// MATTERS OF GRAVITY

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

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Editor

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Editorial

Not much to report here. This newsletter is a bit late, since I wanted to wait till LIGO could report on its first science run. I want to encourage the readership to suggest topics for articles in MOG. In the last few issues articles were solicited by myself. This is not good for keeping the newsletter balanced. Either contact the relevant correspondent or me directly.

The next newsletter is due September 1st. All issues are available in the WWW:
`http://www.phys.lsu.edu/mog`

The newsletter is available for Palm Pilots, Palm PC's and web-enabled cell phones as an Avantgo channel. Check out `http://www.avantgo.com` under technology→science.

A hardcopy of the newsletter is distributed free of charge to the members of the APS Topical Group on Gravitation upon request (the default distribution form is via the web) to the secretary of the Topical Group. 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 of Matters of Gravity

- 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
- Beverly Berger: 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
- Gary Sanders: LIGO Project
- Peter Saulson: former editor, correspondent at large.

Topical Group in Gravitation (GGR) Authorities

Chair: Richard Price; Chair-Elect: John Friedman; Vice-Chair: Jim Isenberg; Secretary-Treasurer: Patrick Brady; Past Chair: Bob Wald; Members at Large: Gary Horowitz, Eric Adelberger, Ted Jacobson, Jennie Traschen, Éanna Flanagan, Gabriela González.

GGR Activities

Richard Price, University of Utah (for the Exec. Committee) rprice@physics.utah.edu

Our Topical Group in Gravitation continues to be a success when measured by its size, as well as by any other metric. We have 1.4% of the total APS membership. Of the 9 APS Topical Groups, GGR is number 3 in size. It is ironic that our membership has grown, but that we recently slipped from our number 2 position due to a jump in membership of the magnetism topical group. (It is tempting to make puns about many body phenomena here.) The topical group in Statistical and Nonlinear Physics remains in first place with 1.6% of APS membership. The larger subunits of the APS are Divisions, with a minimum of 3% of APS membership. Our GGR members come mostly from two APS Divisions: the Division of Astrophysics and the Division of Particles & Fields.

A new GGR activity this past year is the GGR sponsorship of student speaker awards at the regional gravity conferences. A new activity, long in the development, is the presentation of the Einstein awards, at a special Awards session (b6, Saturday 14:30) of the April APS meeting in Philadelphia. As always, a business meeting of our topical group will be held during the April meeting.

Awaiting us further in the future is the international celebration of the World Year of Physics in 2005. Judy Franz, Executive Director of the APS, is the head of US participation in the event. The inspiration for all this is the centenary of Einstein's 1905 papers, so GGR — as the APS unit most closely associated with Einstein — should play some role. The Executive Committee has been discussing ways in which this is to be done, but would benefit from suggestions.

We hear that...

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Stan Whitcomb, Lee Lindblom, Sam Finn, Ashok Das were elected fellows of the American Physical Society.

Vicky Kalogera received a David and Lucile Packard Fellowship and the A. J. Cannon Award of the American Astronomical Society and the American Association of University Women.

Barry Barish was elected to the National Academy of Sciences and to the National Science Board.

Luis Lehner was awarded a Sloan Fellowship.

The Prime Minister of the UK, Tony Blair, opened **The Ogden Centre for Fundamental Physics at the University of Durham** on Friday 18th October 2002. The multi-million pound science complex will create a world-leading centre of excellence in fundamental physics, combining research into the building blocks of the universe and the large scale structure of the universe, coupled with a mission to inspire a new generation of young scientists.

Hearty congratulations!

Institute of Physics Gravitational Physics Group

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The Gravitational Physics Group of the Institute of Physics (UK) was formed at the beginning of 2002. The aim of the group is to form a scientific and public focus for the gravitational physics community, in particular, providing a forum for discussion between the theory and experimental researchers and with UK funding bodies.

Prof. Mike Cruise (Birmingham) currently chairs the group and Prof. Ray d'Inverno (Southampton) is the secretary. Details of the other members of the committee can be found on the group's web-site http://groups.iop.org/GP/. The committee includes theorists and experimentalists with a wide range of research interests and also a representative from industry. The committee representative from BAE Systems, provides a link between industry and academia, enabling liaison for exploring and directing industry supported university programmes in this and related areas of research.

A principal concern of the Group is the funding of Gravitational Physics in the UK where, partly for historic reasons, funding has been inadequate, especially on the theoretical side, since it has often appeared to have fallen between the responsibilities of the two main funding agencies PPARC and EPSRC. The Group plans to carry out a survey of the field in the UK to find out some basic information about its size and composition, prior to setting up a meeting with the two funding agencies to explore ways of increasing the funding base.

The group's first scientific meeting, held in London in February 2002, discussed the interplay between theory and experiment in gravitational physics, with talks by Dr. B.S. Sathyaprakash (Cardiff) on "Gravitational physics: the interaction of theory and experiment", and Prof. Gary Gibbons (Cambridge) on "Gravitational Physics: General Relativity and its role in fundamental physics", as well as a presentation on PPARC funding for Gravitational Physics research by Prof. Richard Wade (PPARC). Subsequently, the group hosted a meeting on "Brane World Gravity", in November 2002 (see separate report), and a joint meeting with the Royal Astronomical Society on "Gravitational Wave Astronomy", in February 2003.

On the industrial side, BAE Systems chaired a meeting in November 2002, attended by Government agencies (MoD, Qinetiq, Dstl), Rolls Royce and several UK universities on research into applications of gravitational physics for advanced propulsion systems.

The group also supports the annual BritGrav meetings. The third British Gravity Meeting is to be hosted by Lancaster University Physics Department, and will take place on 12 - 14 September, 2003. For further details see the web-site: http://www.lancs.ac.uk/depts/physics/conf/britgrav/.

Center for Gravitational Wave Astronomy a new NASA University Research Center

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On January 1st 2003, the National Aeronautic and Space Administration (NASA) created at The University of Texas at Brownsville (UTB) the Center for Gravitational Wave Astronomy (CGWA) as part of its University Research Center (URC) program. As described by NASA, the University Research Centers program is designed to achieve a broad-based, competitive aerospace research capability among the nation's Minority Serving Institutions (MSI) of Higher Education. These centers will foster new aerospace science and technology concepts; expand the nation's base for aerospace research and development; develop mechanisms for increased participation by faculty and students of MSI in mainstream research; and increase the production of socially- and economically-disadvantaged students (who are U.S. citizens and who have historically been underrepresented) with advanced degrees in NASA-related fields.

This particular center will develop excellence in research and education in areas related to the new astronomy which will become technically feasible within the next five to ten years—*gravitational wave astronomy*.

The CGWA will focus on three major research areas: gravitational wave data analysis, gravitational wave source modeling, and phenomenological astrophysics of supermassive black holes. The proposed research is relevant to the NASA Space Science Enterprise of charting the evolution of the universe and understanding its galaxies, stars, and their dynamics and evolution. In particular, we expect the center to make important contributions to LISA, a joint NASA-ESA mission with a projected launch date of 2011. LISA consists of three identical spacecraft located in an equilateral triangle 5×10^6 km on a side in a heliocentric orbit. The spacecraft carry the optical components of a Michelson-Morley interferometer, which will measure the passing of gravitational waves of astrophysical origin in the 10^{-1} to 10^{-4} Hz band. NASA's recognition of the technological and scientific opportunities presented by the LISA mission is exemplified in their selection of the Disturbance Reduction System technology as the Space Technology 7 project for the New Millennium Program.

