MATTERS OF GRAVITY

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

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Editorial

As announced in the last edition, this is the last number I edit. From now on editorship will fall upon our recently elected vice-chair, David Garfinkle. We all wish David good luck with his new responsibilities.

In addition to the election of vice-chair, Alessandra Buonanno and Bob Wagoner were elected to the executive committee. The two modifications to the bylaws (creation of the membership coordination post and correction of a typo in the number of members of the nominating committee) were approved overwhelmingly in the ballot.

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 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.

GGR program at the APS April meeting in Dallas

Jorge Pullin, Louisiana State University pullin-at-lsu.edu

We have an exciting GGR related program at the upcoming APS April meeting in Dallas, Texas, April 22-25 2006. Early registration deadline is February 24. Our chair elect, Éanna Flanagan did a remarkable job putting this program together.

0. Plenary talk on LIGO Speaker: Gabriela González

I. Ground-based Gravitational Wave Detection (Saturday, April 22, 1:30pm)
Chair: Benjamin Owen (joint with Topical Group on Precision Measurements)
Mike Zucker — Status of LIGO
Patrick Brady — Results from LIGO observations I
Patrick Sutton — Results from LIGO observations II

II. Experimental Tests of General Relativity (Saturday, April 22, 3:30pm)
Chair: Marc Favata
John Anderson — Anomalous Acceleration of Pioneer 10 and 11
Slava Turyshev — Science, Technology and Mission Design for the Laser Astrometric Test of Relativity
Eric Adelberger — Tests of the gravitational inverse-square law at the dark-energy length scale

III. Theories of Gravity, Dark Energy and Cosmology (Sunday, April 23, 10:30am)
Chair: Sean Carroll (joint with Division of Particles and Fields)
Shamit Kachru — String Theory and Cosmology
Nima Arkani-Hamed — Implications of the Accelerating Universe for Fundamental Physics
Roman Scoccimarro — Differentiating between Modified Gravity and Dark Energy

IV. Precision Cosmology (Sunday, April 23, 1:15pm)
Chair: John Beacom (joint with Division of Astrophysics)
Lyman Page — Recent Results from WMAP
Josh Frieman — Probing Dark Energy with Galaxy Clusters
Daniel Eisenstein — Acoustic Oscillations in Galaxy Large-Scale Structure

V. Advances in Numerical Relativity (Sunday, April 23, 3:15pm)
Chair: Deirdre Shoemaker (joint with Division of Computational Physics)
Frans Pretorius — Simulations of Binary Black Hole Mergers
Larry Kidder — Numerical Simulation of Binary Black Holes
Thomas Baumgarte — Neutron Stars in Compact Binaries
David Garfinkle — Numerical simulations of generic singularities

VI. Gravitational Wave Sources and Phenomenology (Monday, April 24, 10:45am)
Chair: Gabriela González (joint with Division of Astrophysics)
Curt Cutler — Overview of LISA Science

Alessandra Buonanno — Source-modeling, detection and science of gravitational waves from compact binaries
Coleman Miller — Gravitational Radiation from Intermediate-Mass Black Holes

VII. Heineman prize session (Tuesday, April 25, 10:45am)
Chair: Pierre Sikivie (joint with Division of Particles and Fields)
Citation: "For constructing supergravity, the first supersymmetric extension of Einstein's theory of general relativity, and for their central role in its subsequent development."
Sergio Ferrara — Current topics in the theory of supergravity
Daniel Freedman — Supergravity and the AdS/CFT Correspondence
P. van Nieuwenhuizen — Supergravity

VIII. Focus session on Numerical Relativity
Lead Speaker: Greg Cook — Status of Initial Data for Binary Black Hole Collisions

IX. Focus session on Space-Based Gravitational Wave Detection
Lead Speaker: Neil Cornish — The LISA Observatory: Preparing for a bountiful harvest

X. Focus session on Recent Results in Quantum Gravity
Lead Speaker: Lee Smolin — Physical predictions from loop quantum gravity

We hear that...

Jorge Pullin, LSU pullin-at-lsu.edu

Bruce Allen, Peter Fritschel and Don Marolf were elected fellows of the APS.

Ruth Gregory won the Maxwell Medal of the Institute of Physics (UK).

Alessandra Buonanno and Nergis Mavalvala were awarded Sloan fellowships.

Hearty Congratulations!

