MATTERS OF GRAVITY

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

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Editorial policy:

The newsletter publishes articles in three broad categories,

1. News about the topical group, normally contributed by officers of the group.

2. Research briefs, comments about new developments in research, typically by an impartial observer. These articles are normally by invitation, but suggestions for potential topics and authors are welcome by the correspondents and the editor.

3. Conference reports, organizers are welcome to contact the editor or correspondents, the reports are sometimes written by participants in the conference in consultation with organizers.

Articles are expected to be less than two pages in length in all categories.

Matters of Gravity is not a peer-reviewed journal for the publication of original research. We also do not publish full conference or meeting announcements, although we might consider publishing a brief notice with indication of a web page or other contact information.

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Editorial

This newsletter includes for the first time an editorial policy. This was formulated in consultation with the correspondents and in response to an increased number of unsolicited research papers and conference announcements. I also want to apologize for the delay in publication of this newsletter (it was due the first of the month). Some hackers created a chat room in one of our workstations, and that interfered with the production. As usual I wish to thank the contributors and correspondents for making the newsletter possible. The newsletter ended up being a bit too long for my taste, my apologies to those of you who have insisted over time that I should keep it brief. I will work harder on this in the future.

The next newsletter is due September 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 2-10 are also available in gr-qc). All issues are available in the WWW:
`http://vishnu.nirvana.phys.psu.edu/mog.html`
A hardcopy of the newsletter is distributed free of charge to some members of the APS Topical Group on Gravitation. It is considered a lack of etiquette to ask me to mail you hard copies of the newsletter unless you have exhausted all your resources to get your copy otherwise.

If you have comments/questions/complaints about the newsletter email me. Have fun.

Jorge Pullin

Correspondents

- John Friedman and Kip Thorne: Relativistic Astrophysics,
- Raymond Laflamme: Quantum Cosmology and Related Topics
- Gary Horowitz: Interface with Mathematical High Energy Physics and String Theory
- Richard Isaacson: News from NSF
- Richard Matzner: Numerical Relativity
- Abhay Ashtekar and Ted Newman: Mathematical Relativity
- Bernie Schutz: News From Europe
- Lee Smolin: Quantum Gravity
- Cliff Will: Confrontation of Theory with Experiment
- Peter Bender: Space Experiments
- Riley Newman: Laboratory Experiments
- Warren Johnson: Resonant Mass Gravitational Wave Detectors
- Stan Whitcomb: LIGO Project

Topical group news

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Election News

This year, as well as future years, our election for officers will take place in February. The nominating committee is currently putting together a slate. When they have done so, the slate will be e-mailed to everyone, and there will be an opportunity for everyone to comment and make recommendations. Shortly after that, the election will take place.

Officers

Below, I am including a list of the TGGrav officers last year and this year. Note that the officers change at the time of the April meeting. Abhay Ashtekar will take over as Chair. The newly elected officers will also begin their service at that time.

First Set of Officers (1996-1997)

Chair: Beverly K Berger

Chair Elect: Kip S. Thorne, Vice Chair: Abhay Ashtekar, Secretary Treasurer (1996-1999): Jim Isenberg .

Delegates (1996-1999): Frederick Raab, Leonard Parker, (1996-1998): David Shoemaker, James Bardeen, (1996-1997): Robert Wald, Lee Samuel Finn.

Nominating Committee: David Shoemaker (chair), Jorge Pullin, Peter Bender

Second Set of Officers (1997-1998)

Chair: Kip S.Thorne

Chair Elect: Abhay Ashtekar, Vice Chair: Rainier Weiss, Secretary/Treasurer (1996-1999): Jim Isenberg.

Delegates (1997-2000): Lee Samuel Finn, Mac Keiser, (1996-1999): Frederick Raab, Leonard Parker, (1996-1998): David Shoemaker, James Bardeen.

Nominating Committee: Fred Raab (chair), Jorge Pullin, Eric Poisson, Jennie Traschen

April Meeting

Elsewhere in MOG, the schedule of our sessions in the April meeting is given. Further details can be found on the webpage of our Topical Group. Please come !

Prizes?

There is some discussion of the possibility of setting up a prize (or even two), for work in gravitational physics. The restrictions set by the APS on such prizes are a bit rigid, but many of us think it is a good idea. We welcome suggestions and comments. Please send them to me (jim@newton.uoregon.edu).

Centenary Speaker List

The APS Centenary is coming up in 1999. To help celebrate, the APS is planning to set up a list of top notch speakers who will be called upon to give special colloquia and special public lectures around the country. If you wish to volunteer yourself or anyone else for inclusion on this list, please let me know.

The April Joint APS/AAPT Meeting: GTG Program

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This year, the APS-AAPT will be held in Columbus Ohio from April 18 to 21, 1998. Our Topical Group will have the following activities during this meeting: i) Three Invited Sessions; ii) Two Focus Sessions with invited talks; iii) Three Sessions of Contributed Talks; iv) An Executive Committee Meeting; and, v) Annual Business Meeting (the last half hour of this meeting will be devoted to seeking input for the decennial report, being prepared by Committee of Gravitational Physics).

To facilitate your travel plans, we are enclosing the current program. (However, please note that the APS has not finalized the schedule yet and there may be some minor changes). The titles of the invited talks appeared on the GTG and MacCallum distribution lists and can also be found on the GTG web site: `http://vishnu.nirvana.phys.psu.edu/tig/`

Saturday, April 18th

• 11am - 2.00pm; Classical and Quantum Physics of Strong Gravitational Physics (Focus Session 1); *Marolf, Rovelli, Isenberg, Moncrief.*

• 2:30 - 5:30pm; Extending the Frontiers of Gravitational Physics (Invited Session); *Wolszczan, Friedman, Horowitz, Hartle.*

Sunday, April 19th

• 8.30am - 10.30am; Gravitation Theory 1 (contributed Session)

• 10.45am -12:30pm; Executive Committee Meeting

• 11.00am - 2:00pm; Gravitation Theory 2 (Contributed Session)

• 2.30pm - 5.30pm; Computation, General Relativity and Astrophysics
(GTG/DCOMP Joint Invited Session); *Matzner, Berger, Klein, Stone.*

Monday, April 20th

• 8.30am - 11:00am; Gravitational Radiation: Confronting Theory With Experiment (Focus Session 2); *Will, Price, Wiseman, Bender.*

• 2:30pm - 4:15pm; GTG Business Meeting

Tuesday, April 21st

• 8:30am - 11:00am; Gravitational Experiments (Contributed Session)

• 11:00am - 2:00pm; Precision Measurement Techniques Applied to Fundamental Physics (Joint GTG/DAMOP Invited Session); *Chu, Hall, Libbrecht, DeBra.*

In the last two APS meetings, the GTG sessions have been lively. Through these sessions, we have initiated a healthy interaction with the rest of the physics community. It is to our advantage that the interaction continues to grow. We hope an even greater number of GTG members will come to the next meeting. See you in Columbus!

Formation of the Gravitational-Wave International Committee (GWIC)

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With several major new gravitational-wave detector projects nearing completion in Europe, Japan and the United States, there is a need for an organization where discussion regarding the international aspects of experimental gravitational-wave physics can take place.

Recognizing this need, the directors of the five major interferometer detector projects - ACIGA, GEO, LIGO, TAMA, and VIRGO - met on the two days immediately preceding the Gravitational-Wave Data Analysis Workshop to discuss the formation of such an organization. On Wednesday, 12 November, with these aims in mind, they formed the Gravitational-Wave International Committee, or GWIC.

GWIC's goals are to:

* Promote international cooperation in all phases of construction and exploitation of gravitational-wave detectors;

* Coordinate and support long-range planning for new instrument proposals, or proposals for instrument upgrades;

* Promote the development of gravitational-wave detection as a astronomical tool, exploiting especially the potential for coincident detection of gravitational-waves and other fields (photons, cosmic-rays, neutrinos);

* Organize regular, world-inclusive meetings and workshops for the study of problems related to the development and exploitation of new or enhanced gravitational-wave detectors, and to foster research and development of new technology;

* Represent the gravitational-wave detection community internationally, acting as its advocate;

* Provide a forum for the laboratory directors to regularly meet, discuss, and plan jointly the operations and direction of their laboratories and experimental gravitational-wave physics generally.