As already evidenced by the LIGO project, the success of LISA does not depend only on the expertise of the experimental scientists and engineers who design and implement it, but also on the collaboration of a highly integrated group of scientists in astrophysics, source modeling, and data analysis. Data analysts rely on source modelers and astrophysicists to predict features of gravitational wave signals that allow them to be extracted from instrumental noise. Source modelers rely on astrophysicists and data analysts to guide them in representing the sources that are most likely to be observed. Astrophysicists use source modeling and signals extracted by data analysts (or the lack of such signals) to improve their understanding of the astrophysics of the actual sources.

The proposed CGWA will represent research expertise in all three of these theoretical disciplines, with a focus on LISA research. The core of the center's research personnel will be formed by the UTB Relativity Group (UTBRG). Currently, the UTBRG consists of five faculty (Warren Anderson, Manuela Campanelli, Mario Díaz, Carlos Lousto and Joe Romano), three post-docs and several undergraduate and graduate students. Since its creation, just six years ago, the UTBRG has developed expertise in gravitational wave source modeling and data analysis. Center funding will allow existing research strengths to be augmented by expanding the area of phenomenological astrophysics—especially related to super-massive black holes—with the incorporation of more scientists (at both the faculty and postdoctoral level). The Center is advised at the scientific level by a very distinguished Board of Advisors: Peter Bender (JILA-University of Colorado), Tom Prince (Caltech), Jorge Pullin (LSU), Douglas Richstone (University of Michigan), and Bernard Schutz (AEI).

The strong research programs at the center will help it become a national and international hub for gravitational wave scientists. It will complement a network of recently created institutions/centers devoted to gravitational wave physics. The UTBRG already has strong ties to the NSF Physics Frontier Center for Gravitational Wave Physics recently created at Penn State, to the LIGO Scientific Collaboration (which provides scientific support to ground-based gravitational wave detectors), and to the recently formed source modeling group at NASA's Goddard Space Flight Center. These affiliations will provide additional research avenues to center students and faculty. The center will have a very active visitors program. All center activities are open to the broad scientific community, whose participation will be supported through this program.

In addition, the center will develop one of its major thrusts in student support at the advanced undergraduate and graduate levels. Starting next year, the center will organize, on an annual basis, an advanced undergraduate/beginning graduate summer school in gravitational wave physics.

At the end of this year, the CGWA will hold its inaugurational meeting. For more information about this event and the opportunities provided by the center, please visit the web site (presently under construction) at http://cgwa.phys.utb.edu.

LIGO's First Preliminary Science Results

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In the previous report in MOG [1], I described the completion of the first LIGO science run, S1. The strain spectral sensitivity of LIGO in that run, and the duration of the run, is described in that article. S1 was the first in a series of progressively more sensitive science runs, interleaved with interferometer commissioning and improvement periods. S1 has now yielded preliminary science results. These are being presented, as this article is written, at the AAAS meeting in Denver [2]. The talks from this symposium will be posted shortly on the LIGO Laboratory website [3], and the LSC website [4]. This article follows closely the content of Albert Lazzarini's talk in that symposium. Final results from S1 are in preparation and should appear as preprints in the next several weeks with formal publication after the March LSC meeting.

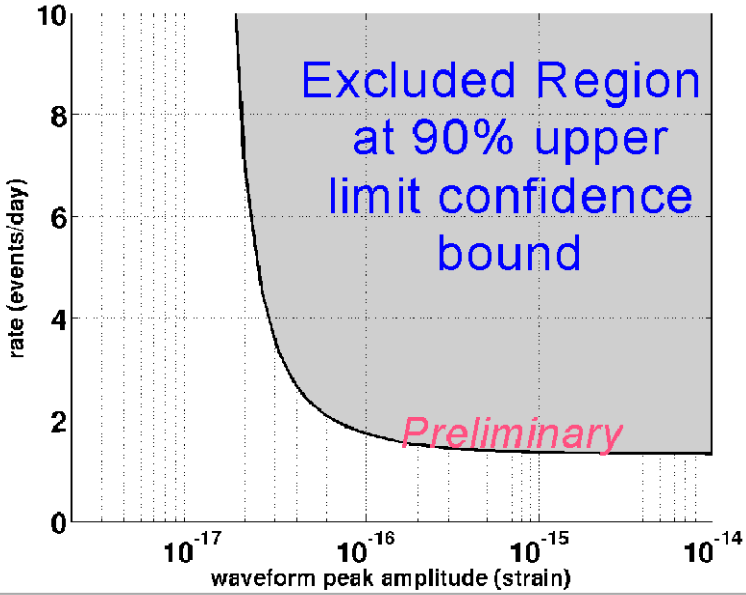
The results below mark the first from LIGO, a milestone in the program. The physics impact of these results is not very significant, but the lessons learned about the interferometer data streams and the analysis algorithms lay the foundation for more meaningful future work as LIGO's sensitivity increases and as the science runs extend over longer periods. In that sense, the analysis methods that will be published are at least as significant as the results themselves.

The GEO-600 interferometer also operated during S1, as we previously reported, and results are quoted below from the joint GEO-LIGO effort. Coincident running with the TAMA-300 interferometer is the subject of analysis by a separate working group and is not reported here.

For the analysis of this data, the LIGO Scientific Collaboration has divided itself into four Upper Limits Working Groups. The terminology clearly reflects the expectation that the early running is most useful to set upper limits on the various gravitational wave fluxes and/or source populations. These working groups are focused on burst, inspiral, periodic and stochastic sources.

The data analysis techniques adapt to the source characteristics. Deterministic signals from inspiral and periodic sources can be parameterized by amplitude and frequency evolution. Template sets can be selected to cover the parameter space covered by the data. Statistical signals, such as stochastic gravitational wave backgrounds, are sought by cross-correlating pairs of interferometers, seeking correlations and statistical variations. Unmodeled signals such as supernovae, gamma ray bursts or entirely new transient sources cannot be addressed by parametric techniques. For these, very basic data trends are sought such as power excesses in the frequency-time domain, or notable amplitude changes in time. In all of these studies, use is made of the coincidence between multiple detectors, a most powerful filter.

The LIGO Burst Sources Working Group has taken on one of the most challenging search topics. In the absence of a waveform model, they have searched for frequency vs. time domain power excesses and time varying amplitude departures, setting a bound on unmodeled bursts of rate vs. strength. The analysis serves as a prototype for any searches for discrete events. Diagnostic triggers from the detectors indicating instrumental or environmental data artifacts confront event triggers from the interferometers. Requiring three-interferometer coincidence further filters event triggers that are not vetoed by this process. Bursts of peak strain amplitude above a given rate have been excluded in this search as shown in Figure 1. The displayed limit is not yet the best achieved as resonant mass detectors have published superior limits [5,6].



