MATTERS OF GRAVITY

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

Number 26 **Fall 2005**

Contents

Editor

Jorge Pullin

Department of Physics and Astronomy
Louisiana State University
Baton Rouge, LA 70803-4001
Phone/Fax: (225)578-0464
Internet: `pullin-at-lsu.edu`
WWW: `http://www.phys.lsu.edu/faculty/pullin`

ISSN: 1527-3431

Editorial

With this newsletter I would like to announce my retirement as editor. I will edit one more newsletter (the February one) but from fall 2006 editorship will be taken over by David Garfinkle, as per decision of the GGR executive committee. It has been 11 years since I started editing the newsletter and it was time for a change. We all wish David great success with the editorship.

Some news from the executive committee: we will put on the ballot a modification of the GGR bylaws to create the post of membership coordinator, as our membership continues to grow (we are now at 782 members!). We will also propose an amendment of a sloppy wording about the constitution of the nominating committee. The current bylaws state it will have three members and then go on to describe how to choose four (!) members. This year the committee is chaired by Bei-Lok Hu, helped by Joe Giaime (APS representative), Don Marolf and Nergis Mavalvala.

The next newsletter is due February 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 hard-copy 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 think a topic should be covered by the newsletter you are strongly encouraged to contact the relevant correspondent. 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,
- Bei-Lok Hu: 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
- Jens Gundlach: Laboratory Experiments
- Warren Johnson: Resonant Mass Gravitational Wave Detectors
- David Shoemaker: LIGO Project
- Peter Saulson: former editor, correspondent at large.

Topical Group in Gravitation (GGR) Authorities

Chair: Jorge Pullin; Chair-Elect: Éanna Flanagan; Vice-Chair: Dieter Brill. Secretary-Treasurer: Vern Sandberg; Past Chair: Jim Isenberg; Delegates: Bei-Lok Hu, Sean Carroll, Bernd Bruegmann, Don Marolf, Vicky Kalogera, Steve Penn.

The WYP speakers program

Richard Price, University of Texas at Brownsville rprice-at-phys.utb.edu

In the spring of 2002 the Topical Group, and Jim Isenberg in particular, calculated that 2005 would be coming, and with it the World Year of Physics. To celebrate and exploit WYP, the Executive Committee approved a plan to sponsor a WYP Speakers Program. A task force (Jim Isenberg, Jennie Traschen, along with me as chair) was appointed, and a clear structure and philosophy were identified. The TGG role would be to assemble a list of speakers who were known to be good at outreach, and would try to find a speaker from that list to meet requests for WYP speakers. From the very outset, the prioritization of filling requests was meant to be based on TGG self-interest; highest priority was to be given to requests from colleges and universities that might supply graduate students to gravity research groups.

The program has been housed at my new academic institution, the Center of Gravitational Wave Astronomy (CGWA) at UT-Brownsville, with the heavy housework done by staff member Danka Mogilska. When a request is received Danka tries to locate a speaker appropriate for the request. What is most appropriate is a speaker living a short driving distance from the site of the request, since the program has had no travel funds. Requests have come almost exclusively through a website

http://www.phys.utb.edu/WYPspeakers/REQUESTS/howto.html

The APS central organization would not offer any direct assistance. Then and now, they did not consider the Speakers Program to be “APS wide.” The APS and the AAPT did help by linking the Speakers Program to their websites. The funding (support for Danka Mogilska) for the program to this point has come from the CGWA.

The program seems to have been a success. We have met about half of about 200 requests for the first half of 2005. A second part of the program was not a success. There was to have been a speakers database, a compilation of talks, images, links, etc. used by speakers, that would ease the preparation of a new presentation. Despite some prodding of speakers there have been almost no contributions to this database, and it will be abandoned.

Several months into the program we were joined by the Forum on the History of Physics (FHP), represented by Virginia Trimble. Virginia also served as a link to the Division of Astrophysics. Speakers from the Forum were particularly useful when groups specifically requested talks about historical and philosophical aspects of Einstein’s science. Furthermore, FHP/DAP had travel money for especially interesting outreach opportunities. For the past several months the program has run as a loose collaboration of our original program and Virginia’s efforts.

The response to the program does indicate that there is a market for the original program. Our 200 requests for the first half of 2005 may not be a good measure of what the program is going to be. A message from the APS recently went out to physics department chairs and we have been swamped as a result: 50 requests in the last week. The requests also show that there is a market out there for talks to high schools, nonacademic organizations, etc., a market we did not focus on. So the 2005 program has taught us some us some interesting lessons, but 2005 is coming to and end.

At their most recent meeting, the TGG Executive Committee approved, in principle, the continuation of the program. The CGWA can no longer support the program, so a source of funding is needed. For the last few months Virginia Trimble and I have been looking into long term possibilities for the program, into short term holding patterns, and have been looking for funding.

The good news is that a funds have been found, at least for the short term, and the program will continue to be housed at the CGWA while longer-term possibilities are explored.

Thanks to Virginia Trimble's efforts the major source of the funding will be a private donor: Wayne Rosing. Rosing, who has been described in the media as "... a legendary figure in the computer industry and a keen astronomer...," is the first senior fellow in mathematical and physical sciences at the University of California, Davis. Following Rosing's request, the program will be called the Las Cumbres Speakers Program, and will include some support for speaker travel. Both TGG and FHP will also be contributing some funds to the program to help support travel. The nature of the program can be expected to shift towards serving a broader set of requests, and the mode of operation will shift away from reliance on a list, and will include more ad hoc improvisational searching for the right speaker to meet a request.

The long term future of the speakers program is still under discussion, a discussion that will greatly benefit from what will be a very interesting year for the program.

We hear that...

Jorge Pullin, LSU pullin-at-lsu.edu

Hanno Sahlmann has won the 2005 "Akademiepreis für Physik" of the Gottingen Academy of Sciences. The citation says that the prize is being awarded for "important contributions to Loop Quantum Gravity, a promising framework for the quantization of Einstein's General Relativity."