100 Years ago

Jorge Pullin pullin-at-lsu.edu

An English version of "On the dynamics of the electron" by Henri Poincaré, is available at http://www.phys.lsu.edu/mog/100

What's new in LIGO

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In an important sense, LIGO has recently turned a corner in its history: It has moved from the commissioning to the observation phase.

Since the last MOG, a number of technical issues have been addressed in all three interferometers. Increases in the laser input power, tuning of the system which compensates for the thermally-induced focusing in optics, work on reducing scattered light paths and acoustic excitation of optic motion, and control-law optimizations are among the specific efforts. This has both improved the strain sensitivity as well as increased the duty cycle of operation of the instruments.

The result is that the two 4km interferometers exceed the performance promised in the 1995 LIGO Science Requirements Document of a sensitivity of 10^{-21} in strain for a 100 Hz bandwidth, with the 2km interferometer also functioning well given its shorter length. The LIGO Scientific Collaboration had given its agreement to proceeding with the definitive S5 science run at the August LSC meeting, and the NSF Annual Review of LIGO held in November 2005 also confirmed that the target sensitivity was achieved.

The S5 science run, underway since mid-November 2005, is intended to collect one year of integrated coincidence data between the two LIGO Observatories. We plan to take breaks in observation from time to time to implement small improvements, and repair any equipment that breaks down during the run. Some observation time is lost to maintenance, and the first stage of construction of an Outreach center at Livingston will impact the day-time duty cycle of that instrument for the beginning of the run. All factors taken into account, we plan to run for about 1.5 years to accumulate these data.

Online (near real time) data analysis tools are characterizing the data on-the-fly, helping the staff optimize the instruments and recognizing quickly any problems that need to be addressed. The four basic searches, for signals with the character of bursts, a stochastic background, periodic or quasi-periodic, and binary inspiral signatures, are being applied to the data, and the LSC plans to keep the analysis process active continuously throughout the run.

Analysis continues on the previous science runs, with better upper limits on a variety of sources established and new techniques exercised which will be employed also in the S5 analysis. Papers have appeared or accepted on searches for periodic sources ("First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the hough transform") and on burst searches 'triggered' by GRB signals ("Search for gravitational waves associated with the gamma ray burst GRB030329 using the LIGO detectors"). A variety of other publications is in preparation; searching on gr-qc for 'the LIGO Scientific Collaboration' is an effective way to stay up-to-date.

Advanced LIGO has also made strides forward. The characterization of the mirror suspensions and of the seismic isolation systems has progressed, and full-scale prototypes of the suspensions and seismic isolation will converge for integrated testing at the MIT LASTI facility in the coming months. The 40m interferometer test bed at Caltech has successfully demonstrated the length control scheme for the Advanced LIGO signal- and power-recycled Fabry-Perot Michelson configuration. Extensive modeling has helped our understanding of thermal compensation, possible parametric excitation of mirror modes, and the requirements to be placed on the mirror figure. Four of the actual to-be-installed fused silica test masses, contributed by the UK, have been delivered and will go through a pathfinding process to identify polishing and coating techniques.

Advanced LIGO has also appeared in the recent 2007 budget materials from the OMB and the NSF as indicated for an FY2008 start. Although the official decision is still in the future, this is a strong indication of the support from the NSF and the interest in the government to support this field, and an affirmation of the LSC's very successful effort to advance the astrophysics and the instrument science to the point where all agree that this is timely. A baseline review will be held in late May 2006 to confirm the cost, schedule, risk handling, and technical plans, and we hope to be very busy with preparing for the start of the project from that point onward.

Last but not least: In the last MOG, we mentioned that the LIGO Laboratory was involved in a search for a new director. Jay Marx, formerly of LBNL, has accepted the position of Director, and we welcome him warmly to the Lab and the field.

LISA Pathfinder

Paul McNamara, ESTEC-ESA Paul.McNamara-at-esa.int

LISA Pathfinder (formerly known as SMART-2), the second of the ESA Small Missions for Advanced Research in Technology, is a dedicated technology demonstrator for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission.

The technologies required for LISA are many and extremely challenging. This coupled with the fact that some flight hardware cannot be tested on ground due to the earth induced noise, led to the LISA Pathfinder (LPF) mission being implemented to test the critical LISA technologies in a flight environment. The scientific objective of the LISA Pathfinder mission consists then of the first in-flight test of gravitational wave detection metrology.