The Inspiral Sources Working Group is searching for 1- 3 solar mass neutron star binaries, black hole binaries heavier than 3 solar masses, and MACHO binaries in the 0.5 - 1 solar mass range. They have completed the neutron star search at this time. The analysis employs template based matched filtering. During the S1 run, the LIGO interferometers were individually sensitive to 1.4 solar mass binaries out to 38 kpc to 210 kpc, for optimal orientation and signal to noise ration (SNR) of 8. With appropriate treatment of the expected population in the Milky Way galaxy, and the Large and Small Magellanic Clouds, and using triggers from the Hanford and Livingston 4 km interferometers, the resulting limit is:

$$\mathrm{R90\,\%\,(MilkyWay)} < 1.7 \times 10^2/\mathrm{yr}$$

The best previously published observational limit was obtained using data from the 40 Meter Interferometer at Caltech [7] ($\mathrm{R90\,\%\,(MilkyWay)} < 4.4 \times 10^3/\mathrm{yr}$).

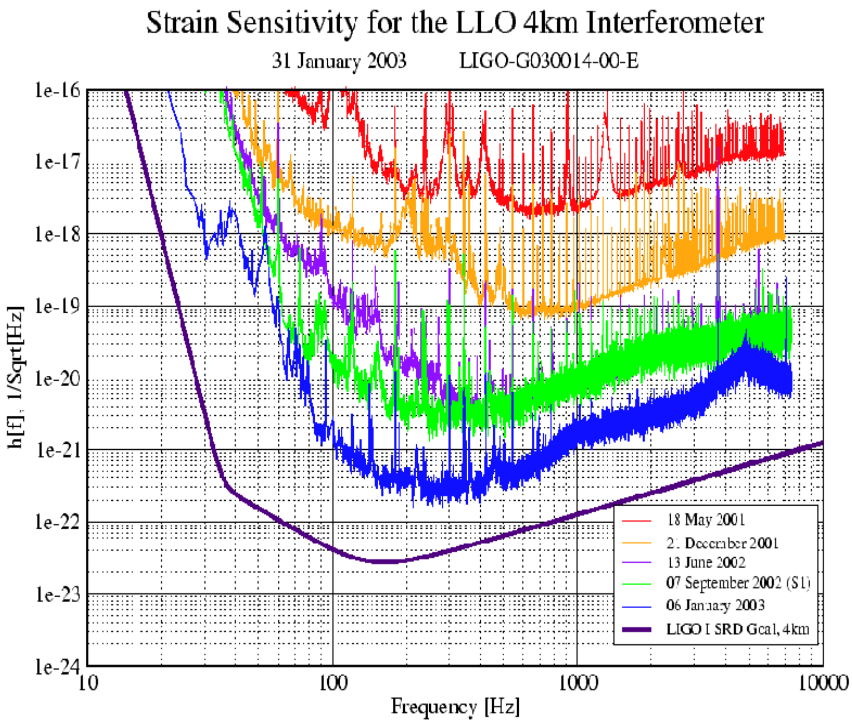
The Periodic Sources Working Group is searching for gravitational waves radiated by periodic sources such as rotating prolate neutron stars with ellipticity in the range $10^{-3} - 10^{-4}$. These would be of best interest in a LIGO search if all of the observed spin-down were attributable to gravitational wave emissions. The search can be carried out in the frequency domain by cross-correlating the data stream with templates, seeking power correlations. A complementary approach uses a time domain search, removing motion of the Earth, and comparing the result with what would be expected from noise in the absence of a signal. The analyses are still in

Interferometer Pair	Measurement bandwidth	Extrapolated Upper Limit for S1 (by scaling 7.5 hrs to 150 hrs)	T_{obs}
H2km - H4km	40Hz < f < 300 Hz	$\Omega_{GW} < 5$ (90% C.L.)	150 hr
H4km - L4km	40Hz < f < 314 Hz	$\Omega_{GW} < 70$ (90% C.L.)	100 hr
H2km - L4km	40Hz < f < 314 Hz	$\Omega_{GW} < 500$ (90% C.L.)	100 hr

progress. However, no signals are seen. Preliminary limits, with 95% confidence, on periodic sources are set on maximum strain amplitudes individually for the GEO interferometer and the three LIGO interferometers ranging from 3×10^{-21} to 2×10^{-22}, the latter limit set by the Livingston 4 km interferometer.

The Stochastic Sources Working Group is searching for these remnant signals by cross-correlating interferometer outputs in pairs, using the long baseline Livingston-Hanford 4 km interferometers and the short baseline co-located Hanford 2 km and 4 km interferometers. The full initial LIGO science run should be able to reach sensitivity of $\sim \Omega_{GW} < 10^{-5}$, comparable to upper limits inferred from Big Bang nucleosynthesis [8] . The best detector-based limit is GW 907 Hz from resonant mass detector results [9]. Based upon analysis of only 7.5 hours of data from the S1 run, the Stochastic Sources Working Group estimates the limits from the full S1 run as shown in Table 1.

This is only an estimate of the S1 result, as stated. Actual results from the full data set will be represented in preprints to be released prior to the LSC meeting in March.



As this S1 analysis matures, LIGO has already begun the S2 run, on February 14. An 8-week run is planned, four times longer than the S1 run. Most important, LIGO sensitivity is more than an order of magnitude better now, across the sensitive spectrum. Figure 2 displays the progression in sensitivity for the Livingston 4 km interferometer, illustrating the improvement since S1.

The S2 run will involve coincident running with the LSC partner GEO-600 instrument, and with the TAMA-300 detector, following the signing of a new LIGO-TAMA Memorandum of Understanding. 2003 promises to be a propitious year for ground-based gravitational wave interferometry!

LIGO is funded by the US National Science Foundation under Cooperative Agreement PHY-0107417. This work is a collaborative effort of the Laser Interferometer Gravitational-wave Observatory and the institutions of the LIGO Scientific Collaboration. LIGO T030021-00-M.

More information about LIGO can be found at: http://www.ligo.caltech.edu.

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Quantization of area: the plot thickens

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One of the key predictions of loop quantum gravity is that the area of a surface can only take on a discrete spectrum of values. In particular, there is a smallest nonzero area that a surface can have. We can call this the 'quantum of area', so long as we bear in mind that not all areas are integer multiples of this one — at least, not in the most popular version of the theory.

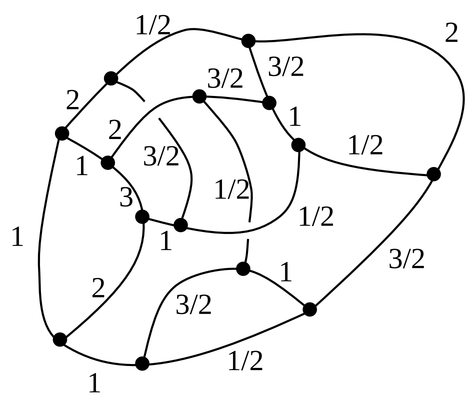
So far, calculations working strictly within the framework of loop quantum gravity have been unable to determine the quantum of area. But now, thanks to work of Olaf Dreyer [1] and Luboš Motl [2], two very different methods of calculating the quantum of area have been shown to give the same answer: $4 \ln 3$ times the Planck area. Both methods use semiclassical ideas from outside loop quantum gravity. The first uses Hawking's formula for the entropy of a black hole, while the second uses a formula for the frequencies of highly damped vibrational modes of a classical black hole. It is still completely mysterious why they give the same answer. It could be a misleading coincidence, or it could be an important clue. In any event, the story is well worth telling.