Abhay Ashtekar has been named the Sir C.V. Raman Visiting Chair of the Indian Academy of Science and was awarded a senior Forschungspreis by the Humboldt Foundation

Hearty Congratulations!

100 Years ago

Jorge Pullin pullin-at-lsu.edu

An English version of "Does the inertia of a body depend on its energy content" (aka "The $E = mc^2$ paper) is available at http://www.phys.lsu.edu/mog/100

What's new in LIGO

David Shoemaker, LIGO-MIT dhs-at-ligo.mit.edu

There has been broad progress in LIGO over the last six months. One first note on the Livingston Observatory, which was in the path of Hurricane Katrina. The observatory staff are all safe. The site is sufficiently inland that the worst of the wind and water damage was avoided, although a building panel was ripped off, debris thrown around, and the power lost for a period of time. At the time of writing, it is being brought back to operational condition, and no obvious significant damage was done.

At the time of the last MOG, we were anticipating the fourth science run (S4). It took place as planned, and the bottom line is that the detectors worked very well. They worked with high sensitivity and duty cycle (thanks to the successful implementation of the hydraulic 'HEPI' pre-isolation system at Livingston). Diagnostic tools, looking at the state of the instruments and the quality of the data, were running in full force, giving feedback to the operators and science monitors to watch for problems and allow tuning for the highest quality of data.

A handful of papers from earlier science runs have now been submitted. Since the last MOG, such bodice-rippers as "Search for gravitational waves from galactic and extragalactic binary neutron stars", "Search for Gravitational Waves from Primordial Black Hole Binary Coalescences in the Galactic Halo", "Upper limits from the LIGO and TAMA detectors on the rate of gravitational-wave bursts", "Upper limits on gravitational wave bursts in LIGOs second science run", and "Upper Limits on a Stochastic Background of Gravitational Waves" have hit the gr-qc newstand. The last paper puts the exciting upper limit of $\Omega_{gw}(f) < 8.4 \times 10^{-4}$ in the band of frequencies from 69-156 Hz, an improvement of some 105 in the limit at those frequencies. We are still catching up on the data collected, and are working hard on the very nice recent S4 data. Einstein@home, described in the last MOG, has been a resounding success. It is providing roughly 20 Teraflops of computing power and is working away at searches for periodic sources, like pulsars, over broad sections of the sky. Please consider donating your spare cycles to http://einstein.phys.uwm.edu/.

Detector commissioning has continued with great success. On all instruments, the core of the progress has been in increasing the laser power. This pushes down the noise in the shot-noise limited region, but equally importantly gives better signal-to-noise in many auxiliary channels. In the case of the Livingston instrument, better alignment control was needed, and achieved, to handle this power. The 4km instrument at Hanford had shown excessive absorption in several optics, and careful sleuthing showed that one of the input optics of a 4km Fabry-Perot cavity was the prime suspect. A foray into the vacuum system was made to switch out that optic, and to clean another. This gave a factor of (at least) ten reduction in absorption, paving the way for useful increases in power for this instrument. The 2km instrument at Hanford also was tuned up, and variety of other optical, mechanical, and controls aspects of the interferometers have been addressed in parallel. The instruments have now all performed effectively at their design sensitivity, and the Collaboration has decided to proceed with the main initial LIGO S5 Science Run, designed to collect a year of integrated data, planned to start late this year.

Advanced LIGO design and prototyping continues apace. A full-size prototype, from Caltech and UK design teams, of the quadruple test mass suspensions has just been assembled. The seismic isolation prototype at Stanford's test facility has demonstrated design performance in many aspects, and we are now moving forward on the prototype for the test mass chambers.

Work has been done at MIT on characterizing the seismic interface and at Caltech on alternative designs for the auxiliary optics 'HAM' chambers. Along with technical progress on the laser at the Max-Planck Institute in Hannover, funding for supplying the pre-stabilized lasers for Advanced LIGO has now been assured. The good technical progress allows us to be ready for and optimistic about a 2008 start of funding for Advanced LIGO from the National Science Foundation.

One important evolutionary change is underway: The reorganization of the LIGO Laboratory and the LIGO Scientific Collaboration (LSC). The two are becoming one organization – referred to simply as 'LIGO' – as a recognition of the crucial role that the LSC plays in the development and exploitation of the Observatories. Individuals from the LSC are taking on central organizational roles, exemplified by the addition of the LSC spokesperson to the leadership group of the LIGO Director and Deputy Director. The LSC is also participating fully in the search for a new Director, as Barry Barish has been asked to take on the leadership of the global design effort for the international linear collider. We will miss his leadership; fortunately he will remain as an active member of the LSC. We are also moving to bring our close international partners into the organization; re-writing the LSC Charter and Bylaws; and generally adjusting to the reality that we have a set of running detectors, with a mature data analysis process, and an Advanced LIGO upgrade which is starting to take on a life of its own.

Recent developments in the information loss paradox

Éanna Flanagan, Cornell
eef3-at-cornell.edu

In 1976 Stephen Hawking noted that the formation and evaporation of black holes as described in the semiclassical approximation appear to transform pure states into mixed states, in conflict with unitarity (Hawking 1976). This apparent paradox engendered a lively debate during the subsequent decades, with no generally accepted resolution. A poll taking during a 1993 conference showed 32% of the participants for information loss, with the remainder in favor of unitarity or other resolutions of the paradox (Page 1994). If such a poll were repeated today, however, the result would probably be markedly different — evidence in favor of the preservation of information has emerged from string theory, and more recently from Euclidean quantum gravity (Hawking 2004,2005) and loop quantum gravity (Ashtekar & Bojowald 2005a,b). There is thus an emerging consensus that black hole evaporation is unitary. However, the flaws in the original semiclassical arguments have not yet been clearly resolved; this aspect of the subject remains a puzzle.