LISA Pathfinder carries two payloads, the European provided LISA Technology Package (LTP) and the NASA provided Disturbance Reduction System - Precision Flight Control Validation (DRS PCFV), formerly known as the DRS.

Mission Goals

The mission goals of the LTP can be summarized as:

• demonstrating that a test-mass can be put in pure gravitational free-fall within one order of magnitude of the requirement for LISA. The one order of magnitude rule applies also to frequency, thus the flight test of the LTP on LPF is considered satisfactory if free-fall of one TM is demonstrated to within

$$S_a^{1/2}(f) \leq 3 \times 10^{-14} \left[1 + \left(\frac{f}{3\text{mHz}}\right)^2\right] \text{ms}^{-2}/\sqrt{\text{Hz}} \tag{1}$$

over the frequency range, f, of 1 to 30 mHz.

• demonstrating laser interferometry with a free-falling mirror (test mass of LTP) with displacement sensitivity meeting the LISA requirements over the LTP measurement bandwidth. Thus the flight test of LTP is considered satisfactory if the laser metrology resolution is demonstrated to within

$$S_{\delta x}^{1/2}(f) = 9.1 \times 10^{-12} \left[1 + \left(\frac{f}{3\text{mHz}}\right)^{-2}\right] \text{m}/\sqrt{\text{Hz}} \tag{2}$$

over the frequency range, f, of 1 to 30 mHz.

• assessing the lifetime and reliability of the micro-Newton thrusters, lasers and optics in a space environment.

LTP

The basic idea behind the LTP is that of squeezing one arm of LISA from 5×10^6 km to a few centimeters and placing it on board a single S/C. Thereby the key elements are two nominally free flying test masses (TM), and a laser interferometer whose purpose is to read the distance between the TM's (Figure 1).

The two tests masses are surrounded by their position sensing electrodes. This position sensing provides the information to a ”drag-free” control loop that, via a series of micro-Newton thrusters, keeps the spacecraft centered with respect to some fiducial point.

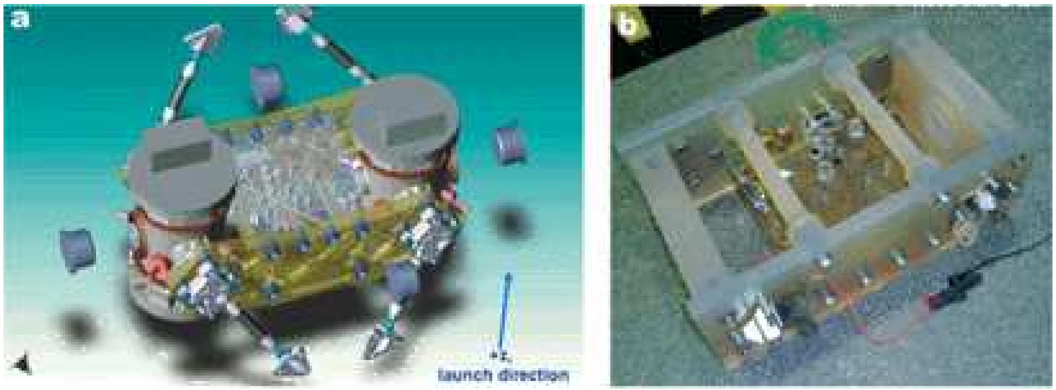

Figure 1: a) CAD drawing of the LISA Technology Package showing the two vacuum enclosures housing the test masses, and the optical bench interferometer (OBI), b) photograph of the EM of the OBI (vacuum enclosures replaced with *end plates*).

In LISA, as in LPF, each spacecraft hosts two test-masses. However these two test-masses belong to different interferometer arms. This has an important consequence for the logic of the spacecraft control. The baseline defined by the system level study for LISA, sees a control logic where the spacecraft is simultaneously centered on both test-masses. However the spacecraft follows each test-mass only along the axis defined by the incoming laser beam. The remaining axes have to be controlled by a capacitive suspension (or by some other controlled actuation scheme). On LPF however, in order to be able to measure differential acceleration, the sensitive axes of the two test-masses have to be aligned. This forces one to develop a capacitive suspension scheme that carries one or both test-masses along with the spacecraft, including along the measurement axis, while still not spoiling the meaningfulness of the test.