The importance of *area* in quantum gravity has been obvious ever since the early days of black hole thermodynamics. In 1973, Bekenstein [3] argued that the entropy of a black hole was proportional to its area. By 1975, Hawking [4] was able to determine the constant of proportionality, arriving at the famous formula

$$S = A/4$$

in units where $\hbar = c = G = k = 1$. Understanding this formula more deeply has been a challenge ever since.

Things took a new turn around 1995, when Rovelli and Smolin [5] showed that in loop quantum gravity, area is quantized. The geometry of space is described using 'spin networks', which are roughly graphs with edges labeled by spins:



Any surface gets its area from spin network edges that puncture it, and an edge labeled by the spin j contributes an area of $8\pi\gamma\sqrt{j(j+1)}$, where γ is a dimensionless quantity called the Barbero–Immirzi parameter [6,7].

Given this, it was tempting to attribute the entropy of a black hole to microstates of its event horizon, and to describe these in terms of spin network edges puncturing the horizon. After some pioneering work by Rovelli and Smolin, Krasnov [6] noticed that the horizon of a nonrotating black hole could be described using a field theory called Chern-Simons theory. He began working with Ashtekar, Corichi and myself on using this to compute the entropy of such a black hole.

By 1997 we felt we were getting somewhere, and we came out with a short paper outlining our approach [7]. While the details are technical [8], the final calculation is easy to describe. The geometry of the event horizon is described not only by a list of nonzero spins j_i label ling the spin network edges that puncture the horizon, but also by a list of numbers m_i which can range from $-j_i$ to j_i in integer steps. The intrinsic geometry of the horizon is flat except at the punctures, and the numbers m_i describes the angle deficit at each puncture. To count the total number of microstates of a black hole of area near A, we must therefore count all lists j_i, m_i for which

$$A \cong \sum_i 8\pi\gamma\sqrt{j_i(j_i+1)}.$$

This is a nice little math problem. It turns out that for a large black hole, the whopping majority of all microstates come from taking all the spins to be as small as possible. So, we can just count the microstates where all the spins j_i equal 1/2. If there are n punctures, this gives

$$A \cong 4\pi\sqrt{3}\gamma n.$$

In a state like this, each number m_i can take just two values at each puncture. Thus if there are n punctures, there are 2^n microstates, and the black hole entropy is

$$S \cong \ln(2^n) \cong \frac{\ln 2}{4\pi\sqrt{3}\,\gamma} A.$$

In short, we see that entropy is indeed proportional to area, at least for large black holes. However, we only get Hawking's formula $S = A/4$ if we take the Barbero–Immirzi parameter to be

$$\gamma = \frac{\ln 2}{\pi\sqrt{3}}.$$

On the one hand this is good: it's a way to determine the Barbero–Immirzi parameter, and thus the quantum of area, which works out to

$$8\pi\gamma\sqrt{\tfrac{1}{2}(\tfrac{1}{2}+1)} = 4\ln 2.$$

This makes for a pretty picture in which almost all the spin network edges puncturing the event horizon carry one quantum of area and one qubit of information, as in Wheeler's 'it from bit' scenario [9]. One can also check that the same value of γ works for electrically charged black holes and black holes coupled to a dilaton field. On the other hand, it seems annoying that we can only determine the quantum of area with the help of Hawking's semiclassical calculation. The strange value of γ might also make us suspicious of this whole approach.

Meanwhile, as far back as 1974, Bekenstein [10] had argued that Schwarzschild black holes should have a discrete spectrum of evenly spaced areas. While this law does not hold in the loop quantum gravity description of black holes, it has some of the same consequences. For example, in 1986 Mukhanov [11] noted that with a law of this sort, the formula $S = A/4$ can only hold exactly if the nth area eigenstate has degeneracy k^n and the spacing between area eigenstates is $4 \ln k$ for some number $k = 2, 3, 4, \ldots$. He also gave a philosophical argument that the value $k = 2$ is preferred, since then the states in the nth energy level can be described using n qubits.

Many researchers have continued this line of thought in different ways, but in 1995, Hod [14] gave an remarkable argument in favor of $k = 3$. His idea was to determine the quantum of area by looking at the vibrational modes of a *classical* black hole! Hod argues that if classically a system can undergo periodic motion at some frequency ω, then in the quantum theory it can emit or absorb quanta of radiation with the corresponding energy. But the energy of a Schwarzschild black hole is just its mass, and this is related to the area of its event horizon by

$$A = 16\pi M^2,$$

so when a black hole absorbs one quantum of radiation its area should change by

$$\Delta A = 32\pi M \Delta M = 32\pi M\omega.$$

And now for the miracle! A nonrotating black hole will exhibit damped oscillations when you perturb it momentarily in any way, and there are different vibrational modes called quasinormal modes, each with its own characteristic frequency and damping. In 1993, Nollert [15] used computer calculations to show that in the limit of large damping, the frequency of these modes approaches a specific number depending only on the mass of the black hole:

$$\omega \cong 0.04371235/M.$$

Plugging this into the previous formula, Hod obtained the quantum of area

$$\Delta A = 4.394444$$

and noticed that this was extremely close to $4 \ln 3 = 4.394449$. On the basis of this, he daringly concluded that $k = 3$.

Our story now catches up with recent developments. In November 2002, Dreyer [1] found an ingenious way to reconcile Hod's result with the loop quantum gravity calculation. The calculation due to Ashtekar *et al* used a version of loop quantum gravity where the gauge group is SU(2). This is why so many formulas resemble those familiar from the quantum mechanics of angular momentum, and this is why the smallest nonzero area comes from a spin network edge labeled by the smallest nonzero spin: $j = 1/2$. But there is also a version of loop quantum gravity with gauge group SO(3), in which the smallest nonzero spin is $j = 1$. Dreyer observed out that if we repeat the black hole entropy calculation using this SO(3) theory, we get a quantum of area that matches Hod's result! One can easily check this by redoing the calculation sketched earlier, replacing $j = 1/2$ by $j = 1$. One finds a new value of the Immirzi parameter:

$$\gamma = \frac{\ln 3}{2\pi\sqrt{2}},$$

and obtains $4 \ln 3$ as the new quantum of area. But ultimately, all that really matters is that when $j = 1$ there are 3 spin states instead of 2. Thus each quantum of area carries a 'trit' of information instead of a bit, which is why Dreyer obtains $k = 3$.

With the appearance of Dreyer's paper, the suspense became almost unbearable. After all, Hod's observation relied on numerical calculations, so the very next digit of his number might fail to match that of $4 \ln 3$. Luckily, in December 2002, Motl [2] showed that the match is exact! He used an ingenious analysis of Nollert's continued fraction expansion for the asymptotic frequencies of quasinormal modes.

While exciting, these developments raise even more questions than they answer. Why should SO(3) loop quantum gravity be the right theory to use? After all, it seems impossible to couple spin-1/2 particles to this version of the theory. Corichi has sketched a way out of this problem [16], but much work remains to see whether his proposal is feasible. Can we turn Hod's argument from a heuristic into something a bit more rigorous? He cites Bohr's correspondence principle in this form: "transition frequencies at large quantum numbers should equal classical oscillation frequencies." However, this differs significantly from the idea behind Bohr–Sommerfeld quantization, and it is also unclear why we should apply it only to the *asymptotic* frequencies of highly damped quasinormal modes. Can the mysterious agreement between SO(3) loop quantum gravity and Hod's calculation be extended to rotating black holes? Here a new paper by Hod makes some interesting progress [17]. Can it be extended to black holes in higher dimensions? Here Motl's new work with Neitzke gives some enigmatic clues [17]. Stay tuned for further developments.