The standard semiclassical argument for information loss is as follows (see, eg, Preskill 1992, Strominger 1994). Consider a solution of the semiclassical Einstein equations that describes the formation and evaporation of a black hole with initial mass $M \gg 1$ in Planck units. It is argued that the domain of validity of such a solution consists of all points in whose causal pasts the local curvature is everywhere sub-Planckian; this belief is supported by detailed calculations in two-dimensional models (Bose, Parker & Peleg 1996, Strominger 1994). One can in principle excise from the spacetime all points outside this domain of validity. The resulting spacetime is generally believed to have the following features (based again in part on explicit calculations in two-dimensional models; see eg. Strominger 1994): (i) It contains an apparent horizon whose area shrinks down to the Planck scale due to Hawking emission. (ii) It can be foliated by spacelike slices whose extrinsic curvatures are everywhere sub-Planckian such that one of the slices, Σ, contains most of the outgoing Hawking radiation (mass $\sim M$), yet intersects the infalling matter inside the black hole in a region of low curvature (Lowe et. al. 1995).

Next, one assumes that the black hole evaporates completely, and that after the evaporation spacetime can again be described using the semiclassical approximation. The initial conditions for this final semiclassical spacetime region are determined in part by quantum gravity. One assumes that this region can be foliated by spacelike slices, the first of which, Σ', can be chosen to coincide with Σ outside of some closed two-surface S. Thus, $\Sigma = \Sigma_{\rm in} \cup \Sigma_{\rm out}$ and $\Sigma' = \Sigma'_{\rm in} \cup \Sigma_{\rm out}$, where $\Sigma_{\rm out}$ is the region outside S, $\Sigma_{\rm in}$ is the portion of Σ inside S, which intersects the infalling matter inside the black hole, and $\Sigma'_{\rm in}$ is the portion of Σ' inside S, which contains the end-products of the last stages of evaporation. The construction can be specialized so that the mass contained within S is of order the Planck mass (since the semiclassical description of the evaporation is accurate down to the Planck scale), and so that the radius R of S is of order the time taken for the black hole to decay completely after it reaches the Planck scale (the "remnant lifetime").

If the quantum state on Σ' were pure, then the entanglement entropies $S_{\rm out} = -{\rm tr}(\hat\rho_{\rm out} \ln \hat\rho_{\rm out})$ and $S'_{\rm in} = -{\rm tr}(\hat\rho'_{\rm in} \ln \hat\rho'_{\rm in})$ of the density matrices on $\Sigma'_{\rm in}$ and $\Sigma_{\rm out}$ would agree. If the Hawking radiation is approximated to be in a thermal state, its entropy is of order $S_{\rm out} \sim M2$ (Page

1976). One might worry that this approximation is not reliable and that subtle correlations between Hawking quanta could make the state on Σ_{out} very nearly pure, giving $S_{out} \ll M2$. However since the state on Σ is pure, $S_{out} = S_{in}$, so a nearly pure state on Σ_{out} would require a nearly pure state on Σ_{in}. This would contradict the linearity of quantum mechanical evolution from initial states of the collapsing matter to states on Σ (Preskill 1992). Therefore the estimate $S_{out} \sim M2$ seems unavoidable. Finally, if the lifetime R is assumed to be of order the Planck time, the region Σ'_{in} is too small and contains too little energy to allow significant correlations, $S'_{in} \lesssim 1$. [Preskill (1992) shows that $S'_{in} \sim M2$ would require a lifetime of order $R \sim M4$.] Therefore $S'_{in} \ll S_{out}$ and the state on Σ' cannot be pure.

This semiclassical argument indicates that the information defined by $I = \ln \dim \mathcal{H} + \mathrm{tr}(\hat{\rho} \ln \hat{\rho})$ decreases, where $\mathcal{H}$ is the Hilbert space. However, as pointed out by Page (1994), it does not necessarily imply that information is lost in the colloquial sense that knowledge of the final (mixed) state on Σ' is insufficient to compute the initial (pure) state: pure-to-mixed evolutions can be described by invertible superscattering matrices. Nevertheless, if one accepts that I decreases, then information loss in the stronger, colloquial sense seems inevitable, since the state on Σ_{out} as computed in the semiclassical approximation depends only very weakly on the initial quantum state of the infalling matter.

Many different resolutions to the information loss paradox have been proposed; see eg. Thorlacius (2004) or Page (1994) for detailed reviews. Some novel recent suggestions are those of Horowitz & Maldacena (2004) and Gambini et. al. (2004). In the remainder of this article I will focus on evidence from various approaches to quantum gravity that black hole evaporation is unitary.

The evidence from string theory is well-known; see the articles by Gary Horowitz in issues 12 and 18 of Matters of Gravity. Briefly, the AdS/CFT duality of string theory implies that the formation and evaporation of small black holes in anti-deSitter space can described completely (albeit indirectly) by a manifestly unitary conformal field theory. String theory also provides an explanation for the failure of the semiclassical argument summarized above. Namely, the low energy effective theory describing evolution in the foliation used in the semiclassical argument is *non-local* even in low-curvature regimes: it contains states of strings stretched over macroscopic distances (Lowe et. al. 1995, Lowe & Thorlacius 1999). This non-locality allows external observers to measure the information coming out in the Hawking radiation, while infalling observers see nothing unusual happening while the infalling matter crosses the horizon. The idea of such low-energy non-locality is anathema to many relativists (see, eg. Jacobson et. al. 2005), but is supported by computations of commutators of spacelike separated operators in string theory (Lowe et. al. 1995). Thus, the key assumption that semiclassical general relativity is a good approximation at sub-Planckian curvatures is invalid in string theory.

Turn now to the Euclidean path integral approach to quantum gravity. For many years, Stephen Hawking has been the most prominent proponent of the view that black holes destroy information. His dramatic and much-publicized reversal on this issue last year at the GR17 conference (Hawking 2004) was described in Brien Nolan's article in issue 24 of Matters of Gravity. Hawking considers scattering processes in anti-deSitter space that classically would be expected to produce a black hole. He argues in this context that a path integral computation of correlation functions of operators at infinity will be dominated by a sum over two topological sectors, one corresponding to no black hole being present and one corresponding to a black hole being present. (Since observers making measurements at infinity cannot be sure if a black hole formed or not, the corresponding amplitudes should be summed.) The contribution from the topologically trivial sector (no black hole), which he had previously neglected, is sufficient to restore unitarity (Hawking 2005). Hawking's arguments so far are schematic and will likely be followed up by more detailed computations. In any case, it is clear that his arguments do not yet explain where the standard semiclassical argument breaks down, if it does.