In LISA, the proper distance between the two free-falling test masses at the end of the interferometer arms is measured via a three step process; by measuring the distance between one test mass and the optics bench (known as the *local measurement*), by measuring the distance between optics benches (separated by 5 million kilometers), and finally be measuring the distance between the other test mass and its optics bench. In LISA Pathfinder, the optical metrology system essentially makes two measurements; the separation of the test masses, and the position of one test mass with respect to the optics bench. The latter measurement is identical to the LISA local measurement interferometer, thereby providing an in-flight demonstration of precision laser metrology directly applicable to LISA.

In LISA and in LPF, charging by cosmic rays is a major source of disturbance, thereby each test-mass carries a non contacting charge measurement and neutralization system based on UV photoelectron extraction. An in-flight test of this device is then obviously a key element of the overall LPF test.

Disturbance Reduction System - Precision Control Flight Validation

The DRS-PCFV is a NASA provided payload to be flown on the LISA Pathfinder spacecraft. When first proposed, the DRS payload closely resembled the LTP, namely in that it consisted of two inertial sensors with associated interferometric readout, as well as the drag-free control laws and micro-Newton colloidal thrusters, although the technologies employed were different from the LTP. However, due to budgetary constraints, the DRS was de-scoped, and now consists of the micro-Newton colloidal thrusters, drag-free and attitude control system (DFACS), and a micro-processor. The DRS-PCFV will now use the LTP inertial sensors as its drag-free

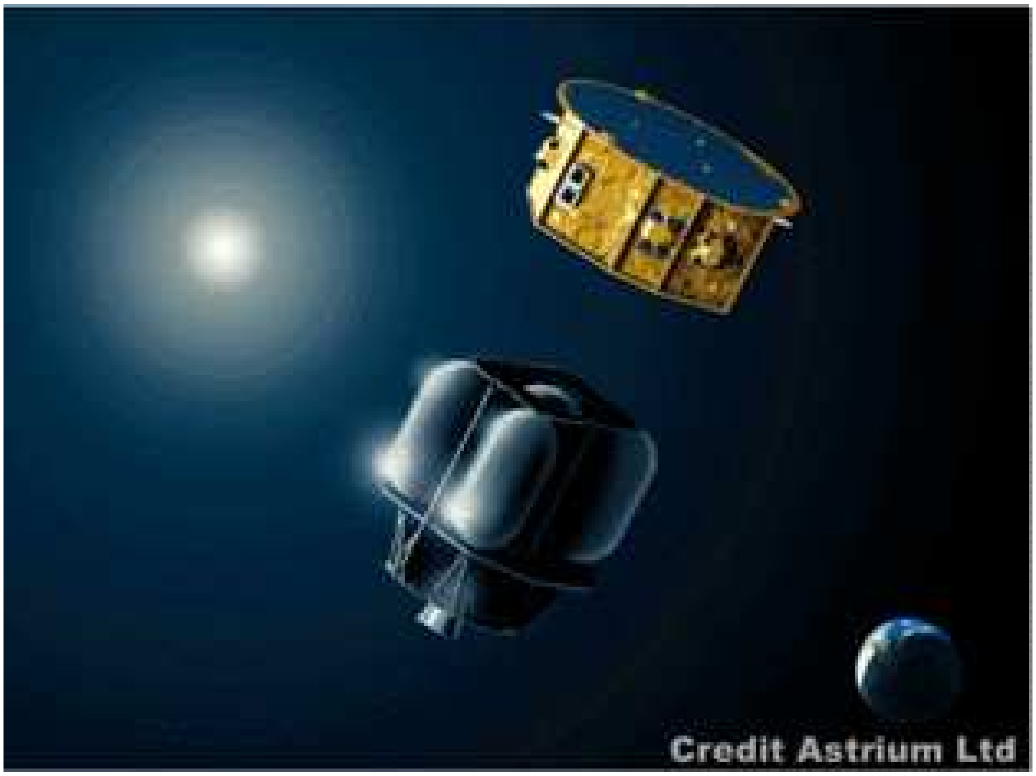

Figure 2: The LISA Pathfinder spacecraft separating from its propulsion module.

sensors.

The primary goal of the DRS-PCFV is to maintain the position of the spacecraft with respect to the proof mass to within $10\text{nm}/\sqrt{\text{Hz}}$ over the frequency range of 1-30mHz.