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Convergence (?) of G Measurements – Mysteries Remain.

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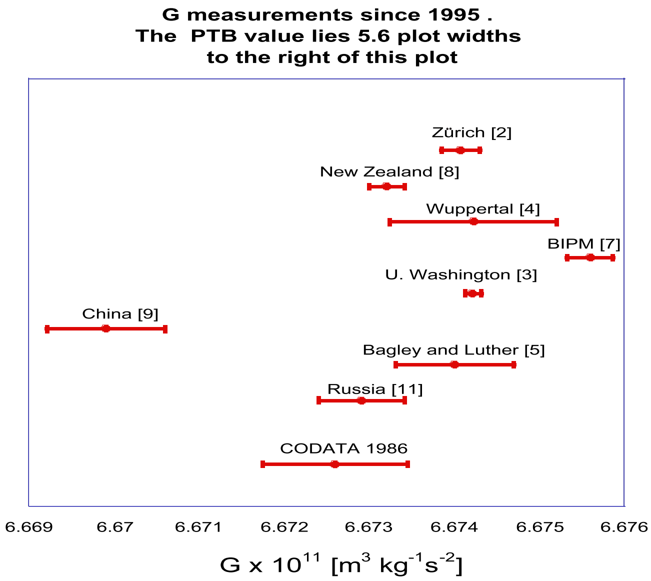
In 1995 the German PTB G measurement group published a startling G value [1] more than half a percent higher than the previously accepted CODATA value. The figure below indicates the most recent results of groups reporting G values since then.



The recently published 33 ppm measurement [2] by the U. Zürich group is nicely consistent with the 14 ppm measurement by the U. Washington group [3] and with the 147 ppm measurement by the U. Wuppertal group [4] and the 105 ppm measurement by Luther and Bagley [5]. These four measurements used very different techniques: The Zürich group measured the weight change of test masses caused by tanks of mercury (this experiment is featured in last November's Physics Today [6].) The Washington group measured the acceleration of test masses suspended on a rotating platform servoed to match the test mass' acceleration as source masses revolved about the system on a separate platform. The Wuppertal group measured the differential lateral displacement produced by a source mass acting on a pair of separately suspended test masses forming reflecting walls of a microwave cavity. The measurement by Luther and Bagley at LANL used the "time-of-swing" technique of Luther and Towler's 1982 G measurement on which the 1986 CODATA value was based – but this time deliberately used low-Q fibers to reveal and then correct for the effect of fiber anelasticity.

The agreement of these measurements – especially the U. Zürich and U. Washington values – is encouraging, but the figure shows significant outliers. Relative to the U. Washington G value, the BIPM value [7] is 206 ppm or 4.9σ **higher** , while the most recent New Zealand value [8] is 152 ppm or 4.6σ **lower**. The value found by Jun Luo and collaborators in China [9] is also lower, by 647 ppm or 6.1σ.

The BIPM measurement uses a torsion balance with two substantially independent techniques, sharing the same mass and suspension configuration. One technique balances the gravitational forces on the pendulum with a calibrated electrostatic force. The second technique is that of Cavendish – a measurement of static deflection, with torsion constant calibration from the frequency of free oscillation. The danger posed by fiber anelasticity is virtually eliminated by the first technique (where the fiber does not twist significantly), and highly suppressed in the second by using a thin strip suspension whose restoring torque is largely gravitational in origin. The two methods give results in excellent agreement. Further work on this measurement is in progress.

The New Zealand group, like the U. Washington group, used a method in which fiber anelasticity dangers are avoided by mounting a torsion pendulum on a rotating platform servoed to match the pendulum's angular acceleration so that the fiber twist is negligible.

The "time-of-swing" measurement by Jun Luo and collaborators in China minimized fiber anelasticity problems by using a very high Q suspension.

Still not ready to report is my own G measurement group at UC Irvine, which uses the "time-of-swing" method with a cryogenic high-Q torsion pendulum. We are troubled by a timing glitch in some of our early data, temperature control problems in more recent data, and most disturbingly, evidence that the value of G we would obtain may depend on the pendulum's oscillation amplitude.

The 1986 CODATA G value became suspect when Kuroda [10] pointed out that fiber anelasticity would have biased Luther's "time-of-swing" measurement on which it was based toward a **higher** G value. The five most recent measurements of G, uppermost in the figure above, all have designs which virtually eliminate anelasticity dangers. Interestingly, the 1986 CODATA value is actually **lower** than the value reported by all five of these measurements, as well as the PTB measurement.

It seems clear that the PTB G value cannot be correct. The PTB measurement balanced gravitational forces against DC electrostatic forces whose calibration involved the measurement of capacitances with 1 KHz AC voltages. A danger which the experimenters recognized is that the capacitances could be frequency dependent, and indeed the BIPM paper [7] suggests that a grounded lossy dielectric in the fringe field of the capacitive electrodes could cause such dependence. But the PTB workers did check for frequency dependence over a frequency range 100 Hz to 1 KHz and found negligible effect – it would seem surprising if a 0.6% capacitance calibration error that could account for the anomalous G value escaped detection. So mysteries remain, and measured G values have not converged satisfactorily, although the excellent agreement of the Zürich and U. Washington G values is encouraging.

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Brane world gravity

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A half-day meeting entitled "Brane-world gravity" was held at Imperial College London on 13th November 2002, under the auspices of the Gravitational Physics Group of the Institute of Physics. The meeting gave an overview of the state of the art in brane world gravity, in a form accessible to non-experts and the many graduate students present.

John March-Russell began with an overview of the physics of brane worlds, including the latest experimental constraints, from colliders, astrophysics and cosmology. He concentrated on the phenomenology of the simplest brane-world model, of Arkani-Hamed, Dimopoulos and Dvali, in which the large extra dimensions are flat but compactified. Ruth Gregory then discussed gravity on the brane, including the construction of brane-world cosmology geometries using patches of Schwarzschild-anti-de Sitter space. She also addressed the more difficult (and as yet unsolved) problem of finding a metric which describes a black hole on the brane. Neil Turok's talk on the cosmology of brane worlds prompted much lively debate. He reviewed recent work with Tolley and Steinhardt on the cyclic universes resulting from colliding branes.

After a break for tea and discussion, Christian Trenkel described the latest experimental work in Birmingham and elsewhere to test gravity at short distances, in particular looking for the deviations from Newtonian gravity predicted by brane-world models. Marco Cavaglia talked about the possibilities of black hole production at the next generation of colliders, including the production cross-sections and decay signatures. Finally, Toby Wiseman described new pure gravity solutions of low-energy string theory representing higher-dimensional black holes, uniform homogeneous strings and non-uniform black strings.

Many thanks to David Wands for organizing a very successful meeting.

Massive Black Hole Coalescence Focus Session at Penn State

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The Center for Gravitational Wave Physics at Penn State ran a series of *focus sessions* in 2002 (see article by Sam Finn in Issue 19 of Matters of Gravity, and Éanna Flanagan in Issue 20). The November 2002 focus session was held the week of the 18th to the 21st, focused on the topic of the astrophysics of the coalescence of supermassive black holes. The session was organised by Ramesh Narayan, chair of the Center's advisory board, Chris Mihos and myself. Focus sessions are, by design, limited to a small number of invited attendees, and student applicants sponsored by their advisors. A web site with most of the presentations made at the meeting is at http://cgwp.gravity.psu.edu/events/MBHMergers/.