Turn lastly to loop quantum gravity. Here, the first key result relevant to information loss is that the singularity inside Schwarzschild black holes is resolved (Ashtekar & Bojowald 2005b). The analysis is similar to earlier analyses of the resolution of cosmological singularities (Bojowald 2001, Ashtekar et. al. 2003). In the Schwarzschild case the theory that is quantized is a a finite-dimensional, minisuperspace model rather than the full, infinite-dimensional theory. However, the particular quantization chosen (which is unconventional) is motivated by considerations of the loop quantum gravity program on the full phase space. With this quantization, the Hamiltonian constraint reduces to a finite difference equation, which can be thought of as describing a discrete time evolution. For appropriate solutions of the difference equation, operators describing the geometry are well defined at the singularity, where they diverge classically. While one might object to the truncation of the phase space it is plausible that similar results might hold in the full theory.

Ashtekar & Varadarajan (2005) also analyze the more complicated model of the two-dimensional CGHS black hole (Callan, Giddings, Harvey & Strominger 1992), which incorporates Hawking radiation and backreaction. The key results here are (i) the singularity is again resolved, and (ii) there exists a region of the spacetime surrounding what would be the singularity where quantum gravitational effects are strong and a classical geometry does not exist. Before this region, and again after it, a semiclassical approximation is valid. In particular there are no baby universes, and no superpositions of macroscopically different geometries at late times. Ashtekar & Bojowald (2005a) argue that these conclusions should also be valid in four-dimensions If this is the case, then the fact that the singularity is resolved should imply that black-hole formation and evaporation is unitary, since there are no singularities in the quantum theory.

How is this loop quantum gravity scenario consistent with the standard semiclassical argument for information loss? The answer to this question is not yet completely clear. Ashtekar and Bojowald (2005a) speculate that the amount of mass that passes through the singularity (the mass contained inside the surface S discussed above) could be much larger than the Planck mass. This would require the semiclassical solution that describes the evaporation outside the black hole to break down before the Planck regime is reached, or to have properties other than those usually assumed (for example, an apparent horizon area of order the Planck area at the same retarded time as a Bondi mass much greater than the Planck mass; Ashtekar 2005). This option cannot be ruled out since a complete and detailed computation of the semiclassical solution has not yet been carried out in four dimensions; however it seems unlikely given the two-dimensional computations that have been performed. If it is true that the mass that passes through the singularity is much larger than the Planck mass, then the semiclassical argument for information loss can be evaded.

One of the appealing features of the loop quantum gravity computations, in my view, is that they are sufficiently explicit, direct and local that it should be possible with additional computations to pin down where and why the semiclassical argument fails. By contrast, the Euclidean quantum gravity approach restricts itself to computing asymptotic observables;

it is difficult using only these observables to try to understand why the local semiclassical arguments fail. Similarly, in string theory the most detailed understanding of the evaporation process is in terms of the dual description in the boundary conformal field theory; it is not easy to translate this into a detailed local understanding of the evaporation process (although see Lowe & Thorlacius 1999).

The most satisfying resolution of the information loss paradox, in my view, would be an explanation of why the semiclassical theory breaks down earlier than naively expected. Ideally this explanation would use only minimal assumptions about quantum gravity, and would be applicable to all three of the approaches to quantum gravity discussed here. The recent loop quantum gravity computations might be a step in this direction.

References:

Ashtekar, A., 2005, private communication.
Ashtekar, A. & Bojowald, M., 2005a, Class. Quant. Grav. **22**, 3349 (also gr-qc/0504029).
Ashtekar, A. & Bojowald, M., 2005b, *Quantum geometry and the Schwarzschild singularity*, gr-qc/0509075.
Ashtekar, A., Bojowald, M. & Lewandowski, L., 2003, Adv. Theor. Math. Phys. **7**, 233.
Ashtekar, A. & Varadarajan, M., 2005, in preparation.
Bojowald, M., 2001, Phys. Rev. D **64**, 084018
Bose, S., Parker, L. & Peleg, Y., 1996, Phys. Rev. D **53**, 7089.
Callan, C. G., Giddings, S. B., Harvey, J. A. & Strominger, A., 1992, Phys. Rev. D **45**, R1005.
Gambini, R., Porto, R. & Pullin, J., 2004, Phys. Rev. Lett. **93**, 240401.
Hawking, S.W., 1976, Phys. Rev. D **14**, 2460.
Hawking, S.W., 2004, presentation at 17th International Conference on General Relativity and Gravitation, Dublin, Ireland; transcript available at http://pancake.uchicago.edu/~carroll/hawkingdublin.txt.
Hawking, S.W., 2005, *Information Loss in Black Holes*, hep-th/0507171.
Horowitz, G. & Maldacena, J., 2004, JHEP **008**, 0402 (also hep-th/0310281).
Jacobson, T., Marolf, D. & Rovelli, C., 2005, *Black hole entropy: inside or out?*, hep-th/0501103.
Lowe, D.A., Polchinski, J., Susskind, L., Thorlacius, L. & Uglum, J., 1995, Phys. Rev. D **52**, 6997 (1995).
Lowe, D.A. & Thorlacius, L., 1999, Phys. Rev. D **60**, 104012.
Page, D.N., 1976, Phys. Rev. D **14**, 3260.
Page, D.N., 1994, *Black Hole Information*, in "Proceedings of the 15th Canadian Conference on General Relativity and Relativistic Astrophysics", Eds. R.B. Mann and R.G. McLenaghan, World Scientific, Singapore (also hep-th/9305040).
Preskill, J., 1993, *Do black hole destroy information?*, in "International symposium on black holes, membranes, wormholes and superstrings", World Scientific, River Edge, NJ (also hep-th/9209058).
Strominger, A. 1994, *Les Houches lectures on black holes*, hep-th/9501071.
Thorlacius, L. 2004, *Black Holes and the Holographic Principle*, hep-th/0404098.