GWIC's initial membership includes representatives of all the interferometer detector projects (ACIGA, GEO, LIGO, TAMA, and VIRGO), all the acoustic detector communities (ALLEGRO, AURIGA, EXPLORER, GRAIL, NAUTILIS, and NIOBE), and the space-based detector community (LISA). GWIC has a home-page on the web

http://cithe502.cithep.caltech.edu/~donna/GWIC/GWIC_doc1.html,

where information on current and future activities can be found.

The 1997 Xanthopoulos Award

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Professor Matthew Choptuik of the University of Texas at Austin won this year's Basilis C. Xanthopoulos International Award in General Relativity and Cosmology.

The Award was set up by the Foundation for Research and Technology -Hellas in memory of Professor Xanthopoulos who was gunned down (while giving a seminar) by a madman in 1990. It is given tri-annually to a scientist, below 40 years of age, who has made outstanding (preferably theoretical) contributions to gravitational physics. The monetary value of the Award is approximately $10,000. The previous winners of the Award are Professors Demetrios Christodoulou, Gary Horowitz and Carlo Rovelli.

Over the past two years, the International Society for General Relativity and Gravitation (GRG) and the Foundation for Research and Technology -Hellas reached an agreement and from now on the prize be presented by the President of the GRG Society during its tri-annual conferences. Before each conference, the winner will be chosen by a selection committee consisting of five to seven distinguished scientists, each serving for two to three rounds. An advisory Board will oversee the Award and ensure that the original intent of the Award continues to be served.

Professor Choptuik received the Award during the last GRG conference in Poona, India from the then President of the GRG Society, Professor Jürgen Ehlers. He was honored for his seminal contributions to numerical relativity, in particular for the discovery of critical phenomena associated with gravitational collapse.

We hear that...

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Three members of our Topical Group were named Fellows of the American Physical Society. I enclose email addresses so you can flood them with congratulatory notes.

Abhay Ashtekar, ashtekar@phys.psu.edu nominated through the Topical Group on Gravitation, "For his various contributions to classical and quantum gravitational physics, in particular the new canonical variables and the development of rigorous techniques for the quantization of gravity and other non-Abelian field theories."

Reinaldo Gleiser, gleiser@fis.uncor.edu nominated through the Forum for International Physics "For his role in the development of physics in Córdoba, and for his contributions to the application of exact solutions to Einstein equations and gravitational radiation theory."

Bill Hamilton, hamilton@phgrav.phys.lsu.edu nominated through the Topical Group on Instrumentation and Measurements "For his wpioneering work and continuing leadership in developing gravitational-wave detectors, for back-action evading measurements of mechanical squeezed states, and for the development of techniques for magnetic shielding."

LIGO project update

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Construction is nearing completion at the LIGO Hanford, Washington site, and is in full swing at Livingston, Louisiana. The Hanford site civil construction at the site (buildings, roads, power) is almost complete (door bells are being installed), and the labs and technical spaces are starting to fill. At the Livingston site, the construction of the buildings is largely finished and the forming of the concrete covers for the beam tubes is well underway.

Chicago Bridge and Iron, the company building the LIGO beam tubes (which connect the vertex and ends of the two arms), has completed the fabrication and installation of all 8 km of beam tube at the Hanford site. Those tubes have been tested and are in the process of being formally accepted. The fabrication equipment has been moved to a facility near the Livingston site, and production is well underway. Our contractor for the fabrication of the vacuum chambers and associated equipment which will be in the located in the buildings, Process Systems International, has installed many of the large chambers and associated hardware for the Hanford site; testing is starting. The vacuum chambers for the Livingston site are in construction.

The sites are now home to permanent staff, and the Hanford Observatory has now hosted to several LIGO-related meetings. It is extraordinarily exhilarating to see the dreams of a gravitational wave observatory turned into steel and concrete, and the scale of it all is overwhelming. The next meeting at the Hanford Observatory will be of the LIGO Science Collaboration (or LSC), and is scheduled for March 12-13.

Fabrication of the LIGO Detector components is underway for parts of the seismic isolation system, mirror suspensions, and optical components. A large fraction of the critical test-mass mirrors have been polished and coating will commence shortly. Testing of the first article of one of the isolation system designs will take place early in Spring 98, with production to shortly follow. Electronic designs are being tested in prototype forms, and the first complete stabilized Nd:YAG laser source is being assembled for delivery to the Hanford site this summer.

A test of the phase-sensing system for LIGO is wrapping up in a prototype interferometer at MIT. A record sensitivity of 1.5×10^{-10} rad $\mathrm{Hz}^{-1/2}$ has been demonstrated, using the basic laser, suspension, and isolation technology planned for LIGO. This is the last experiment in MIT's beloved Building 20 site, as the lab will move this summer to a new location on the Campus; this enables a reworked test interferometer which will help test second-generation suspension and isolation concepts developed by the LSC.

Our schedule calls for shakedown of the interferometers starting in mid-'99, and operation in 2001. Additional information about LIGO, including our newsletter and information about the LSC, can be accessed through our WWW home page at http://www.ligo.caltech.edu.

The Search for Frame-Dragging by Neutron Stars and Black Holes

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The dragging of inertial frames has been in the news lately with recent reports that the Rossi X-ray Timing Explorer (RXTE) satellite has observed the gravitomagnetic precession of the inner edge of accretion disks around neutron stars and black holes. If verified, this would be the first observation of a strong field general relativistic effect. However, the result is far from conclusive with the present data. In this report, I'll give a short review of the observations that have been made and describe some efforts to test the hypothesis that frame-dragging has been seen. For a review of frame-dragging and efforts to measure the effect due to the Earth's motion, see Cliff Will's article in MOG [1].

The truly exciting aspect of NASA's RXTE satellite is its ability to resolve time variations in the x-ray spectrum occurring on time scales of order $0.1ms$. Consider motion occurring at $r = 6M$ outside of a $M = 1.4M_{\odot}$ neutron star: test particles orbit with a frequency of $\sim 1kHz$ at this radius, corresponding to a time scale well within Rossi's resolution. Within the last two years, Rossi has discovered quasi-periodic oscillations (QPOs) occurring at repetition frequencies of kHz order, suggesting that they are seeing phenomena near neutron stars or black holes. A nice review of the kHz QPO phenomenology is given by van der Klis [2]. RXTE has seen kHz QPOs from 14 sources which are neutron stars in binaries. Their partners are difficult or impossible to observe, so the masses of these neutron stars aren't known. Typically, twin peaks in the Fourier analyzed x-ray spectrum are seen in these sources. (Take a look at figure 4 of reference [2] for an example.) The peaks' frequencies (approximately $1kHz$) drift with time, but their frequency separation stays constant. A model, the sonic-point beat frequency model [3] explains the twin peak phenomenon by identifying the higher frequency peak with Keplerian motion of the accretion disk's inner edge. The peak separation is identified with the star's spin frequency. This leads to star rotation periods near $3ms$. Some of these stars are occasional x-ray bursters and an analysis of the burst spectrum leads to a spin frequency which either agrees with the peak separation or with twice the peak separation providing an independent check of the model.

Suppose that the inner section of the accretion disk is tilted out of the star's equatorial plane. If this is the case, then the frame-dragging effect will cause the plane of the orbit to precess around the star, periodically obscuring the star. We would then expect to see a peak in the power spectrum occurring at a frequency corresponding to the precession frequency. It was pointed out by Luigi Stella and Mario Vietri [4] that a peak with around the correct frequency appears in the spectrum. Moreover, they provide a consistency check. As the inner edge of accretion disk changes location (due to radiation drag), the Keplerian frequency increases approximately as $2\pi\nu_K = \sqrt{M/r^3}$ (remember that the star is rotating, so this is not exact). The Lense-Thirring precession varies as $2\pi\nu_{LT} = 2J/r^3$, where J is the star's angular momentum. Therefore, the peak which is to be identified with Lense-Thirring precession should vary as the square of the Keplerian frequency peak. The data does show this rough trend. However, it is not this simple, since the star is not spherical, and Newtonian gravity predicts a precession due to the star's quadrupole moment which subtracts from the frame-dragging precession frequency. Depending on the equation of state assumed for the neutron star, the quadrupole precession can range from a couple percent to half of the frame-dragging precession. Using a semi-Newtonian approximation, Stella and Vietri found that if the equation of state is very stiff, the data seemed to fit well. However, a more precise calculation, using general relativity [5], shows that the quadrupole (and higher multipole moments) become very important and greatly reduce the total precession. If the equation of state is not overly stiff then the frame-dragging effect is dominant when the star is close to its maximum allowable mass. For typical equations of state, the total predicted precession frequency (including all effects) is still only half of the peak's observed frequency. There is some possibility that the factor of two could be explained by a geometric effect. The system's geometry is essentially the same when the plane of the orbit has made a half period rotation, leading to a factor of two. However, this is still a bit speculative. In any case, astronomers are analyzing the RXTE data to find the observed variation of these peaks for a number of sources. If it should turn out that the dependence of the "precession" peak with the Keplerian peak is correct, up to the factor of two, there may be some truth in the model. It should be mentioned that a similar effect has been suggested in the sources which correspond to alleged black holes [6], but in these cases there are no twin peaks, so there is really no way to test the hypothesis.