The astrophysical processes that can remove energy and angular momentum from a pair of supermassive black holes, bound to each other, but embedded in a surrounding stellar population with significant total mass, have been investigated to various levels of approximation for many decades. Despite a lot of research on the issues, the fundamental problem of how supermassive black holes can transit from the "dynamical friction regime" to the "gravitational radiation dominated regime" remains intractable. The fundamental problem, as noted by Begelman, Blandford and Rees (1980, see Quinlan 1996 for historical review), is that once the BH binary becomes "hard", further increases in binding energy is primarily achieved by ejecting stars, which depletes the population of central stars available to interact with the BH binary. Relaxation processes can generally refill the so-called "loss-cone" - the region in phase space where particles can interact strongly with the binary, but only on very long time scales. In simulations, the BH binary "stalls" at the "last parsec", and additional physics is required if the binary is to merge.

While BH binaries are observed (cf Komossa et al 2003, in fact the announcement of the first confirmed detection of a bound binary supermassive black hole was made, independently by NASA, during the focus session), there is not an obvious, large population of tightly bound binaries in the "loss-cone" regime, suggesting that there are processes which enable rapid transit of the last parsec. Candidate processes include rapid refilling of the loss-cone by dynamical processes and hydrodynamical processes. There was also some discussion of whether angular momentum extraction could be efficient, leading to high eccentricity binaries (cf Aarseth 2002).

The session was split into a series of talks reviewing the physical issues and discussing some recent results by some of the groups working on the problem. Peter Bender, Doug Richstone and Tim de Zeeuw reviewed the observational situation; Josh Barnes, Scott Tremaine and myself reviewed some of the dynamical issues; Jeremy Goodman and Ramesh Narayan reviewed the hydrodynamical issues and Martin Haehnelt review the cosmological context and presented some new results on estimated net merger rates in the context of hierarchical galaxy formation. Qingjuan Yu, Pinaki Chatterjee, Priya Natarajan, Milos Milosavljevic, Andres Escala, Kelly Holley-Bockelmann and Sverre Aarseth presented some very interesting new results from recent research.

The meeting finished with a very lively discussion led by Scott Tremaine, and a review of the science and policy issues by Tom Prince.

Scott Tremaine summarised the work of the meeting, by preparing a list of issues that are perceived to be decidable in by current research efforts.

Decidable questions:

- Does the eccentricity of a hard binary BH increase or decrease?
- Is a given density of gas more effective than stars in merging binary BHs?
- Does triaxiality reduce the merger timescales for binary BH?
- Complete kinematic & photometric data on all galaxies with measured BHs.
- Why do mergers of individual galaxies not give an NFW profile?
- What is the level of triaxiality in the centers of galaxies?
- What is the Brownian motion of a BH at the center of a cusp?
- Why are the orbits of stars near Sgr A^* so eccentric?
- What are the limits on a massive binary BH in the Milky Way?
- What simulation method should we use for binary BH with gas?
- Can $M - \sigma$ relation be extended to higher and lower masses?
- Are intermediate mass BHs real?

And open issues of concern.

- What is the evidence for binary BHs in AGNs?
- Is there any way to detect binary BHs in nearby inactive galaxies?
- Is there any way to detect BHs that are not at galactic centers?
- Will LISA tell us anything about quasars?
- Do we believe any N-body simulation?
- What is the gravitational radiation recoil in a BH merger?

See http://cgwp.gravity.psu.edu/events/focus_sessions.shtml for past and upcoming focus sessions.

We thank Ramesh Narayan and Chris Mihos for their efforts in organizing the meeting.

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GWDAW 2002

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The seventh installment of the Gravitational Wave Data Analysis Workshop was held in Keihanna Science City in Kyoto Prefecture, Japan, on 17-19 December 2002. This meeting marked the rapid progress of the various gravitational wave detection efforts around the globe. LIGO Lab Director Barry Barish summarized the mood of most attendees in his remarks to the workshop banquet, when he said that the meeting program represented a mature field, with rapid progress on many instruments, discussions of new analyses of unprecedentedly sensitive data, and ongoing research on data analysis.

The first day's talks were devoted to instrument progress reports. Interferometer reports all described substantial progress in commissioning and initial data taking runs. TAMA, GEO, and LIGO have all collected some science data in runs interspersed with commissioning aimed at achieving full design sensitivity. VIRGO has had a very successful commissioning exercise of its Central Interferometer, and will soon start commissioning its 3 kilometer arms. Attendees also learned of the vigorous prototyping program preparing for Japan's Large Cryogenic Gravitational Telescope (LCGT), slated for installation in the Kamioka mine. A 7-meter single-arm cryogenic test facility, CLIK, has been built at ICRR, while the LISM 20-meter room temperature interferometer is in operation at Kamioka. Construction of the 100-meter cryogenic CLIO interferometer has begun in the Kamioka mine; the tunnel has been prepared, and infrastructure work is now in progress. LCGT aims to take advantage of the low seismic noise of its underground site, and the low thermal noise of 20 K cryogenic test masses, to reach sensitivities sufficient to see neutron star binary inspirals at a distance of 200 Mpc. Advanced LIGO and others are also aiming at similar goals, although via different technological means.

The growing excitement about the prospects of space-based detectors were the subject of the first afternoon's talks. LISA is at the center of the world's planning (it is a joint ESA-NASA project), but attendees also heard about a Japanese initiative called DECIGO, promoted by Seiji Kawamura, which is aimed at the 0.1 Hz band between LISA's most sensitive band and that of the ground-based interferometers. Among the bars, EXPLORER and NAUTILUS are operating well (more about them later), and ALLEGRO and AURIGA are about to come on line after major transducer upgrades.

The second day's talks began the discussion of data analysis per se. The discussion was organized around signal character (burst, inspiral, sinusoidal, and stochastic), and moved fluently between bar and interferometer analyses. There were a number of talks from LIGO authors on the methods used to analyze data from the recent (late August to early September 2002) S1 run. Preliminary results are still embargoed to allow for revision during discussions internal to the LIGO Scientific Collaboration; most members of the LSC had only heard the first results of the analyses a week or two before the meeting, and an active review process is now under way. (The first big announcement of still-preliminary results is expected in mid-February at a meeting of the AAAS.)

The most-anticipated session of the meeting was the late-afternoon section devoted to recent coincident analyses of data from bars. Giovanni Prodi opened with a very clear discussion of the methods used by the IGEC collaboration to set upper limits using several years worth of data from the entire worldwide bar network. The rest of the talks had as their subject the recent result from the Rome group on 2001 data from EXPLORER and NAUTILUS (Astone et al., Class. Quant. Gravity 19, 5449-63 (2002) and gr-qc/0210053.) In that paper, "indications" were reported of the emission of gravitational waves from sources scattered throughout the Galactic disk. Pia Astone led off with a discussion of a Bayesian interpretation of the results, (Eugenio Coccia having summarized the frequentist analysis of the paper, during his status report the previous day.) Then came two strong critiques of the statistical significance of the result, presented in turn by Sam Finn and Warren Johnson. Finn demonstrated that results as significant as those reported would be expected due to chance alone 25% of the time, hardly dramatic evidence of a discovery. Astone, in remarks interspersed during Johnson's presentation, emphasized that no discovery was claimed. Coccia closed the session by defending the significance of the result, on the grounds that detections at sidereal time 4 hours were special because of the link to the Galaxy, but also reiterating that only further observations could promote the claimed "indications" into a discovery (or, of course, rule them out.)