Gravity Probe B mission ends

Bob Kahn, Stanford University cmw-at-howdy.wustl.edu

On August 15, 2005, Gravity Probe B completed 352 days of science data collection and conducted a series of final instrument calibration tests before the liquid helium in the Dewar was exhausted around Labor Day. At that point, the main focus of GP-B shifted from mission operations to data analysis. The scientific analysis work will require over a year to complete, followed by up to six months of preparing and submitting scientific papers to major scientific journals. This process will culminate in the announcement and publication of the results, now anticipated to occur around April 2007. Thus it seems appropriate to provide an overview of what is involved in the GP-B data analysis process.

Recall that GP-B consists fundamentally of four spinning gyroscopes and a telescope. Conceptually the experimental procedure is simple: At the beginning of the experiment, we point the science telescope on-board the spacecraft at a guide star, IM Pegasi, and we electrically nudge the spin axes of the four gyroscopes into the same alignment parallel to the telescope axis. Then, over the course of a year, as the spacecraft orbits the Earth some 5,000 times while the Earth makes one complete orbit around the Sun, the four gyros spin undisturbed—their spin axes influenced only by the relativistic warping and twisting of spacetime. We keep the telescope pointed at the guide star using attitude control thrusters on the spacecraft, and each orbit, we record the cumulative size and direction of the angle between the gyroscopes' spin axes and the telescope. According to the predictions of Einstein's general theory of relativity, over the course of a year, an angle of 6.6 arcseconds should open up in the plane of the spacecraft's polar orbit, due to the warping of spacetime by the Earth (geodetic effect), and a smaller angle of 0.041 arcseconds should open up in the direction of Earth's rotation due to the Earth dragging its local spacetime around as it rotates (Lense-Thirring effect).

In reality, what goes on behind the scenes in order to obtain these gyro drift angles is a complex process of data reduction and analysis that will take the GP-B science team more than a year to bring to completion. We continuously collect data during all scheduled telemetry passes with ground stations and communications satellites, and this telemetered data is stored–in its raw, unaltered form–in a database at the GP-B Mission Operations Center at Stanford University. This raw data is called Level 0 data. The GP-B spacecraft is capable of tracking some 10,000 individual values, but we only capture about 1/5 of that data. The Level 0 data includes a myriad of status information on all spacecraft systems in addition to the science data, all packed together for efficient telemetry transmission. The first data reduction task is to extract all of the individual data components from the Level 0 data and store them in the database with mnemonic identifier tags. These tagged data elements are called Level 1 data. We then run a number of algorithmic processes on the Level 1 data to extract around 500 data elements that will be used for science data analysis; this is Level 2 data. While Level 2 data include information collected during each entire orbit, the science team generally only uses information collected during the portion of each orbit when the telescope is locked onto the guide star. We do not use for science any gyroscope or telescope data collected during that portion of each orbit when the spacecraft is behind the Earth, eclipsed from a direct view of the guide star.

If there were no noise or error in our gyro readouts, and if we had known the exact calibrations of these readouts at the beginning of the experiment, then we would only need two data points–a starting point for the gyroscope orientations and an ending point. However, since we are determining the exact readout calibrations as part of the experiment, collecting all of the data points in between enables us to determine these unknown variables.

Another important point is that the electronic systems on-board the spacecraft do not read out angles. Rather, they read out voltages, and by the time these voltages are telemetered to Earth, they have undergone many conversions and amplifications. Thus, in addition to the desired signals, the GP-B science data includes a certain amount of random noise, as well as various sources of interference. The random noise averages out over time and is not an issue. Some of what appears to be regular, periodic interference in the data is actually important calibrating signals that enable us to determine the size of the scale factors that accompany the science data. For example, the orbital and annual aberration of the starlight from IM Pegasi is used as a means of calibrating the gyro readout signals. As the telescope is continually reoriented to track the apparent position of the guide star, an artificial, but accurately calculable, periodically varying angle between the gyros and the readout devices is introduced. This allows the precise measurement of the voltage-to-angle scale factor. Measurement of this factor is optimized by a full year's worth of annual aberration data.

Finally, there is one more very important factor that must be addressed in calculating the final results of the GP-B experiment. We selected IM Pegasi, a star in our galaxy, as the guide star because it is both a radio source and it is visually bright enough to be tracked by the science telescope on-board the spacecraft. Like all stars in our galaxy, IM Pegasi moves relative to the solar system because of its local gravitational environment and because of galactic rotation. Thus, the GP-B science telescope is tracking a moving star, but the gyros are unaffected by the star's so called proper motion; their pointing reference is IM Pegasi's position at the beginning of the experiment. Thus, each orbit, we must subtract out the telescope's angle of displacement from its original guide star orientation so that the angular displacements of the gyros can be related to the telescope's initial position, rather than its current position. The motion of IM Pegasi with respect to a distant quasar has been measured with extreme precision over a number of years using Very Long Baseline Interferometry (VLBI) by a team at the Harvard-Smithsonian Center for Astrophysics (CfA) led by Irwin Shapiro, in collaboration with astrophysicist Norbert Bartel and others from York University in Canada and French astronomer Jean-Francois Lestrade. However, to ensure the integrity of the GP-B experiment, we added a "blind" component to the data analysis by insisting that the CfA withhold the proper motion data that will enable us to pinpoint the orbit-by-orbit position of IM Pegasi until the rest of our data analysis is complete. Therefore, the actual drift angles of the GP-B gyros, the quantities that are to be compared with the predictions of general relativity, will not be known until the very end of the data analysis process.

For additional information about the GPB project, go to the website http://einstein.stanford.edu/.

6th Edoardo Amaldi Meeting

Matthew Benacquista, Montana State University-Billings benacquista-at-msubillings.edu

The 6th Edoardo Amaldi Conference on Gravitational Waves was held at Bankoku Shinryoukan in Okinawa, Japan on June 19th to 24th. It was attended by approximately 200 participants. The maturity of the field of gravitational wave detection was reflected in the two sessions devoted to current detectors, three sessions on data analysis, and two sessions on research and development for advanced detectors. In addition to an overview session, there were also one session devoted to gravitational wave sources and one to LISA.