Launch and orbit

LISA Pathfinder is due to be launched in October 2009 on-board a dedicated launcher. Rockot is presently the baseline vehicle, while VEGA is considered the target vehicle that will be used if available. The spacecraft and propulsion module (Figure 2) are injected into a low earth orbit (200 x 900km), from which, after a series of apogee raising burns, will enter a transfer orbit towards the first Sun-Earth Lagrange point (L1). After separation from the propulsion module, the LISA Pathfinder spacecraft will be stabilized using the micro-Newton thrusters, entering a Lissajous orbit around L1 (500,000km by 800,000km orbit).

Following the initial on-orbit check-out and instrument calibration, the in-flight demonstration of the LISA technology will take place in the first half of 2010. The nominal lifetime of the mission is 180 days, this includes the LTP operations, the DRS operations, and a period of joint operations when the LTP will control the DRS thrusters.

Status

LISA Pathfinder is currently in Implementation Phase. The contract with the prime industrial contractor, Astrium UK, was signed in May 2004. During the last year, all ITTs for spacecraft subcontractors have been issued.

In October 2004, the Science Program Council (SPC) approved the LTP Multi-Lateral Agreement, detailing the national agency responsibilities for the construction of the LTP. All subcontracts for the LTP have started.

The project has also successfully completed a number of significant agency level reviews over the last year, including the Technology Readiness Review, the LTP Preliminary Design Review, System Preliminary Design Review, and the Mission Preliminary Design Review. Also, all the LTP subsystems have undergone PDR within the last year.

With the deletion of the GRS from the DRS, it was recommended that the DRS undergo a joint ESA/NASA delta-Critical Design Review (δ-CDR)/Risk Review. This was completed successfully in January 2006.

The first LTP subsystem flight hardware is due to be delivered to the LTP Architect (Astrium GmbH) during the third quarter 2006. The delivery of the assembled and tested LTP instrument to the prime contractor is scheduled for July 2008.

Recent progress in binary black hole simulations

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The past year has seen dramatic progress in numerical relativity simulations of binary black holes. A number of groups have reported significant advances and are now able to model the binary inspiral, coalescence and merger together with the emitted gravitational wave signal.

Simulating binary black holes has been a long-standing problem because it poses a number of "grand challenges". An incomplete list of these challenges includes the following

- Einstein's equations form a complicated, coupled set of non-linear PDEs, and it is far from clear which form of these equations is most suitable for numerical implementation.
- Somewhat related is the coordinate freedom, and the question what coordinate (or gauge) conditions lead to a non-pathological evolution.
- Black holes contain singularities, which can have very unfortunate consequences for numerical simulations.
- The individual black holes are much smaller than the wavelength of the emitted gravitational radiation. The resulting range in length-scales is difficult to accommodate in numerical simulations.

The different groups have approached these issues in different ways.

Pretorius (2005) first announced his new results at a numerical relativity workshop at the Banff International Research Station. Departing from numerical relativity convention he does not integrate a "3+1" decomposition of Einstein's equations that separates spatial and timelike parts, but instead discretizes the four-dimensional spacetime equations and their second derivatives directly. As suggested by a number of previous authors he introduces gauge source functions H_μ, in terms of which Einstein's equations reduce to wave equations for the components of the spacetime metric. In this formalism the coordinates are fixed through the gauge source functions (instead of the lapse and shift in 3+1 formalisms). Pretorius chooses H_t to satisfy a somewhat ad-hoc wave equation and $H_i = 0$ (which is related to spatial harmonic coordinates $H^i = 0$).

Pretorius uses black hole excision, whereby the black hole interior is removed from the computational grid. This is justified since the event horizon disconnects the interior causally from from the exterior. He also uses adaptive mesh refinement (AMR), which automatically allocates additional gridpoints in regions where they are needed to resolve small scale structures.

Several other features of his code are worth pointing out. The spatial coordinates are compactified, so that physically correct outer boundaries can be imposed at spatial infinity. He also introduces some numerical dissipation to control high-frequency instabilities, and added some "constraint-damping" terms that proved crucial for simulations of black holes.

With this code Pretorius has been able to simulate – without encountering a numerical instability – the inspiral and coalescence of black hole binaries through merger until late stages of the ring-down as the remnant settles into equilibrium. This is remarkable progress indeed.