Discussion spilled over into the evening and on to the workshop banquet, aided by freely flowing sake and Asahi beer. Warren Johnson and Eugenio Coccia mugged for the cameras, pretending to throw roundhouse punches at one another. Then, Johnson and Pia Astone kissed and made up, literally and repeatedly, until everyone's camera had recorded the public reconciliation.

The third and final day was filled with talks on new data analysis methods, discussions of sources, and accounts of detector characterization techniques. While less easily summarized than the previous two days' talks, these in some way were the most future-oriented heart of the meeting, laying the foundations for the new results to be expected in time for the next year's workshop.

On the sidelines of the meeting, another important discussion was taking place. After the first day, representatives of TAMA and LIGO met in the International Institute of Advanced Studies' beautifully appointed seminar lounge to sign a Memorandum of Understanding for joint analysis of data from the upcoming S2 data run. This brought to fruition a series of negotiations spearheaded by Nobuyuki Kanda for TAMA and Albert Lazzarini for LIGO. After the third and final day's talks, a first working meeting of the two teams was held. Plans were sketched for joint searches for burst signals and for chirps from binary inspirals, intended to be completed six months after S2 concluded in mid-April 2003.

Intensely-focused discussions of other ongoing or soon-to-be-initiated analyses were held during coffee breaks and in the evenings. Combined with the work formally presented in talks, these indicate a field truly mature, and ready for a steady stream of new scientific results over the next few years.

Source simulation focus session at PennState

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The Center for Gravitational Wave Physics at Penn State organized during October 28-30, 2002 a special "Focus Session" to address the topic of "Source Simulation and Gravitational Wave Data Analysis". The goal of this focus session was the interplay between source simulations and gravitational wave data analysis: how the results of source simulations can be used to design data analysis that extracts more information, or information more efficiently, from gravitational wave detector data. The program dealt with the concrete, as opposed to the abstract: on developing analysis that make use of calculations relating to specific characteristics of specific sources.

The Program consisted of the following talks:

"Data Analysis in the Real World" Sam Finn started his talk reviewing the goals in source simulations and in data analysis. In particular, he stressed the importance in carrying out source simulations that identify the science reflected in the gravitational waves. For the data analyst, he stressed the need for developing techniques that make science stand-out and provide astrophysical interpretation of observations. He also review the different classes of sources: stochastic, periodic and bursts.

"Linguistics of LISA Sources" Scott Hughes presented an overview of key LISA sources. In particular, he discussed questions such as: What do we hope to learn from LISA sources? What is the character of the signals these sources generate? He also addressed the issue of how to design a strategy to measure LISA sources. He pointed out that there is a big difference between detection and measurement. He also discussed whether we can combine GW information with other channels to maximize the astrophysical payoff.

"Structure, Stability and Dynamical Behavior of Compact Astrophysical Objects" Joel Tohline presented a review of a meeting that took place the weekend before the workshop. This meeting was focused on two types of mechanisms in instabilities of compact objects: Hydrodynamical instabilities such as bar-mode instabilities, and GR driven instabilities (e.g. r-modes). Some of the issues discussed in this meeting were: Mode identification, damping mechanisms, expected maximum amplitude and duration, effects from GR on mode character and likelihood of producing detectable GW signals.

"Gravitational Waves from the Tidal Disruption of Neutron Stars in Binaries" Michele Vallisneri emphasized the importance of investigating the correspondence between the EOS and mass-radius function of NS. He discussed the possibility of using information from NS tidal disruption in NS-BH binaries as a probe of the NS EOS.

"Gamma Ray Bursts and Gravitational Waves" After a short review of GRBs, Shiho Kobayashi discussed how the detection of counterparts of GRBs in GWs could revolutionize the field. He pointed out that one can use GRBs and afterglow observations about the time and location of the event to perform a cross-correlation and obtain information of the association between GRBs and gravitational wave bursts.

"Predicting the Gravitational Wave Signatures of Core Collapse Supernovae: The Road Ahead" Tony Mezzacappa presented the road required in order to solve the core collapse supernovae problem, including the gravitational radiation produced by these events. He pointed out that waveforms will not be available any time soon. This is an extremely difficult problem

requiring a 3D-GR-Radiation-MHD code plus state of the art nuclear and weak interaction physics. His talk provided an overview of the current state of these simulations. In particular, he showed simulations of accretion shock instabilities and neutrino driven convection.

"Gravitational Waves from Supernova Core Collapse: What Could the Signal Tell Us" Harald Dimmelmeier presented results from simulations of supernova core collapse. He reviewed the physical complexity and numerical difficulties involved in relativistic simulations of rotational core collapse to a neutron star. He pointed out that because of these complications it is necessary to introduce several approximation. However, these approximations do not prevent us from extracting new physics encoded in the waveforms. Their simulations show that the remnants are more compact with higher densities when compared with Newtonian results. In addition, relativistic effects seem to increase the rotation rate, and in many instances these effects could trigger tri-axial instabilities.

"Low Frequency Gravitational Waves from the Galactic Halo" Shane Larson gave a talk reviewing first the MACHO search. He then discussed the potential for LISA observations of gravitational radiation from white dwarfs and black hole MACHO binaries.

"Binary Black Hole Coalescence in Galaxy Mergers" Steinn Sigurdsson stressed that although BBH coalescences in galaxy merger could potentially have large S/N, the rate of these events is likely to be low. He also addressed E&M and Spin signatures as well as the possibility of observing stars bound to the BHs.

Other talks in the meeting included: "Gravitational Wave Observations of Galactic Populations of Compact Binaries" by Matthew Benacquista, "An Overview of 3D Black Hole Simulations" by Pablo Laguna, "Bothrodesy: The Promise and Challenges of Extreme Mass Inspirals" by Teviet Creighton, "Probing the Equation of State of Neutron Stars with LIGO" by Fred Rasio

Links to presentations as PDF files can be found at

http://cgwp.gravity.psu.edu/events/SrcSimDA/

Raman Research Institute Workshop on Loop Quantum Gravity

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During two weeks in November and December 2002, approximately 20 researchers in quantum gravity gathered at the Raman Research Institute in Bangalore for an intensive meeting on Loop Quantum Gravity and related issues. Talks were divided into morning sessions, shared by Abhay Ashtekar and Martin Bojowald, and afternoon sessions for the rest of the participants.