The reports on the status of current detectors stressed the approach to design sensitivity for the interferometers, remarkable improvements in duty cycle and bandwidth for the bar detectors, and the impending science run for the spherical resonant detector miniGrail.

TAMA reported the accumulation of over 3000 hours of data and the beginning of automated, crewless runs in late 2003. The increase in sensitivity has been up to four orders of magnitude at some frequencies in the sensitivity band and the detector is approaching design sensitivity. This has given TAMA sufficient sensitivity to observe the entire galaxy. The planned installation of the seismic attenuation system will offer improved sensitivity for the next planned science run in early 2006. LIGO reported that all three interferometers are within roughly a factor of 2 of design sensitivity and that the installation of a preisolator system for the Livingston interferometer has significantly reduced the impact of the local anthropogenic seismic disturbances. Virgo has been commissioning since November, 2003 and now, after a reduction in noise of 10^4 in one year, it is less than 2 orders of magnitude above design sensitivity at frequencies around 200 Hz and higher. Although the low fequency sensitivity is still several orders of magnitude above design sensitivity, continued noise hunting is expected to bring this level down as well. GEO continues in its role as both detector and prototype as its sensitivity has improved to within an order of magnitude of design in narrowband tuning at 1 kHz.

ALLEGRO has achieved a 95% duty cycle since May, 2004. It has run with 3 rotations during S4 of LIGO to search for a stochastic signal. Otherwise, it was run in parallel with the European bars as part of IGEC-2. Hardware improvements are planned for ALLEGRO in the near future. AURIGA reports a resolution of a problem of spurious peaks that had plagued it in early 2004. It has now achieved design sensitivity and a 95% duty cycle since May, 2005. They report remarkably stable, Gaussian noise over its broad 100 Hz bandwidth. The Nautilus/Explorer bars have now been running in coincidence since March, 2004 with an 85% duty cycle and a strain sensitivity of $\sim 3.5 \times 10^{-19}$ near 920 Hz. Finally, miniGRAIL anticipates the first science run in early 2006 after improvements in the sphere and the transducer.

The data analysis sessions yielded a variety of talks covering ongoing analysis on current data, as well as proposed analysis schemes for current and future data. Of particular interest from the talks on ongoing analysis was the results from Explorer/Nautilus '03 science run which has ruled out the suggestion of an excess of coincidences in the '01 science run. Although still too large to be of astrophysical interest, the upper limits on continuous wave strain amplitudes of $h \sim 6 \times 10^{-23}$ from LIGO are approaching an order of magnitude above astrophysically reasonable values. The reports on binary coalescence rates from LIGO are still far too large, but the scientific reach of more than 20 Mpc from S4 is beginning to become interesting. Improvements in the search for stochastic backgrounds with LIGO/ALLEGRO have also begun to approach limits achieved by big bang nucleosynthesis. A number of talks focused on progress in the development of joint data analysis projects between detectors. This is of significant interest as it heralds the development of a worldwide network of detectors. In particular, the outline of a new agreement for IGEC-2 is expected to produce significant improvements in performance of a search for events. Finally, an implementation of maximum entropy techniques was presented that may have implications for improved angular resolution of both ground-based and space-based interferometers.

The sessions on advanced detectors included summaries of the plans and progress for improving existing detectors as well as designs for completely new detectors. For most of the existing interferometers, the anticipated improvements are expected to come from better seismic control at low frequencies, higher power lasers at high frequencies, and lower thermal noise in the mid-band. Advanced LIGO is now planning for installation at LLO in 2010 with commissioning runs expected to begin in 2012. Improved Virgo is still in the creative stage but is studying similar solutions to improve the sensitivity. Progress is reported on LCGT which will achieve its improved sensitivity by going underground and going cryogenic. They have begun testing mirrors for thermal noise in cryogenic conditions, and have measured significantly improved seismic noise at the planned site. The first underground cryogenic interferometer, CLIO, reports that construction is ongoing with the completion of the vacuum system and significant parts of the cryogenic systems.

Overall plans for improving the existing bar detectors have focused on increasing sensitivity by going to lower temperature, and increasing bandwidth by improving transducers and amplifiers. Most reports focused on new transducer technology and double SQUID amplifiers. Progress is being made on the Brazilian spherical detector. Work is ongoing with the DUAL detector, which anticipates achieving a wide bandwidth by nesting two bars with different resonant frequencies. Progress is reported on the development of transducers for this arrangement.

Research and development in advanced detectors has covered a number of areas for improving sensitivity. Work on squeezed light has continued with a goal of beating the quantum limit. Improvements in high power lasers were reported, along with the necessary work on improved thermal noise properties and coatings for mirrors. Alternate beam shapes (flat top profiles) have also been investigated.

The session devoted to LISA was more devoted to LISA Pathfinder, the upcoming technology demonstrator with a planned launch in 2009. The planning and design of LTP is almost completed and testing indicates that it approaches or exceeds the requirements. Construction is now underway. The ongoing design and testing of the LISA gravitational reference systems at Trento using their torsion pendulum is also approaching the LTP requirements and the capabilities of the pendulum are now limiting further testing. In addition to LISA, there were talks about possible designs for the gravitational reference system of the proposed LISA follow-on mission (BBO). An update on DECIGO, the proposed Japanese deciHertz detector, reports progress and a possible launch date of 2022. Details of the model dependence of the probable Galactic white dwarf binary background were presented as well as a discussion of testing the non-linear aspects of gravity with LISA.

The session on sources included an overview of expected sources for ground-based detectors, focusing mainly on compact object inspirals. Of particular note was a seven-fold increase in the expected event rate for neutron star inspirals based upon the observation of J0737-3039. Additional work on numerical simulation of waveforms using Whisky was reported. This will be of value to both ground-based and space-based interferometers. A detailed study of a simulation of the white dwarf binary population that included mass transfering systems was presented as a background signal for LISA. Finally, at the high frequency end of the spectrum, the potential for Low-Mass X-ray Binaries to excite f-modes may provide gravitational wave signals at high frequencies.