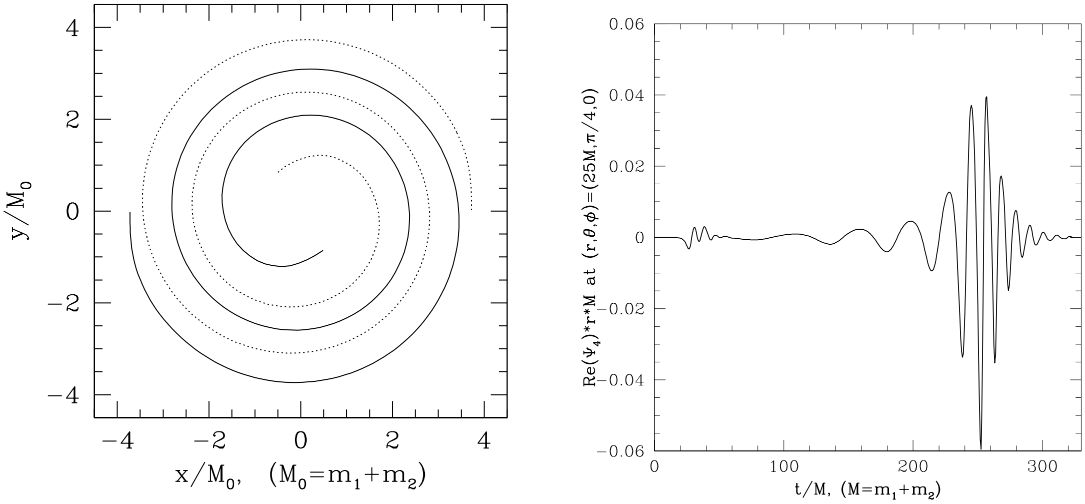

Figure 3: The left panel shows black hole trajectories in a recent binary black hole simulation of Pretorius (2006, private communication), starting with an initial data configuration of Cook and Pfeiffer (2004). The right panel shows the corresponding "gravitational waveform" $Re(\psi_4)$.

Figure 1 shows the trajectory of an inspiraling black hole binary and a gravitational waveform from his very recent calculation that adopts the state-of-the-art initial data of Cook and Pfeiffer (2004).

Following Pretorius' success four other groups (Campanelli *et.al.* (2005), Baker *et.al.* (2005), Diener *et.al.* (2005) and most recently Herrmann *et.al.* (2006)) have announced significant progress in their binary black hole simulations. All of these calculations have several features in common. They all use finite-difference implementations of the BSSN equations[1], which are based on a 3+1 formalism in contrast to Pretorius' four-dimensional approach. They also use very similar gauge conditions, namely "1 + log" slicing for the lapse, and a "driver" implementation of "Gamma-freezing". Finally they all use "puncture" initial data, which are constructed by absorbing the singular terms in the black hole interior into an analytical expression and solving for regular corrections.

The approach of Campanelli *et.al.* (2005) and Baker *et.al.* (2005) differs from the others in that they do not excise the black hole interiors, and instead continue to use the "puncture" approach to handle the singularities during the evolution. Campanelli *et.al.* (2005) introduce a new variable that is the inverse of the diverging term. This new term vanishes at the "punctures", and given suitable gauge conditions all equations remain regular. Baker *et.al.* (2005) finite difference the diverging term directly, but arrange the computational grid in such a way that the singularity never encounters a gridpoint. In situations with equatorial symmetry, when both singularities reside on the equatorial plane, this can always be achieved simply by using cell-centered differencing schemes. The two calculations also use different grid structures and differencing; Campanelli *et.al.* (2005) adopt 4th order differencing on a uniform grid

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[1] In the BSSN formalism a set of auxiliary connection functions Γ^i is introduced that simplify the three-dimensional Ricci tensor ${}^{(3)}R_{ij}$ in the same way as the H^μ simplify the four-dimensional Ricci tensor ${}^{(4)}R_{\mu\nu}$ in the formalism adopted by Pretorius.