There is a bit of a Catch 22 [7] in the situation. Bardeen and Petterson showed [8] that the combination of frame-dragging and viscosity produces a torque which tends to align the disk with the star's equatorial plane, so that Lense-Thirring precession won't occur. It is this effect which is thought to keep the jets seen in active galactic nuclei aligned. Although warped, precessing disks can occur, typically the inner part of the disk, up to $100M$ must be co-planar. If it is possible to find a physical mechanism which will cause a perturbation to lift the inner edge of the disk, there will now be another force acting on the inner edge of the disk. The precession frequencies computed assume geodesic motion, i.e., that all other forces besides gravity are negligible. If precession occurs, the frequencies may change. Some work in this direction indicates that this is the case [9,10], in fact reducing the possible frequencies by a large factor and/or damping them strongly [10]. This is not to say that the peaks observed can't be due to frame-dragging, but it is difficult to find a physical mechanism which may cause a tilt without changing the frequencies.

In the meantime, we will have to wait for further analysis to learn whether there is a statistically significant correlation between the proposed precession peak and the Kepler peak. If so, it may be possible that frame-dragging has been observed near neutron stars.

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Gamma-ray bursts: recent developments

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What are GRBs? Gamma-ray bursts (GRBs) are brief gamma-ray flashes detected with space-based detectors in the range 0.1-100 MeV, with typical photon fluxes of $0.01 - 100$ photons/cm^2/s and durations 0.1-1000 seconds. Their origin is clearly outside the solar system, and more than 2000 events have been recorded so far. Before there was any firm evidence on the isotropy of classical gamma-ray bursts, the most plausible interpretations involved magnetospheric events on neutron stars (NS) within our Galaxy. However, the remarkable isotropy of these events discovered within the last two years by the BATSE experiment on the NASA Compton Gamma Ray Observatory (together with the 'flatter than Newtonian' counts) clearly shifts the odds substantially in favor of a cosmological interpretation. Irrespective of the distance (i.e., even in the galactic halo, but more so in cosmological models), the energy density in a GRB event is so large that an optically thick pair/photon fireball is expected to form, which will expand carrying with itself some fraction of baryons (e.g. Cavallo and Rees, 1978, Paczynski, 1986, Shemi and Piran, 1990). The main challenge in these models is not so much the ultimate energy source (which may involve stellar collapse or binary compact star merger) but rather how to turn the energy of a fraction of a stellar rest mass into predominantly gamma rays with the right non-thermal broken power law spectrum with the right temporal behavior. The dissipative relativistic fireball model proposed by Rees and Meszaros (1992, 1993, 1994; see also Narayan, Paczynski and Piran, 1992; Meszaros, Laguna and Rees, 1993, Meszaros, Rees and Papathanassiou 1994, Katz, 1994; Sari, Narayan and Piran, 1996) is largely successful in solving these problems, and is discussed in several reviews, e.g. Meszaros (1995, 1997).

The Significance of GRB After-glows and Counterparts The recent discovery (1997) of X-ray, optical and radio after-glows of gamma-ray bursts (GRB) amounts to a major qualitative leap in the type of independent observational hand-holds on these objects. Together with existing gamma-ray signatures, these provide significantly more severe constraints on possible models, and may indeed represent the light at the end of the tunnel for understanding this long-standing puzzle of astrophysics. The report of long wavelength observations of GRB 970228 over time scales of days to weeks at X-ray (X), and months at optical (O) wavelengths (Costa etal, 1997) was the most dramatic recent development in the field. In this and subsequent IAU circulars, it was pointed out that the overall behavior of the long term radiation agreed with theoretical expectations from the simplest relativistic fireball afterglow models published in advance of the observations (Meszaros & Rees, 1997a). A number of theoretical papers were stimulated by this and subsequent observations (e.g. Tavani, 1997; Waxman, 1997a; Reichart, 1997; Wijers, etal, 1997, among others), and interest has continued to grow as new observations provided apparently controversial evidence for the distance scale, possible variability and the candidate host (Sahu etal, 1997). New evidence was added when the optical counterpart to the second discovered afterglow (GRB 970508) yielded a redshift lower limit placing it at a clearly cosmological distance (Metzger etal, 1997), and this was strengthened by the detection of a radio counterpart (Frail etal, 1997; Taylor etal, 1997) as well as evidence for the constancy of the associated diffuse source and continued power law decay of the point source (Fruchter, etal, 1997). A third GRB afterglow (GRB971214) has also been detected in X-rays and optical, and appears to follow the canonical power law time decay (Heise, et al, 1997, and follwing IAU circulars). This new evidence reinforces the conclusions from previous work on the isotropy of the burst distribution which suggested a cosmological origin (e.g Fishman & Meegan, 1995). Observational material on this is provided chiefly by a superb data base (currently of over 1800 bursts in the 4B catalog) which continues being accumulated by the BATSE instrument, complemented by data from the OSSE and Comptel instruments on CGRO, as well as Ulysses, KONUS and other experiments. At gamma-ray energies, much new information has been collected and analyzed, relevant to the spatial distribution, the time histories, possible repeatability, spectra, and various types of classifications and correlations have been investigated. At the same time, investigations of the physics of fireball models of GRB have continued to probe the gamma-ray behavior of these objects, as well as the after-glows. Much of the recent theoretical work has concentrated on modeling the time structure expected from internal and external shock models, multi-wavelength spectra, the time evolution and the spectral-temporal correlations (e.g. Papathanasiou & Meszaros, 1996; Kobayashi, Sari and Piran 1997; Waxman, 1997b; Katz & Piran, 1997; Panaitescu & Meszaros 1997a, 1997b; Sari, Piran & Narayan, 1997, etc.).

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Moving Black Holes, Long-Lived Black Holes and Boundary Conditions: Status of the Binary Black Hole Grand Challenge

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The Binary Black Hole Grand Challenge has completed more than four years of existence. A large fraction of that time has been devoted to developing a coherent infrastructure for assault on the two-black-hole problem. The Alliance approach involves a central Cauchy strong field region, a boundary (matching) module, and an outer module (perturbative, or strong-field characteristic) which carries the radiation to infinity. The interior module is an ADM (Arnowitt-Deser-Misner [1]) "$\dot{g}, \dot{K}$" code, with fundamental variables the 3-metric g_{ij} and extrinsic curvature K_{ij}; the extrinsic curvature is the momentum of the 3-metric. An extensive investigation has been made of the Choquet-Bruhat/York [2] version of a "hyperbolic" Cauchy formulation, but the more traditional ADM form has the advantage of more mature development. Hence in 1996 the Alliance focused on the ADM version.

Important infrastructure features include DAGH, which allows a single-processor unigrid code to be distributed on a parallel machine, and supports adaptive mesh refinement. This system is now in use for the very largest of our black-hole runs. Another very important tool is RNPL, which takes a high-level description of the physics and the differencing scheme and generates C or FORTRAN code. Another tool, on the collaborative level, is SCIVIZ, which allows researchers to collaborate to manipulate and visualize computational results. A new file format, SDF, has been developed, which overcomes efficiency and size limitations of some other formats, for large parallel applications.

All of the Alliance codes are, and continue to be, demonstrated second order convergent. In all of our models, black holes are handled by excising the domain inside the apparent horizon. We have not yet begun (we are about to begin) carrying out multiple black hole evolutions. For single black holes (Schwarzschild or Kerr, and their strongly perturbed forms), where we expect a stationary final state, we use the analytic solution as an outer boundary condition.

Black Holes The characteristic module evolves the strong-field Einstein equations in a characteristic formation which has a very rigid coordinate gauge, and which therefore has a simpler equation set. Unfortunately it cannot be used alone for the binary black hole problem, since gravitational focusing causes caustics in the rays generating the null surfaces of the coordinatization. Thus the basic approach of the Alliance code is centered on a Cauchy strong field module. However, the characteristic code can handle *single* black hole spacetimes.