This was an exciting meeting as several detectors are now operating and producing data, while at the same time work is progressing toward the implementation of second generation detectors. Meanwhile, a number of collaborative efforts are underway that promise to usher in the era of a world-wide network for the detection of gravitational radiation. The next Amaldi meeting, to be held in Sydney, should be equally exciting as much of the progress reported here will be producing results in two years.

Workshop on Numerical Relativity, Banff International Research Station

Carsten Gundlach, University of Southampton C.Gundlach-at-maths.soton.ac.uk

The workshop was organized Doug Arnold, Matt Choptuik, Luis Lehner, Randy LeVeque and Eitan Tadmor, with the purpose of bringing together researchers in GR working numerically and analytically. 20 invited half-hour talks were given over 4 days, with plenty of time for discussions between talks, over meals, and in the evening.

The BIRS page on the programme can be found on

http://www.pims.math.ca/birs/

and Matt Choptuik's page including PDF files of talks is

http://bh0.physics.ubc.ca/BIRS05/

To complement this, I shall highlight only a few of the talks.

In the 1990s, some researchers were concentrating on obtaining physics insight from effectively 1+1 dimensional problems: what cosmological spacetimes with two commuting Killing vectors can tell us about the nature of generic singularities (Berger and collaborators), and what we can learn about cosmic censorship from spherical collapse (Choptuik and students). More ambitious, axisymmetric or 3D, work confronted overlapping problems hard to disentangle in the low resolution available in 3D. In particular, instabilities already present in the continuum problem were not clearly distinguished from those added at the discretization stage. The Banff meeting showed that now at least we have a clearer view of the problems facing us.

3+1 approaches need to start from a well-posed initial-boundary value problem in the continuum, with boundary conditions that are compatible with the constraints. Well-posedness can be proved by energy methods, based on a symmetric hyperbolic form of the field equations. *Olivier Sarbach* drops the energy estimate based on the symmetrizer in favor of a "physical" energy plus a constraint energy. The remaining "gauge" energy is estimated separately using elliptic gauge conditions. This intuitively appealing programme has been completed for electromagnetism, although the gauge seems a bit restrictive. Work with Nagy is under way on general relativity. By contrast *Oscar Reula* emphasized that strong hyperbolicity is often enough. He could prove that whenever a first-order system subject to constraints is strongly hyperbolic (eg the BSSN formulation) then so is the associated constraint evolution system. *Heinz Kreiss* surprised some of his disciples in the numerical relativity community by also stressing that energy methods are too limited. In a series of examples, he proposed a general approach based on reducing initial-boundary value problems to half-space problems with frozen coefficients and analyzing the dependence of each Fourier mode on its initial and boundary data.

On the numerical methods front, *Manuel Tiglio* reported on collaborative work to discretize systems of first-order strongly hyperbolic equations on multiple touching patches (for example 6 cubes to form a hollow sphere), using summation by parts and penalty methods. Their animations of toy problems looked very impressive, and the whole technology will be available as a general tool through the Cactus infrastructure. *Michael Holst* and *Rick Falk* gave review talks on finite elements for both elliptic and evolution equations. This is promising for nontrivial domains, but has not yet been applied to numerical relativity.

Other talks showed what 3D simulations can do. *David Garfinkle* reported on simulations of cosmological singularities without any symmetries on T^3. The key elements of his approach are the use of inverse mean curvature flow slicing ($\alpha = 1/K$) and a tetrad and connection formulation used successfully by Uggla and coworkers in analytical studies. His results are compatible with the BKL conjecture, although soon the resolution becomes too low to follow the development of ever more decoupled Bianchi IX regions. *Thomas Baumgarte* summarized the state of the art in binary neutron star simulations by himself and others, notably Masaru Shibata. There seems to be no real showstopper for such simulations. Rather what is needed now is more resolution, and the modelling of physical phenomena such as neutrinos, viscosity, and magnetic fields. Interesting results include the formation in binary mergers of a hot neutron star held up only by differential rotation, and expected to collapse later.

The most noted talk of the meeting was that of *Frans Pretorius* giving preliminary results on binary black hole mergers using harmonic coordinates. His simulations no longer seem to be limited by instabilities, but rather by computer power and time, and by unphysical initial data (there is evidence that his initial data are very far from circular inspiral data). The key ingredients seem to be the following: a working 3D AMR code on still massive computers, compactification of the Cartesian spatial coordinates (that is, at i_0) together with damping of outgoing waves, modified harmonic coordinates, and a damping of the harmonic gauge constraint through lower order friction terms (Gundlach). Generalized harmonic gauge (Friedrich) is $\Box x^\mu = H^\mu$, where the gauge source functions H^μ are treated as given functions. Pretorius makes H^0 obey a wave equation $\Box H^0 \sim \alpha - 1$, which prevents the lapse from collapsing without affecting the well-posedness. This works less well for critical collapse.

8th Capra Meeting on Radiation Reaction

Leor Barack, University of Southampton L.Barack-at-maths.soton.ac.uk

The *Capra* meetings are annual gatherings of theorist working on the problem of radiation reaction in General Relativity. Previous meetings were held in Southern California (in 1998, at a ranch donated to Caltech by former Caltech alumnus, Hollywood director Frank Capra), Dublin, Caltech, Potsdam (Germany), Penn State, Kyoto, and Brownsville (Texas). The Capra meetings focus on the study of radiation reaction and self interaction ("self force") in curved spacetime, especially in the context of the general relativistic two-body problem. Recent interest in this problem has been strongly driven by the prospects of detecting gravitational waves from inspirals of compact objects into supermassive black holes, using the planned LISA detector. There has been a remarkable progress over the last few years on the problem of modeling such inspirals, much through the work of the Capra community.