Abhay Ashtekar gave quite a detailed overview of three main topics: Quantum geometry, black hole entropy, and semi-classical issues. After an introductory talk to set the stage of his series of lectures and a discussion on the quantum mechanics on SU(2), he gave two talks about connections on graphs and field theories of connections, both from the classical and the quantum perspective. They were followed by a lecture devoted to quantum Riemannian geometry and the definition of area and volume operators. After his introduction on quantum geometry he talked about the quantum geometry of isolated horizons and black hole entropy; he discussed, in particular, new results on the computations of entropy for non-minimally coupled scalar fields. Finally his three last talks were devoted to the discussion of semi-classical issues. In the first he used the quantum mechanics of a particle to study how the polymer-like quantum theory of a particle reduces to the usual Schrödinger Quantum Mechanics in the low energy regime. He then considered Maxwell theory in the next lecture, complementing a previous discussion of Madhavan Varadarajan's first talk and finished with an enlightening lecture on the relationship between the Fock, r-Fock, and polymer representations of Maxwell theory. On Dec, 4th he gave a public Academy Lecture on loop quantum gravity in front of a full auditorium. The ten one-and-a-half hour talks succeeded in providing an introduction to the main topics for non-experts and yet gave an insightful review of the present state of loop gravity and its applications. The talks sparked a lot of interaction among the participants in coffee breaks and informal discussion sessions and gave a clear idea of the status of the program and its future development. In spite of a winter cold Abhay displayed a lot of enthusiasm and energy that were certainly inspiring for the rest of the participants.

Martin Bojowald's talks we devoted to the mathematical issues related to symmetry reductions of theories of connections and their application to the study of loop quantum cosmology. He devoted his first three talks to the discussion of the mathematics of symmetry reductions for theories of connections and the definition of symmetric states in quantum geometry. After that he gave a thorough introduction to the kinematics of cosmological models, matter Hamiltonians, quantization ambiguities, and the study of homogenous and isotropic models. He discussed several cosmological issues from the loop quantum gravity perspective; in particular he gave a detailed overview of the meaning of the initial singularity and initial conditions, evolution through classical singularities, large volume behavior and corrections to the classical approach to singularities. He also discussed the possibility of explaining inflation within his framework. It was really impressive to see how far the developments on loop quantum cosmology have reached and the impulse that Martin's work is giving to the whole loop quantum gravity program.

Afternoon sessions covered a much broader set of topics on classical and quantum gravity, cosmology, and quantum field theory. Talks were shorter and were given by a number of speakers.

Sukanya Sinha reviewed the approach to the semiclassical Einstein equations pioneered by Bei Lok Hu and to which she has made recent contributions. P. Majumdar discussed some aspects related to the computation of quantum corrections to black hole entropy, in particular he discussed computations for BTZ and AdS-Schwarzschild black holes. L. Sriramkumar gave two introductory talks discussing some issues related to inflation and quantum gravity. T. R. Govindarajan gave us a talk about recent developments in de Sitter gravity, specifically on the thermodynamics of the cosmological horizon of the de Sitter space-time. J. Samuel discussed a novel proposal to test general relativity by using radio interferometers with intercontinental baselines and measuring the curvature of the wavefront emitted by a distant source. G. Date gave a talk on a recent model of his to describe discrete time evolution in a simple quantum mechanical system that mimics some of the features of the symmetric cosmological models discussed by Bojowald. Madhavan Varadarajan gave several talks about his last work on quantum linearized gravity and the r-Fock representation, in particular the use of U(1) flux nets in the context of the simple model provided by electromagnetism. Finally, the author of these lines discussed his work on diff-invariant and non diff-invariant free actions and their use in perturbative quantum gravity.

The meeting was very successful in all the possible aspects. The talks were interesting and illuminating with a lot of discussion during and after the seminars. The atmosphere among the participants was excellent and the scientific exchange really fruitful. I would like to emphasize the perfect organization of the meeting by Madhavan and the very warm hospitality of the whole theory group at RRI. I believe that all the participants are looking forward to attending future meetings at the Raman Institute.

Lazarus/Kudu Meeting at PennState

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On Sept. 7-9, 2002, the Center for Gravitational Wave Physics (CGWP) at Penn State hosted a small informal meeting to discuss the results of the Lazarus project and their relationship to the detection of gravitational waves from merging black holes. This meeting, organized by Manuela Campanelli, Sam Finn (CGWP director) and Pablo Laguna, was designed to maximize the rate of information exchange by limiting participation to just a few people, most of whom were already active in the Lazarus and Kudu projects. In attendance were Abhay Ashtekar, John Baker, Bernd Bruegmann, Jordan Camp, Manuela Campanelli, Joan Centrella, Jolien Creighton, Sam Finn, Pablo Laguna, Ben Owen, Deirdre Shoemaker and I.

For those not familiar with the Lazarus project, it is an attempt to model black hole mergers using the limited available numerical evolution only when absolutely necessary. The goal of the project, led by John Baker, Manuela Campanelli and Carlos Lousto, is to seamlessly sew a complete 3+1D, nonlinear numerical evolution in between a suitable early time approximation of the binary system, such as the PN approximation, and a suitable late time approximation, such as the close limit approximation, and thus produce merger waveforms which are suitable for data analysis. At present, the waveforms produced by Lazarus are not of sufficient accuracy to use for the standard data analysis algorithm of matched filtering. This has led to a second project, the Kudu project, whose goal is to define a framework for going from imperfect waveforms to data analysis algorithms, and to implement the framework on the Lazarus waveforms.

As with many "working meetings" that are being hosted by the CGWP, the agenda featured brief talks followed by long discussion periods, a format which I like very much. The first day of the meeting focused on the machinery of the Lazarus approach. Manuela Campanelli started with an overview of the Lazarus and Kudu projects. Almost immediately, there was a flurry of questions and discussion which set the tone for the day - a detailed, highly interactive dissection of the Lazarus project. Carlos Lousto's presentation of Lazarus methodology and John Baker's talk on Lazarus results were direction markers which primarily served to guide the general course of the conversation in which we were already engaged. It would be futile to try to detail the flow of this freeform discussion. Let me instead summarize with what I think was the main conclusion of the day - the Lazarus project has developed a framework which must overcome many technical hurdles, and at each of these hurdles, there is room for error to enter into the calculation. At present, much of the knowledge about these errors has been gleaned by the Lazarus researchers project seeing how things go awry when a mistake is made or they adjust a parameter. However, in order to use these waveforms, data analysts will need quantitative error estimates. Providing these estimates will be a long and arduous process, but the Lazarus project members who were present seemed to agree that it was possible and worthwhile.

The second day of the meeting focused on the Kudu project. This day was much more speculative - the Kudu project had barely started when the meeting was held. As a result, the nature of the meeting changed from critical review to exploring new horizons. I gave the first talk of the day, in which I described how one could devise an optimal (in a certain sense) search algorithm for signals about which only incomplete information was available.

Much interesting discussion followed on how one could use this to help refine source modeling efforts by concentrating the effort on those aspects of the model whose refinement would lead to the greatest increase in detection rate. Jolien Creighton then outlined the methods that are currently being used within LIGO to search for unmodeled signals, and how these methods might be improved to look for the Lazarus waveforms.

On the final morning, we had a discussion of where we stood and future directions. However, as with all such discussions, it is in the doing that progress will be made, rather than in the discussion. And this leads me to what I believe was the most fruitful aspect of this meeting. Over coffee, dinners, and late into the evenings, a subgroup of us discussed specific ideas that we wanted to explore, and agreed to have weekly teleconferences to discuss the results we have obtained. This group continues to meet (biweekly now) and to discuss results obtained and brainstorm new directions. It is unlikely that this nucleus could have self-assembled without the environment of a working meeting to stimulate it, and it is exactly by providing such opportunities that I feel that the CGWP will have its greatest impact on our community.