The characteristic module can exist in two forms based on either ingoing or outgoing characteristic surfaces. In its form based on ingoing null hypersurfaces it shows unlimited long-term stability for evolving single, isolated (distorted) black holes. In these cases data are set on an ingoing initial null hypersurface. The inner edge of the domain is set at a marginally trapped surface; no boundary condition is needed there since it is inside the horizon. The outer boundary is set analytically to the black hole solution. These problems evolve to the stationary black hole form. They have been evolved to times of $60,000M$, at which time differences are on order of machine precision, the operational definition of running forever. In some cases the coordinates are deliberately "wobbled" producing a time dependence in the description at late times, but producing a stationary geometry nonetheless [3]. In the 1970s and 1980s, the difficulty of stably simulating even a single black hole in strictly spherical symmetry (one spatial dimension) led to the formulation of "the Holy Grail of numerical relativity" - requirements for a hypothetical "code that simultaneously:

- Avoids singularities
- Handles black holes
- Maintains high accuracy
- Runs forever." [4]

It is clear that the characteristic code has achieved the grail in the 3-dimensional single-black-hole case, a dramatic improvement over the state of the art only a few years ago. However, goals recede, and from the viewpoint of the Binary Black Hole Alliance, this is a step along the way, important because it validates the stability and accuracy of the characteristic code.

The interior code, the Cauchy code, has not yet shown the very long-term stability of the characteristic code. With fixed Dirichlet boundaries, the code runs for a maximum [5] of $100M$ for isolated Schwarzschild data written in Kerr-Schild [6] form. With blended outer boundary conditions, the code has been evolved beyond $500M$. (The blended outer conditions are applied gradually by mixing the computed results with the analytic ones over a shell of a few computational zones' thickness; see also the discussion of this technique for perturbative matching below.) In this case there is still some influence from the outer boundary and there are additional modes (small oscillations in the supposedly static solution) which are not fully understood. What is apparent is that inaccurate outer boundary setting disturbs the code substantially (which is why the matching algorithm is so important), but the inner edge of the domain, handled with causal differencing (hence "no boundary condition") is well behaved, and this free evolution shows (at worst) controllable constraint drifting.

The Kerr-Schild data are represented by two fields on a background flat space: a scalar function ($= M/r$ for Schwarzschild), and a null vector (ingoing, unit for Schwarzschild). Because of this very simple structure, *boosting* these data is trivial, and we have used such boosted initial data to start evolutions of black holes moving across the computational domain. So far as we know, only the Alliance has achieved this. The characteristic code has demonstrated a linearly moving black hole [7]. However (because of the caustic problem), the characteristic module cannot evolve a black hole moving farther than one diameter. The Cauchy module can do so, and has been demonstrated to do so for $60M$ in time at $0.1c$, hence a translation through $6M$ in distance [5]. The boundary conditions for this moving case are analytical Dirichlet with no blending. (Since we know the analytic form for the boosted black hole as a function of time, we compute new outer boundaries as a function of time for the evolution.)

The black hole interior is excised in all our evolutions. At the resolutions we use (typically 60 to 100 grid zones in each direction), there is room for only a few ($\sim 10 - 15$) points interior to the black hole. We find the best behavior when the hole is excised with a buffer zone ~ 5 zones wide for both the moving and the stationary evolutions. Thus the excision of the interior occurs ~ 5 zones inside the apparent horizon location. This is probably relevant to the fact that we do not lock the horizon coordinate location. Rather, the excision is based on the analytically expected coordinate location of the horizon; and all our code crashes seem to be related to the excised, un-evolved, region eventually extending beyond the horizon. (This can happen because coordinate drift, which we do not attempt to control, changes the coordinate location of the horizon, while our excision domain has a *fixed* coordinate location.) To our knowledge only Daues [8] has demonstrated active horizon locking in 3-dimensional black holes. Daues achieved $\sim 140M$ non-moving Schwarzschild black hole evolutions. Implementing this tracking in the Alliance code is a high priority and holds out the hope of even longer evolutions.

Exterior Modules and Matching

The *perturbative* exterior module is written in explicitly Cauchy form. The terms neglected in this perturbative module are wave-wave interactions, while the background is explicitly modeled (Kerr or Schwarzschild). The matching to the Cauchy interior *works* in this case; this matching has been demonstrated for linear waves with very long evolution [9]; some more recent results are at the Alliance web site (see below). The matching is accomplished in a way that correctly treats the outgoing nature of the solution; in fact, the Sommerfeld condition is modified on its right-hand side from 0, to a contribution arising from the perturbative outer evolution, so there is a strong similarity between the perturbative and the characteristic boundary application.

In practice, the perturbative outer boundary match is handled in a "thick" shell. At some radius r_E, the inner solution is sampled. These data are used for a perturbative evolution to a very large radius $r_{outer} \simeq \infty$. At a finite radius $r_1 > r_E$ begins the boundary region $r_2 > r > r_1$. The computed inner solution is merged in this region with the value determined from the exterior module. This provides a merged boundary condition on the interior solution: that the Sommerfeld condition properly reflect the terms describing backscatter, derived from the perturbative evolution. *For the weak wave case this is a successful complete expression of the inner-module/boundary/outer-module paradigm of the Alliance philosophy.*

To match the *characteristic* module to the Cauchy inner module, the outgoing characteristic form must be used. (This *match* has not yet been achieved.) For outgoing radiation near the coordinate outgoing null surfaces, the wave variables have slow variation, and the system can be compactified so that infinity is a finite distance away while still maintaining finite derivatives. Hence, a characteristic code can compute the whole exterior spacetime in a finite domain. For nonlinear scalar radiation [10], for spherical general relativity [11], for cylindrically symmetric relativity [12], and as we saw, for the weak field problem in full 3-d general relativity, the match has been carried out. But so far a stable match between the full 3-d strong-field Cauchy and characteristic modules has not been achieved. We are now attempting such a match through blending, as in the successful perturbative case, and there is hope that such an approach will work to match the Cauchy and the characteristic codes.

Immediate future work involves setting data and beginning 2-hole evolutions. Because of the apparently better behavior of Kerr-Schild formulated single holes, the initial data is being recomputed for this case. (These slices differ macroscopically from the "standard" conformally flat data that were solved completely prior to the beginning of the Alliance [13].) This work will proceed while further runs for single holes continue. The Cauchy module requires standardization, validation against known behavior of distorted black holes, and an explicit demonstration of its ability to evolve rotating (Kerr) black holes.

Recent developments, including the points discussed here, are frequently posted to the Los Alamos preprint archive, and can also be found at the Alliance Web page:

http://www.npac.syr.edu/projects/bh/
Select "New developments."

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Quantum gravity at GR15

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The appropriate starting point for this review is Carlo Rovelli's plenary talk 'quantum spacetime.' Rovelli took upon himself the unenviable task of commenting on the vast variety of approaches to and aspects of the subject of quantum gravity. In the first part of his talk, we found Carlo wearing an unfamiliar hat – that of an experimental sociologist – as he presented an inventory of the preprints that appeared on hep-th and gr-qc during the first 10 months of 1997. With a total flux over 400 papers per month, roughly 1 in 4 addressed quantum gravity or related issues. Breaking these up by topic, he found 69 string papers per month, 26 loop gravity papers per month, 8 on QFT in curved spacetime, 7 on lattice Quantum Gravity, and perhaps 29 per month for all other aspects combined (with a given such approach averaging no more than 5 papers per month). In GR15, there were four plenary talks (by Gibbons, Rovelli, Kozameh, and Zeilinger) with quantum themes, as well as a large number of parallel sessions: one afternoon of superstrings and supersymmetry, one afternoon of quantum cosmology and conceptual issues, one afternoon of quantum fields in curved spacetime and semiclassical issues, and two afternoons of 'quantum general relativity.'

Since Gary Gibbons gave a talk about M-theory (the theory formerly known as 'strings'), Rovelli spent most of his time discussing the loop approach, though he did comment on QFT in curved spacetime, dynamical triangulations, Regge Calculus, and other ideas. I will follow the results of his xxx experiment and address first string issues, then loop issues, and finally other issues in quantum gravity. Unfortunately, it will not be possible to discuss here more than a few talks from the 5 afternoons of parallel sessions on quantum issues.