This year's meeting—the eighth in the series—took place July 11-14th in Abingdon (Oxfordshire), UK. Organized jointly by the Southampton Relativity Group (N. Andersson, L. Barack, K. Glampedakis) and the Centre for Fundamental Physics at RAL (R. Bingham), the meeting was hosted at RAL's *Cosener's house*—a conference facility situated at a picturesque Thames side in the grounds of the medieval Abbey of Abingdon. 41 researchers attended the meeting this year, representing universities in 8 countries. The scientific agenda included 1-hour contributed talks, with a significant portion of the time reserved for questions and discussion. The topics covered ranged from issues in the fundamental formulation of self forces in curved spacetime, through advances in black hole perturbation theory, to actual computations of the self force effect in black hole orbits. The last part of the meeting focused on detection aspects and data-analysis strategies.

The meeting opened with a user-friendly "self-force primer" by Steve Detweiler (Gainesville). Eric Poisson (Guelph) followed with a talk on the metric of tidally distorted black holes, and Warren Anderson (Milwaukee) presented results from an analytic computation of the local tail contribution to the gravitational self force. Leor Barack (Southampton) concluded the first day with a talk on the Lorenz-gauge formulation of black hole perturbation theory, with applications to self force calculations. In the second day of the meeting, Dong-Hoon Kim (Gainesville) presented his calculation of the "regularization parameters" necessary for calculating the gravitational self-force on particles in circular orbits around Schwarzschild black holes. Steve Detweiler then showed how these can be used to deduce some gauge-invariant self-force effects for such orbits. Hiroyuki Nakano (Osaka City University) next explained how to derive the regularization parameters for generic orbits in Schwarzschild, and was followed by Waratu Hikida (Kyoto), who presented first results from calculations of the scalar self-force for eccentric orbits. Sophiane Aoudia (Nice) discussed the calculation of the regularization parameters in the case of a particle plunging radially into a black hole. A fully-numerical approach to the problem was introduced by Carlos Sopuerta (Penn State), who presented first results from time-domain finite-element numerical simulations of extreme-mass-ratio inspirals.

The third day of the meeting was opened by Carlos Lousto (Brownsville) with a talk on recent progress on the problem of reconstructing the metric perturbation in black hole spacetimes. This was followed up by Bernard Whiting (Gainesville), who discussed further ideas on how one might go about reconstructing the metric perturbation in Kerr spacetime, and by Larry Price (Gainesville) who presented a useful Maple toolkit for carrying out calculations in the

GHP approach to Kerr perturbations. Eran Rosenthal (Guelph) wrapped up this part of the meeting with a talk on regularization of the second-order self force.

In opening the final, “detection aspects” part of the meeting, Jonathan Gair (Cambridge) presented work done to develop a set of “quick and dirty” approximate waveforms for extreme-mass-ratio inspirals, which had been used to scope out data-analysis issues. Norichika sago (Osaka) reviewed the underlying formalism for an alternative set of approximate waveforms, based on a form of adiabaticity assumption and a time-averaging procedure. A numerical code for calculating such adiabatic waveforms was presented by Steve Drasco (Cornell) at the beginning of the last day of the meeting. He argued that such waveforms are likely to be sufficiently accurate to enable detection of extreme-mass-ratio inspirals with LISA, but perhaps not accurate enough to allow full extraction of system parameters. Next, Kostas Glampedakis (Southampton) presented a formalism that could be used to quantify deviations from Kerr geometry, as encoded in the waveforms from extreme-mass-ratio inspirals. Jonathan Gair then discussed the challenges and work done on developing data-analysis techniques for searching over inspirals in the LISA data stream. Gareth Jones (Cardiff) described a search method based on an algorithm for identifying “clusters and ridges” on a time-frequency spectrogram. Alberto Vecchio and Alexander Stroeer (Birmingham) presented a data analysis scheme for detecting interacting white-dwarf binaries, with lessons for detection of extreme-mass-ratio inspirals. Finally, Charles Wang (Aberdeen) discussed the consequences of photons interacting with gravitational waves from compact objects.

An electronic version of all talks given in the meeting is available online at

http://www.sstd.rl.ac.uk/capra/

The organizers acknowledge the generous financial support of RAL and the IOP Gravitational Physics Group.

Theory and experiment in quantum gravity

Elizabeth Winstanley, University of Sheffield E.Winstanley-at-sheffield.ac.uk

Quantum gravity is a wide-ranging subject, with many different theoretical approaches and the exciting possibility of probing quantum gravity phenomenology in the near future. The aim of this meeting was to give an overview of current research in at least some areas of quantum gravity, both theoretical and experimental. The talks were pedagogical in nature and accessible to PhD students, and the meeting informal, with plenty of time for discussion. The meeting was held in the Ogden Centre for Fundamental Physics, University of Durham, on July 7-8, and organized by Ruth Gregory (Durham) and Elizabeth Winstanley (Sheffield).

The first day began with three talks on theoretical approaches to quantum gravity. Fay Dowker (Imperial College London) gave an introduction to the concept of causal sets and the new construction of swerves for particle paths on a causal set; John Barrett (Nottingham) reviewed current research in spin foams and the latest developments in $3 + 0$-dimensional quantum gravity; and Bernard Kay (York) introduced the theory of quantum field theory in curved space, and its applications to the Casimir effect and black hole radiation. The second session of the first day was devoted to higher dimensions and branes. Tony Padilla (Oxford) explained the particular features of brane world gravity, and focussed on the idea of braneworld holography; and Christos Charmousis (Orsay) covered higher derivative (particularly Lovelock) gravity, and its importance for $4+N$-dimensional spacetimes. The first day ended with a talk by Panagiota Kanti (Durham) on the Hawking radiation of higher-dimensional brane black holes.

The second day began with cosmology: Ian Moss (Newcastle-upon-Tyne) spoke about quantum effects in brane cosmology, and the role of boundary conditions in Horava-Witten theory. Ivonne Zavala (Boulder) brought us up-to-date with developments in brane inflation in string theory. Then the emphasis changed to experimental areas: Joy Christian (Oxford) explored the forthcoming experimental possibilities of probing the Planck scale with cosmogenic neutrinos, and Giles Hammond (Birmingham) introduced the new experiments testing the Casimir force and the inverse square law at short range.

This two-day meeting was attended by over 60 people, including many graduate students. The organizers would like to thank the Mathematical & Theoretical Physics and Gravitational Physics Groups of the Institute of Physics for financial support.