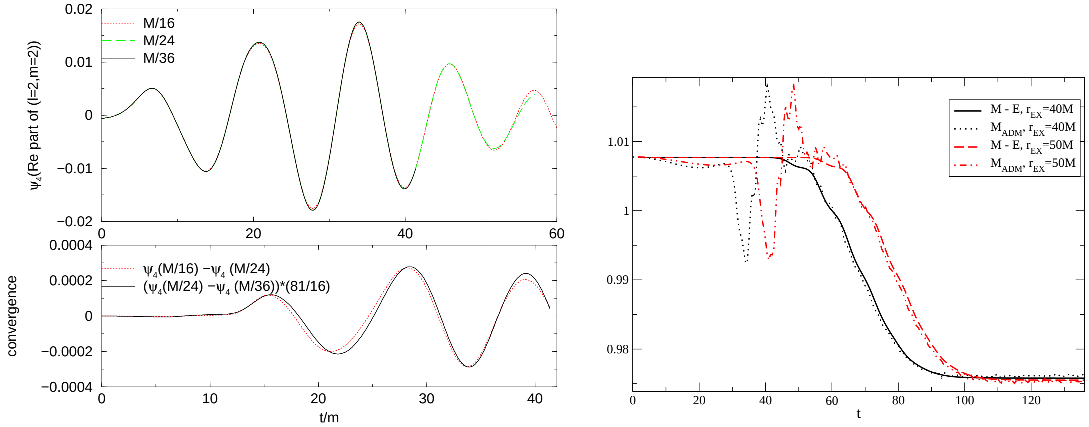

Figure 4: Left Panel: The gravitational waveform $Re(\psi_4)$ in the calculation of Campanelli *et.al.* (2005). This convergence test demonstrates 4th order convergence. Right Panel: Demonstration of energy conservation in the calculation of Baker *et.al.* (2005). The initial energy M minus the energy E lost in gravitational radiation agrees with the current total energy $M_{\rm ADM}$ to high accuracy.

but introduce a "fish-eye" coordinate that provides additional resolution for the black holes, while Baker *et.al.* (2005) use 2nd order differencing and FMR in an inertial coordinate system. Figure 2 shows a gravitational wave form from Campanelli *et.al.* , and a demonstration of energy conservation from Baker *et.al.* . Both groups also report satisfactory agreement with earlier "Lazarus" results which combines numerical relativity with perturbative techniques (e.g. Baker *et.al.* (2001)).

Diener *et.al.* (2005) report on impressive improvements of their earlier results (Alcubierre *et.al.* (2005); compare Brügmann *et.al.* (2004)). Like Pretorius, they use black hole excision to eliminate the curvature singularities in the black hole interior. They use a fixed mesh refinement (FMR) in a corotating coordinate system to resolve the black holes. A schematic of their black hole trajectories is shown in the left panel of Figure 3. Starting from an initial proper separation of about 9 M the black holes spiral toward each other until a common apparent horizon forms after about 1.5 orbits. Diener *et.al.* (2005) also demonstrate that the spurious effect of finite difference error on the binary orbit depends on the gauge condition. All gauge choices converge to the same physical solution, as expected, but at finite resolution different choices may lead to either a widening or closing of the orbit, which helps to explain earlier discrepancies (compare Brügmann *et.al.* (2004), Alcubierre *et.al.* (2005)).

The simulations of Campanelli *et.al.* (2005) and Baker *et.al.* (2005) demonstrate that standard numerical relativity codes can handle binary black holes with only very minor modifications, potentially opening the field to a number of other groups. Herrmann *et.al.* (2006), for example, adopt a technique very similar to that of Baker *et.al.* (2005). While all other simulations focus on equal-mass black holes they consider unequal-mass black holes with mass ratios $q = M_1/M_2$ ranging from unity to 0.54. Their calculation represents a first step toward analyzing the effect of binary parameters – including mass ratios and black hole spins – on the gravitational waveforms in fully dynamical simulations (even if the astrophysical relevance of their initial data is somewhat limited). They also see evidence for gravitational radiation recoil leading to a remnant "kick" (compare the right panel of Figure 3).