The plenary lecture by Gary Gibbons gave a brief overview of what has become known as M-theory; the lecture was quite well received. Briefly, M-theory is a project arising out of string theory which is supposed to be a more fundamental and, when complete, nonperturbative formulation of quantum gravity. Gibbons made an analogy between M-theory and a Northern European Medieval cathedral whose many parts, created by individual artisans, are works of art on their own, but whose real beauty and structure are apparent only when the cathedral is completed – perhaps long after the deaths of the earliest contributors. M-theory is to be viewed as such a cathedral under construction. Some pieces are in place, and there are many architects who share a common vision for what the cathedral will become. However, the building process is far from complete, and Gibbons reminds us that many cathedrals were completely redesigned as they were being built so that, in the end, they bore little resemblance to the original conception. Indeed, some designs were simply impossible to build.

Nevertheless, Gibbons emphasized the solidity of the of the foundation of M-theory (which rests on all of the successes of string theory, understandings of string duality, and the impressive calculations of black hole entropy by Strominger, Vafa, etc.) as well as the sweeping vision of the architects. He also described the "landscape and architecture of the partially completed cathedral and of the surrounding countryside." His talk focused on the relationship of M-theory with supergravity, and with various BPS (aka supersymmetric) objects. [The most commonly discussed supersymmetric objects are extremal black holes.] Readers interested in an introduction to this subject will surely enjoy the version of his talk to be published in the conference proceedings.

The other major contribution to GR15 in the string/M-theory vein was a review talk "Strings and Semiclassical properties of black holes" given by Gautam Mandal in the parallel session on superstring theory and supergravity. His review was necessarily short and condensed, but fairly thorough. The 1996 work on reproducing black hole thermodynamics from string calculations was also nicely summarized in a talk given by A. Dasgupta, who reported some new results on fermionic Hawking radiation in effective string models of black holes. In addition, some observations about superstring inspired cosmological models and the graceful exit problem for inflation were made by S. Bose.

Let us now return to Rovelli's discussion of loop quantum gravity. He stressed the fact that this approach is essentially non-perturbative so that it could, in principle, provide a complete definition of the theory. However, this also means that it is difficult to compute the kind of perturbative scattering results that are common in, for example, string theory. As major results, Rovelli described the predicted quantization of areas and volumes, the recent calculations of black-hole entropy by Ashtekar et. al., and the fact that a set of constraints has been proposed which, if correct, could provide a complete non-perturbative definition of Quantum Gravity.

On the other hand, Rovelli also mentioned two difficulties: one was the lack of a general algorithm for computing physical results (such as scattering phenomena) and the other was a concern over whether the proposed constraints do indeed describe gravity or whether they need to be modified or replaced in some way. This concern was largely based on the results of Lewandowski and Marolf showing that the algebra of the proposed constraints does not seem to match the classical hypersurface deformation algebra (instead, it gives $[H(N), H(M)] = 0$ for the commutator of two Hamiltonian constraints) and the corresponding work by Lewandowski, Marolf, Gambini, and Pullin. This issue was a matter of some discussion both in the parallel session on quantum general relativity and in informal discussion. An overview of the results was presented by J. Lewandowski, and comments were made in the talks by T. Thiemann and J. Pullin. As the subject is still under consideration (and since I am a participant in this discussion), I will summarize the comments only very briefly without drawing particular conclusions: Thiemann and Pullin each suggested a possible way to modify the loop approach in order to improve the situation, while other comments were made that, since the constraints themselves are not directly physical observables, it is unclear exactly what physical problems the above algebra would cause. Discussion continues, and should remain interesting.

A few words are now in order regarding other quantum aspects of the conference. Kozameh's plenary talk on the null surface formulation of GR was mostly classical, but described some recent results concerning linearized quantum theory in this framework, in which the coordinates of certain events become quantum operators. He also expressed a hope that this formulation will help to untangle deeper mysteries of quantum gravity.

Without going into details, let me say that a high point of the conference was the plenary talk by A. Zeilinger on precision experiments using quantum correlations. These ranged from classic EPR tests to 'quantum teleportation' – all effects predicted by standard quantum mechanics and verified in his laboratory. A hope was expressed that, in the near future, experimental techniques would be refined to the extent that they could directly test Roger Penrose's ideas about the effects of gravity on quantum decoherence. I would strongly recommend a visit to Zeilinger's web site at

http://info.uibk.ac.at/c/c7/c704/qo/.

Finally, a number of extremely interesting (non-string, non-loop) papers were presented in the parallel sessions. Unfortunately, there is only space to mention a few of them here. The talks by L. Ford, E. Flanagan, and S. Carlip seemed to be the most popular. Very Briefly, Ford reviewed the latest results on providing inequalities that restrict the negative energy that states of a quantum field may have in static spacetimes. Flanagan discussed the (quantum) stability of Cauchy horizons in 1+1 dimensions and described a necessary condition for the horizon to be classically stable but quantum mechanically unstable. Carlip discussed his recent paper in which he argues that, if a sum over topologies is to be performed, the partition function for $3+1$ gravity with negative cosmological constant cannot converge, and that it is formally analogous to a system with negative specific heat. He also noted that the formal role of the cosmological constant is similar to the temperature of such a system, and this observation led him to speculate that it might provide a mechanism for setting $\Lambda = 0$. The idea is that, somehow, due to the negative 'specific heat,' processes that would normally increase $|\Lambda|$ would instead drive it to zero.

An Experimentalist's Idiosyncratic Report on GR15

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It wasn't long ago that the knock on General Relativity was that it was a theorist's playground, blissfully disconnected from confrontation with experiment. If there was anyone who was still unaware that things had changed, all she would have had to do was attend the 15th International Conference on General Relativity and Gravitation, held at IUCAA, Pune, India, from December 16-21, 1997.

In this reporter's opinion, GR15's suite of plenary talks was the strongest and most varied of any international meeting in years. Credit must be given to Ted Newman and the Scientific Organizing Committee he chaired for fine choices of topics and speakers. No fewer than ten invited talks were devoted either fully or in large measure to observable phenomena. Five of those were devoted in one way or another to gravitational waves. Talks by Flanagan on the range of possible sources, by Seidel and by Pullin on ways of calculating the gravitational waveforms from the particularly interesting case of black hole coalescences, and by Cerdonio and by Robertson on methods of detection, together gave an unusually complete review of the bustling state of this branch of activity.

But it was the other observationally flavored talks that gave this meeting its most distinctive character. There were two talks on aspects of gravitational lensing: the graceful review of the astrophysical situation with which S.M. Chitre opened the conference, and the whirlwind tour of the optics of caustics and related subjects provided by Michael Berry. The latter included enough novel physics to send everyone away with something new to think about; interferometer jocks will be investigating the phase singularities near the waists of their Gaussian beams with new interest.

There were two other unabashedly astrophysical plenary talks. Malcolm Longair presented a personal overview of the state of our knowledge of astrophysical cosmology, rooted in the remarkable growth of observational knowledge that has occurred in the past few years. All signs point to further dramatic improvement in the situation, including further exploitation of HST's capabilities and the expected detailed maps of the Cosmic Background Radiation from the upcoming satellites MAP and Planck. Ramesh Narayan performed the unlikely feat of interesting a roomful of relativists in the subtleties of energy transport in accretion disks, in the cause of achieving something this reporter would have thought impossible a year ago: demonstrating by conventional (X-ray) astronomy that objects with event horizons inhabit known binary star systems.

Special notice must be given to the talk farthest removed from the ordinary topics of a general relativity meeting, that of Anton Zeilinger on experimental demonstrations of the spooky non-locality of quantum mechanics. This is another subject that has made dramatic progress in the past few years, most recently with the demonstration by Zeilinger's group of teleportation of a quantum state. The breakneck pace of progress was made evident by Zeilinger's remark that the violations of locality of the sort treated by Bell's Theorem were so strong in their experiments (they were detected at the 100-sigma level) that this phenomenon was used as a calibration.

There was, as well, a rich set of contributed papers on experimental topics. These were strongly dominated by talks on gravitational wave detection, which in turn fell into two classes: progress reports on the many interferometers now under construction (LIGO, VIRGO, GEO600) or in the planning stage (LISA, OMEGA), and reports brought back from the trenches by the grizzled veterans already making gravitational wave observations. Among the latter, W. Hamilton and L. Iess emphasized to the raw recruits the tricky issues posed by non-Gaussian noise statistics in, respectively, resonant-mass detectors and spacecraft tracking experiments.

