcolm MacCallum of Queen Mary and Westfield College, London was elected as the Secretary. Professors Ehlers, Penrose and MacCallum constitute the executive committee of the Society. Professor Clifford Will of Washington University at St. Luis was elected as the new U.S. representative on the International Committee of the Society. He will serve a nine year term.

•**GR15** The next tri-annual international conference on General Relativity and Gravitation will take place in Poona, India in December of 1997. It will be hosted by the Inter-University Center for Astronomy and Astrophysics (IUCAA). The conference was moved to December because June and July fall in the monsoon season in India and because December-January period is the best for travel within the country. 1997 was chosen (as opposed to 1998) to avoid conflict with the Texas symposium. Professor E. T. Newman of University of‘ Pittsburgh will serve as the Chair of the Scientific committee. If you have general suggestions for the format of the scientific program –e.g. on distribution of topics, number of workshops, etc– please let him know soon. Planning for the conference will begin already this fall since the committee has half a year less than usual to come up with the program.

•**Xanthopoulos Prize** From now on, the Basilis Xanthopoulos Prize for General Relativity and Cosmology will be presented during the International Conferences on General Relativity and Gravitation. The prize is given for outstanding original work in our field to researchers less than forty years of age. Preference is given to theoretical work. It carries a monetary award of approximately $ 10,000 and a citation. The endowment comes from the Foundation for Research and Technology – Hellas (FORTH) which is based in Heraklion,Crete, where Basilis Xanthopoulos taught for many years before his untimely death. The winners are selected by an international committee of relativists.

This year's Xanthopoulos prize was awarded to Professor Carlo Rovelli of the University of Pittsburgh during the general assembly of the Society. Professor Sotirios Persidis opened the ceremony by recalling how the prize originated. (For details, see Matters of Gravity, number 3). Professor Penrose then presented the prize. The citation read: *Forth Foundation and the Selection Committee is pleased to present the 1995 Xanthopoulos award to Professor Carlo Rovelli of the University of Pittsburgh for his wide ranging contributions to classical and quantum gravity, in particular for his stimulating papers on the issue of physical observables in diffeomorphism invariant theories and his pioneering ideas in the development of the loop representation in quantum general relativity.* The ceremony concluded with an acceptance speech by Professor Rovelli. The full text of this acceptance speech as well as the opening remarks by Professor Persidis will appear in the proceedings of the conference.

Canadian General Relativity Conference

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Black holes seemed to occupy the center of discourse, much as they (conjecturally) occupy centers of certain galaxies, at the *Sixth Canadian General Relativity and Relativistic Astrophysics Conference* which took place May 25-27 at the University of New Brunswick in Fredericton, NB.

Jim Isenberg and Charles Torre discussed mathematical foundations of classical and quantum gravity. Jim reported on the work of he and his group on solutions of the constraints when the mean curvature is not constant. Charles reported on the search (so far unsuccessful) for generalized symmetries in GR.

John Friedman discussed problems that appear when formulating quantum field theory in non-globally hyperbolic geometries-i.e. in spacetimes where time travel is allowed!

Alan Coley and Michael West reported on topics in cosmology. Alan discussed self-similar models; while Michael built a persuasive case for a strong role of black holes in the formation of the galactic structures. This provided the transition to a number of talks on various problems in black hole physics.

Werner Israel and Bob Wald provided surveys of, respectively, the classical and semi-classical physics of black hole interiors, centered around the phenomena of mass inflation; and of the laws of black hole mechanics in arbitrary gravity theories, using his "Noether charge" formalism.

Cliff Burgess and Gabor Kunstatter reported on their respective work in stringy black holes and in 1+1 dimensional dilaton-gravity models. In particular, Cliff discussed the role of superstring duality transformations in black hole physics; while Gabor discussed the interpretation of observables in generic dilaton-gravity theories.

Finally, Eric Poisson and Jorge Pullin reported on the progress of their work on numerical relativity. Eric very kindly put together a plenary talk to replace another speaker who was unable to present. He surveyed the issues involved in the production of gravity waves from colliding binaries. Jorge presented a bravura multi-media display of a numerical study of the linearized theory of colliding black holes.

We heard contributed talks from a number of gravity-oids, many of which are grad students and postdocs from all over North America and beyond. The plenary and contributed talks will be published by the Fields Institute for Research in Mathematical Sciences. We wish to thank them, as well as the Natural Sciences and Engineering Research Council of Canada, the Canadian Institute for Theoretical Astrophysics and the Universities of New Brunswick and Moncton for partial support. We also thank the many lobsters that very graciously allowed themselves to be eaten by us at our conference banquet.