General relativity has undoubtedly been enriched by its new-found observational character. There is every reason to hope that the next GR meeting, slated for summer 2001 in Durban, South Africa, will be an occasion to share further experimental progress in our subject.

GR Classical

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This is by necessity a selective summary, based primarily on the plenary talks, not because they encompass the most important results reported at the meeting, but because of the author's limitations; among other difficulties, overlapping parallel sessions mean that it is impossible for one person to attend most of the relevant workshops.

1a. Relativistic Astrophysics: Black holes

Ramesh Narayan reviewed the current status of black-hole observation, as well as advances in understanding accretion disks. After recalling the limit set by causality on the mass of spherical and rotating neutron stars, he turned to a list of best candidates for stellar-size black holes. At present, the single best current candidate appears to be V404 Cyg (Casares and Charles 1994), a low mass X-ray binary. Among X-ray binaries, V404 Cyg has the largest mass function known, $f(m) = 6.08 \pm 0.06 M_\odot$, implying for the compact object a mass $12.3 \pm 0.3 M_\odot$. The 9 best candidates include 7 LMXB's; and the narrow error bars for several of these mean with near certainty that there is a class of compact objects with mass well above the upper mass limit for neutron stars (or any stars above nuclear density). Two high-mass X-ray binaries, Cyg X-1 and LMC X-3, made the list, but are no longer the candidates to quote. ('High' and 'low' refer to the mass of the X-ray source's companion).

Vastly increased resolution in observations of the centers of galaxies has, within the past five years, given us similarly compelling evidence for super-massive black holes in the centers of 15-20 galaxies. The evidence suggests that nearly every large galaxy hosts a central black hole. Measured masses range from 2-3 million $M_\odot$ in the Milky Way to 3 billion in M87. Observations of NGC 4258 (Miyoshi et al 1995) are an example of the extraordinary current resolution: $3.6 \times 10^6 M_\odot$ lies within a diameter of 0.03 pc.

Narayan claimed a significant advance in our understanding of accretion disks, with "advection-dominated accretion flow" models giving striking agreement with observation for accretion below the Eddington limit on $\dot{M}$. When the density of accreting matter is low, infalling ions do not have enough collisions to transfer their energy to the lighter electrons that could radiate it away. Instead, a substantial fraction of the infall energy is swallowed by the black hole. Narayan emphasizes that one indirectly sees the existence of a horizon in accreting black-hole systems: With a central star, simple energy bookkeeping implies a larger energy of infall than is observed in radiation. Steady flow is consistent with observation only if there is a horizon into which the energy can flow.

1b. Relativistic astrophysics: Numerical Relativity

Ed Seidel presented an optimistic report on the Grand-Challenge project to compute numerically the inspiral and coalescence of two black holes. Significant progress was reported in developing 3+1 codes that use a grid that does not include black-hole interiors. One incorporates the lack of influence of a black-hole interior on the exterior spacetime by causal differencing at the apparent horizon, and 3+1 evolutions of stationary and boosted black holes have run past $t = 1000M$. A first 3+1 evolution based on a foliation by null surfaces and using the *characteristic* initial value problem has evolved Kerr and Schwarzschild spacetimes to $t = 20,000M$, but the code does not yet allow caustics. Seidel did not have time to talk about corresponding work on the analogous 3+1 evolution of neutron-star binaries, but substantial progress by Oohara and Nakamura in the numerical relativity workshop. (Others reporting advances on the neutron-star evolution problem were Bonazzola et al and, for the grand-challenge group, Miller.) A public-domain CACTUS code from the Grand Challenge group will soon be available on a Web Server.

Jorge Pullin spoke about the recent development (with Price) of a second-order perturbation theory of perturbations about a Schwarzschild background (Tomita had previously developed a second-order formalism in a Newman- Penrose framework). Because a single horizon can surround two black holes well before the individual apparent horizons meet, perturbation theory can describe the coalescence of black holes with unexpectedly high accuracy and for an unexpectedly large part of the coalescence. In fact, the second-order formalism accurately gave the *phase* of waves emitted in the outgoing modes that dominate black-hole ringdown.

Matt Choptuik won this year's Xanthopoulos Prize for his work on Choptuik scaling and critical phenomena in black-hole formation, and his talk summarized work in this area by a number of people. Critical behavior has recently been examined in a broader class of settings. For collapse in an Einstein-Yang Mills framework, one again sees critical behavior (and discrete self-similarity) for families of solutions that interpolate between no black hole and a black hole of nonzero mass. The critical exponent relating black-hole mass near $M = 0$ to a smooth parameter for the family is 0.20, clearly different from the value(s) of 0.36 that were first seen in spherical collapse of massless scalar fields and perfect fluids. Collapse of fields that have stationary solutions with nonzero mass show mass gaps; this was suspected from, e.g., neutron stars, where continuously adding mass pushes the star over the upper mass limit to a black hole that first forms at about that limiting mass. And a mass gap is seen for massless quantum scalar fields in a QFTCST calculation with back-reaction.

2. Cosmology

Malcolm Longair and Vladimir Lukash presented, with opposite conclusions, summaries of recent cosmological observations. Both mentioned recent successes, many associated with the Hubble telescope, in measuring with improved accuracy key cosmological parameters, $\Omega_0 \equiv \rho_0/\rho_{\text{critical}}$, H_0, q_0, Λ, and the age T_0. I'll pick out two things from Longair's wide-ranging talk. First, the small dispersion of Type IA supernovae (associated with the collapse of white dwarfs pushed over their upper mass limit) makes them "a clear market leader" as a standard candle at large redshift. Two 1997 supernovae tighten the evidence for an open universe:

Garnavich et al (1998) at $z = 0.97$ and $z = 0.83$ imply,	Perlmutter et al (1998)
If $\Omega_0 + \Omega_\Lambda = 1, \Omega_0 < 1$ at the 95% confidence level.	If $\Omega_0 + \Omega_\Lambda = 1, \Omega_0 = 0.6 \pm 0.2$.
If $\Omega_\Lambda = 0$, $\Omega_0 = -0.1 \pm 0.5$.	If $\Omega_\Lambda = 0$, $\Omega_0 = 0.2 \pm 0.4$.

Second, the Hipparcos satellite's revision of the local distance scale means that stars are brighter (and hence burn faster) than had been thought. The age of globular clusters is now $T_0 = (11.5 \pm 1.3) \times 10^9$ years, consistent with the H_0 measurements.

S. M. Chitre presented a history of gravitational lensing with emphasis on its increasing role in cosmology. Gravitational lenses now serve as tools for diagnosing the mass distribution of both luminous and dark matter and as giant telescopes that intensify objects at high redshifts.

3. Classical Gravity

Carlos Kozameh spoke about dynamics of null surfaces in GR. This is a program pursued by Kozameh and collaborators over several years, intended to reformulate the field equations as equations governing a family of null surfaces. The formulation uses a function Z describing a sphere's worth of surfaces at each point of spacetime (or at each point of phase space). Recent applications of the formalism involve specifying Z in terms of radiative data at $\mathcal{I}$, leading to an asymptotic approach to quantization that associates operators with spacetime points.

Bangalore gravitational wave meeting

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The Raman institute hosted a very pleasant and informative meeting on December 11-12 1997, covering a number of topics of key importance in gravitational wave astrophysics. The meeting's format consisted of ten plenary sessions providing an overview of theoretical and observational aspects of gravitational radiation.

The construction of LIGO, GEO and other interferometric gravitational wave detectors has opened up the possibility of making astronomical observations using gravitational radiation. Harold Lueck presented a historical overview of the development of the experimental techniques and technological improvements which have made these detectors possible. The signal-to-noise ratio for these detectors will be quite low so sophisticated data analysis methods will be needed. Addressing this problem, S. Dhurandhar discussed how the matched filter method will be used to detect gravitational wave signals. He reviewed recent work in detecting signals artificially injected into sample background noise. B. Sathyaprakash provided us with an overview of the types of sources which LIGO may be able to detect, including the inspiral of compact binaries, pulsars and supernovae, to name a few. One of the possible sources are rapidly rotating neutron stars which become unstable due to the CFS mechanism. Nils Anderson provided an introduction to this instability and described his recent work which suggests that axial perturbations may play as important a role as the polar modes. In the discussion of possible sources of gravitational radiation, it is usually assumed that general relativity is, in fact, the correct theory of gravity. Gilles Esposito-Farese reviewed the extent to which general relativity has been tested. He stressed that although GR has been successfully tested in the weak field limit, there are scalar-tensor theories which agree with GR in the weak field but provide different strong field predictions, such as boson stars.

The bulk of our knowledge of gravitational wave sources (e.g. compact binary systems) comes from perturbation theory. The main problem of interest is to find the relation between the outgoing radiation and the matter and motion of the source. The remaining speakers discussed different aspects of this problem with reference to the inspiral of neutron star and black hole binaries. Blanchet discussed a method based on matching of expansions in near, exterior and wave zones which he calls the Multipolar-post-Minkowskian approach. This approach allows one to calculate various non-linear non-local effects such as tail radiation, tails of tails and memory terms. Clifford Will presented a different approach which he has dubbed DIRE (Direct Integration of the Relaxed Einstein Equations). DIRE addresses the problem of divergent integrals in the near and far zones and has been used to compute post-Newtonian corrections to 3.5 order, agreeing with results discussed by Blanchet. Given that we know the radiation emitted by a source, can we predict the backreaction onto the system caused by this emission? This problem, known as radiation reaction, was discussed by Bala Iyer. He presented an approach which assumes the validity of the principle of energy balance: the work done by the reactive force is equal to the negative of the energy flux. It is important to verify that perturbation theory provides the correct results for all problems which can be solved exactly. Misao Sasaki discussed black hole binary inspiral in the limit that one of the black holes is much less massive than the other. This approach has been used to show the validity of the post-Newtonian expansion in this limit. The holy grail of numerical relativity is the exact computation of binary black hole mergers, and Ed Seidel reported on recent progress in this direction. In particular, he focused on highly distorted isolated black holes, and showed that the full non-linear evolution agrees well with the results of perturbation theory in the regimes where perturbation theory should be valid. I would like to thank our hosts, Bala Iyer, Joseph Samuel and all the students at the Raman Institute for organizing such an enjoyable and interesting conference!

Bangalore quantum gravity meeting

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On December 13.-14., just prior to GR15, the Raman Research Institute at Bangalore in India hosted a discussion meeting on quantum general relativity as part of its Golden Jubilee celebrations. The plan was to have three talks each morning and one in the afternoon, then followed by longer discussion sessions. The beautiful setting of the institute, together with the un-forced and smooth organization indeed created a perfect atmosphere for inspiring discussions. The topics covered a fairly wide range, from (2+1)-dimensional quantum gravity, loop gravity, lattice approaches and 3-dimensional topology to the quantum theory of black holes and, in particular, the issues associated with black hole entropy. Canonical approaches dominated the scene, but this was partly due to the unfortunate fact that Ashoke Sen had to cancel his talk on string calculations of black hole entropy.

The first speaker was Steve Carlip who presented five main lessons that could so far be learned from (2+1)-dimensional gravity. He listed numerous consistent ways for quantization and pointed out their partial inequivalences. For example, consistent quantizations with or without topology change exist, hence topology change is consistent with, but not required by, quantum gravity. Another striking lesson concerns the euclidean path integral approach. In (2+1)-dimensions it can be shown that the contribution from the many arbitrarily complicated interpolating topologies cannot be neglected (as is sometimes assumed). Once more it became clear that, despite all differences to (3+1)-dimensions, (2+1)-dimensional gravity is an important and useful test bed to study concepts and expectations in quantum gravity.

Carlo Rovelli gave a large scale survey on progress and problems in loop quantum gravity. Recent progress in physical predictions at the Planck scale mainly originate from calculations of spectra of operators (on the auxiliary Hilbert space of pure gravity) representing area and volume of two- and three-dimensional subsets. In absence of any matter degrees of freedom these subsets are mathematically specified in a non diffeomorphism invariant fashion. Progress on the mathematical side was also reported. The long standing problems concerning the lack of a scalar product, overcompleteness of the loop basis and the implementation of the reality conditions seem to be settled now. Anomaly free regularizations of the super-hamiltonian have been constructed, but there is still an ongoing debate as to its physical correctness, since it does not define a deformation of the classical constraint algebra and hence seems to reproduce the wrong classical limit. Rovelli ended by emphasizing the complementary strengths and weaknesses of loop quantum gravity and string theory.

Renate Loll reported on the status of discrete approaches to 4-dimensional quantum gravity based on the Einstein action. She discussed results from Hamiltonian path-integral approaches with connection variables and dynamical triangulations. The common open problem is the absence of appropriate measures on the discretized configuration spaces. The choices explored so far seem too simple to lead to an interacting, diffeomorphism-invariant field theory.

There were two talks on topological issues in (3+1)-dimensional canonical gravity. Domenico Giulini started with discussing the role and significance of three-dimensional topology in the classical and quantum theories. One of the issues addressed was whether and how classical topology leaves its fingerprints in the quantum theory. In this context the mapping class groups of three-dimensional manifolds were argued to be the natural objects to look at, since they carry significant amounts of topological information and also enter the quantum theory through the reduction procedure. Giulini concluded by listing some general properties of 3d mapping class groups, like finite presentations, residual finiteness and semi-direct product structures. Sumati Surya reported on some work using Mackey theory to find interesting representations of 3d mapping class groups and discussed their physical implications. Thinking of the 3-manifold as configuration of elementary 'geons' (i.e. prime-manifolds), she showed and discussed the general absence of spin-statistics correlations at the kinematical level, and also the possibility of novel 'cyclic' statistics types which she encountered with three RP-3 geons.

Two talks and an additional discussion session – filling the gap that the cancellation of Ashoke Sen's talk left – were devoted to black hole entropy. V. Frolov's talk centered around the problem of universality of black hole entropy which, despite some impressive derivations, like e.g. by counting states of D-branes, is still an open one. He discussed the idea of entanglement entropy, some of its problems, and how they can be solved in some models of induced gravity. He reported on recent work on such models showing that universality exists within a special class. In Parthasarathi Majumdar's talk the different approaches to understand black hole entropy were compared. In particular, the string calculations and viewpoints now came to their right. A final discussion session, solely devoted to all kinds of questions relating to black hole entropy, marked the end of this most pleasant meeting.

Cleveland Cosmology-Topology Workshop

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On a crisp fall weekend in Cleveland, an unlikely collection of mathematicians and physicists met at Case Western Reserve University to discuss the large scale topology of the universe. There was a certain irony to the location, as the meeting was being held just a short walk from where Michelson and Morely dispensed with the ether one hundred years earlier, while the cosmologies being discussed come with an absolute frame of reference.

The main aim of the meeting was to foster closer ties between geometers, cosmologists and theoretical physicists. Through this exchange of ideas and expertise, we hoped to arrive at a better understanding of the theoretical and observational characteristics of multi-connected cosmologies.

The meeting ran to a workshop format with a small number of talks providing a springboard for extensive and lively discussions. This meant that all 30 participants did indeed participate, even though only half the participants gave talks. One of the most active participants was Bill Thurston, who got things rolling by taking us on a tour of topology and geometry in dimensions 1 through 5. We learnt how topology becomes more flexible with increasing dimensionality while geometry becomes more rigid. The majority of Thurston's talk was devoted to 3-manifolds, where both topology and geometry find their optimal balance between flexibility and rigidity. Concepts such as the prime decomposition of 3-manifolds were made accessible to the physics audience by relating the underlying ball-gluing construction to wormholes. Thurston emphasised that most 3-manifolds are hyperbolic. Picking up on this lead, David Spergel reviewed the mounting observational evidence that we live in a sub-critical universe with hyperbolic spatial sections. Gary Gibbons took us back to the quantum gravity epoch and considered how the universe might arrive at a non-trivial topology. The mathematicians were introduced to the Euclidean path integral approach and semi-classical real tunnelling geometries. Steve Carlip continued in a similar vein, but argued that the density of topologies might dominate the gravitational action in the path integral. Later in the meeting John Freedman discussed multi-connected spacetimes from a Lorentzian quantum gravity perspective and Bai-Lok Hu described the Casimir and other finite size effects. Closely related to this was Jean-Philippe Uzan's description of the obstructions to forming topological defects, such as cosmic strings, in universes with non-trivial topology.

The majority of the workshop was devoted to observational searches for topology. The meeting organizer, Glenn Starkman, introduced this topic with a historical review of global topology in cosmology, starting in 1917 with de Sitter's RP^3 variant to Einstein's static universe and moving to the present. Since the best window on topology is provided by the cosmic microwave background radiation, David Spergel provided a review of CBMR physics and observations. We also heard how the MAP and Planck satellites will transform our view of the CMBR early next century. Speaking for the Toronto group, Turan Souradeep told us about their efforts to model the CMBR power spectrum in multi-connected hyperbolic universes. On the same topic, Janna Levin entertained us with her quirky description of the work done by the Berkeley group, showing how cusped manifolds lead to flat spots in the CMBR. Still on this theme, I outlined the work Neil Turok and I have done to develop a simple numerical method for finding the eigenmodes of arbitrary compact manifolds. Moving to more direct detection methods, I explained how Spergel, Starkman and I hope to use the MAP satellite to search for topologically matched circles in the CMBR. Searching a lot closer to home, Boud Roukema showed how matched quasar groupings could be used to test for non-trivial topology. This method should be quite useful when the Sloan and Quest digital sky surveys deliver millions of new quasars positions. As a fitting testament to the cross-disciplinary nature of the workshop, one of the most intriguing observational prospects was described by the topologist Jeff Weeks. Using his *SnapPea* computer program, Weeks showed how the size and position of just a few matched circle pairs could be used to completely reconstruct the topology of the universe. A similar procedure can also be used with the quasar groupings.

All the talks stimulated enthusiastic discussion that brought in the other participants, including the topologist Colin Adams, Rob Meyerhoff, John Ratcliffe and Bill Goldman and physicists Ted Jacobson, Tanmay Vachaspati and Rich Gott. By the end of the workshop the topologists were arguing about the Sachs-Wolfe effect and the physicists were arguing about Dehn surgery on cusps. All the participants agreed that it was one of the best meetings they had been to in years. If you want to hear more about what went on at the meeting, keep an eye out for the workshop proceedings that will be appearing as a special issue of *Classical and Quantum Gravity*. Or you could do the nineties thing and visit the workshop website at http//theory5.phys.cwru.edu. There you will find contributed talks, a copy of the Cleveland Plain Dealer article covering the workshop (complete with a picture of Glenn Starkman eating a hyperbolic potato chip) and perhaps an audio file of the radio coverage by the CBC radio program “Quips and Quarks”, produced by Dan Falk.

Quantum Gravity in the Southern Cone II

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The second edition of the Quantum Gravity in the Southern Cone workshop was held at the Centro Atómico Bariloche, Argentina on January 7-10, 1998. It brought together 50 researchers from South America as well as experts from the northern hemisphere, working on different aspects of quantum gravity and related topics. The plenary lectures enabled the participants to obtain a global picture of the status of the field in the various approaches. The meeting was further enriched by poster sessions. The following list summarizes the topics covered by the lecturers.

Canonical Quantum Gravity

J.Pullin overviewed of the attempts to apply the rules of canonical quantization to GR. He stressed the important role played by spin networks and by Thiemann's Hamiltonian. The problems presented by this Hamiltonian (it commutes on non diffeomorfism invariant states) were addressed by *R. Gambini,* who reported on progress made to solve them. Midi-superspace models of canonical quantum gravity were considered by *C. Torre* who indicated that one can satisfactorily quantize quantum parameterized field theories on a two-dimensional spacetime, but that the quantization of such theories in higher dimensions is still an open problem. A framework for modelling quantum gravitational collapse was discussed by *K. Kuchar* who considered the canonical dynamics of matter shells. Both the dynamics of the shell and of the surrounding spacetime were shown to follow from a single variational principle. By formulating GR as a theory of surfaces, *C. Kozameh* showed how to construct a quantum spacetime using only Scri equipped with free functions as the kinematical structure

String theory and higher dimensional objects

J. Maldacena discussed the large N limit of certain field theories and its relation to gravity. In a similar context, *A. Schwimmer* referred to N=1 (Seiberg) duality in field theory and its realization through branes. Phenomenological aspects of string theory were covered by *G. Aldazabal* who discussed non-perturbative orbifold vacua. Branes in supergravities, string theory and M theory were discussed by *M. Cederwall. M. Henneaux* referred to dyons, charge quantization and electric-magnetic duality for p-form theories in $2(p+1)$ spacetime dimensions with arbitrary gauge invariant self-interactions. *B. Carter* discussed the geometry of non null p surfaces embedded in n dimensions. Electric 2 branes were presented by *R. Aros. J. Zanelli* reviewed Chern-Simons supergravity in $(2n-1)$ dimensions, showing that they contain non trivial dynamics leading to interesting classical solutions such as black holes, solitons, membranes, etc.

Black hole physics, semiclassical theories and cosmology

In the context of a two dimensional exactly solvable model, *J. Russo* outlined the construction of an S-matrix and showed that black holes will radiate out an energy of Planck order, stabilizing after a transitory period. A similar picture appears in 3+1 Einstein gravity with spherical symmetry. *R. Bousso* discussed the evaporation of Schwarzschild-De Sitter black holes including the one-loop effective action. *B.Hu* addressed the problem of fluctuations and backreaction in semiclassical cosmology and black holes by presenting a complete history of the subject and conjectured that a stochastic description in terms of Einstein-Langevin equation becomes relevant at the Planck scale. Semiclassical theories were also considered by *C. Molina-Paris* and *S. Ramsey. H. Rubinstein* reviewed the status of the big bang standard model and the latest data available from observations.

Baltimore AMS meeting

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At the Baltimore meeting of the American Mathematical Society, there was a special session on quantum gravity and low-dimensional topology. The session was organized by J. Baez (University of California, Riverside) and S. Sawin (Fairfield University). The session lasted two days: January 7 and the morning of January 8. This and the other sessions of the AMS meeting took place at Baltimore Convention Center, located in the tourist attraction center of Baltimore called Inner Harbor.

On the first day, *Louis H. Kauffman* spoke about "Discrete Physics", *Abhay Ashtekar* on "Quantum Theory of Riemannian Geometry" and *Jim Stasheff*, gave "A Survey of Cohomological Physics". *Roger Picken* spoke about "Kontsevich Integrals, Knot Invariants and TQFT", *Lee Smolin* discussed how to get "Perturbative Strings from Perturbations of Evolving Spin Networks" *Alexander A. Voronov* presented "The Homotopy Algebraic Structure of Topological Gravity" and *John W. Barrett* talked on "Quantum Gravity: Path Integrals and state Sums". *Louis Crane* presented "A State Sum Formulation for Quantum General Relativity" and *Seth A. Major* discussed his work with *Roumen Borissov* on "Q-Deformed Loop Representation for Quantum Gravity: Structure and Open Problems". *Kirill V. Krasnov* discussed "Spin Networks, Chern-Simons Theory and Black Holes" and *Donald M. Marolf* presented his work with *Jerzy Lewandowski* "Loop Constraints: A Habitat and their Algebra"

In the evening of that day *Edward Witten* delivered his Josiah Willard Gibbs Lecture on *M Theory* to more than a thousand mathematicians gathered at the Ballroom of the Convention Center.

The session continued in the morning of the next day with *David N. Yetter* talking about a "Grist for a 4-D State-Sum Mill: Examples of Monoidal Bicategories", *Carlo Rovelli* presenting "From Loop Quantum Gravity to a Sum over Surfaces" and *Dana S. Fine* discussing "Path Integrals Linking Chern-Simons and WZW Partition Functions". *Laurel T. Langford* spoke on "2-Tangles as a Free Braided Monoidal 2-Category with Duals" and *Fotini G. Markopoulou* discussed "Quantum Space and Causality", *Takashi Kimura* presented his work with *Alexandre Kabanov* on "Tautological Classes and Cohomological Field Theories in Genus One" and *Doug Bullock* his work with *Charles Frohman* and *Joanna Kania-Bartoszynska* on "Lattice Gauge Field Theory and Deformation Quantization". Finally, *Steven J. Carlip* discussed "Einstein Manifolds, Spacetime Foam, and the Cosmological Constant".

The session was a very interesting mixture of mathematics and physics: talks on Topological Quantum Field Theory and Quantum Gravity usually followed each other. In fact, it was quite surprising to see the growing influence of the two fields on one another: many of the talks on the Quantum Gravity side were devoted to the application of the ideas and techniques from TQFT's to gravity and some talks given by mathematicians were on issues that used to be of interest only to physicists. Belonging to this last category were the two very exciting talks by J. Barrett and L. Crane on their new state sum formulation of quantum general relativity.

After the session was finished, some of us gathered for an informal discussion guided by J. Baez, L. Crane, C. Rovelli and L. Smolin. The discussion was devoted to some aspects of the path integral formulation of quantum gravity.