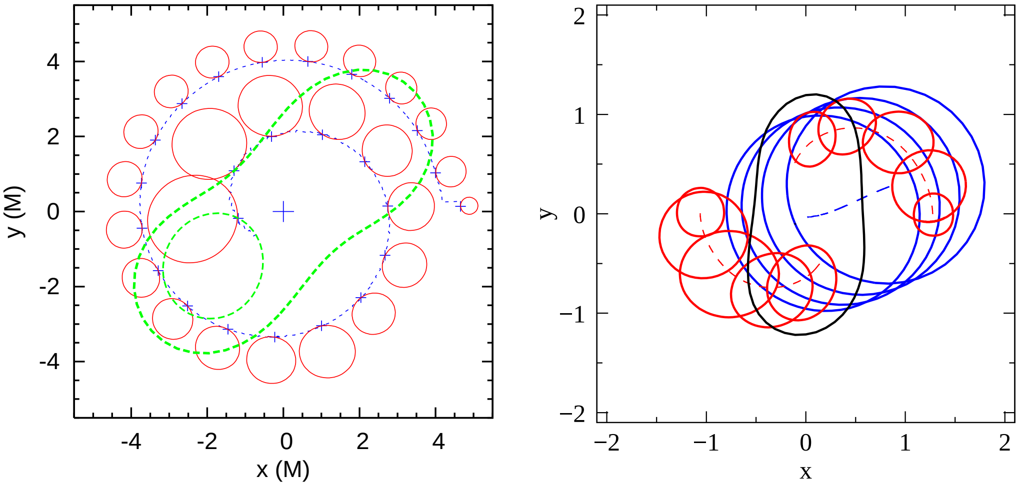

Figure 5: Left Panel: Motion of one of the black holes with time in the simulation of Diener *et.al.* (2005). Cross-sections of the apparent horizon (AH) with the equatorial plane are shown at intervals of $\Delta t = 5M$. The apparent growth of the AHs with time is a pure coordinate effect. The first appearance of a common AH at $t = 124M$, and the corresponding final detached AH, are shown as dashed lines. Right Panel: Snapshots of the apparent horizon locations for the $q = 0.85$ unequal-mass binary calculation of Herrmann *et.al.* (2006). The snapshots are taken every 4 $M_{\rm ADM}$ prior to merger (red) and every 17 $M_{\rm ADM}$ after merger (blue). The trajectories of the common horizons' centers are shown as a dashed lines.

All of these calculations can clearly be improved in multiple ways. However, especially comparing with the situation just a year ago, it is quite remarkable and reassuring that different groups using independent techniques and implementations can now all carry out reliable simulations of binary black hole coalescence and merger. It may soon be possible to simulate the black hole binary inspiral starting from a sufficiently large binary separation so that it can be compared with and matched to post-Newtonian predictions. The past year has indeed seen dramatic progress in numerical relativity simulations of binary black holes.

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Workshop on Emergence of Spacetime

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On the weekend of November 18 the Perimeter Institute hosted a workshop on the emergence of spacetime. The workshop was organized by B. G. Sidharth from the Birla Science Centre in Hyderabad, Lee Smolin from the Perimeter Institute, and Olaf Dreyer, now at Imperial College London.

The aim of the workshop was to discuss a problem that all quantum theories have in common: How does a classical spacetime emerge? This problem of emergence has a technical and a conceptual component. The technical part is that it is usually very hard to infer details of the dynamics for a given large quantum system. The conceptual problem is the added difficulty that arises when a basic concept such as time is to emerge, as is widely expected to be the case in quantum gravity. The workshop was conceived to address both these issues.

To shed light on the technical problem we invited solid state physicists to the workshop. The solid state community has always dealt with large quantum systems and has developed techniques to describe their dynamics. This community has in particular stressed the importance of emergence. Large quantum systems can have properties that emerge on the level of the whole system but do not make sense on the level of the constituents. In recent years, members of the solid state community have started to see this emergent point of view as a paradigm for all of physics including gravity. Their views then also provide a new take on the conceptual problem.

In order to allow for in depth discussions the workshop limited the number of formal talks. All formal presentations were given on Friday. The speakers were Grigori Volovik, Renate Loll, Xiao-Gang Wen, Fotini Markopoulou, Peter Horava, and Seth Lloyd. These presentations set the stage for the weekend where the atmosphere was much more informal. The presentation can be found on the website of the Perimeter Institute http://www.perimeterinstitute.ca.

The in-depth discussions on the weekend lasted one to two hours and consisted of a short presentation on the black board followed by a long set of questions. This format allowed the participants to really familiarize themselves with the different approaches and see their advantages as well as their shortcomings. The final overview on Sunday was unique in that it reviewed all the approaches and listed their pros and cons. I think this last part was a first in a workshop on quantum gravity.

The point of view presented by Grigori Volovik posits that the physics we see around us is described by the ground state of a fermionic many body system. Such ground states are characterized by the topology in momentum space. The relevant momentum space topology for us is that of a Fermi point. These are points on the Fermi surface where the excitations become gapless. The physics near such a Fermi point is remarkable in that it looks a lot like current high energy physics. Lorentz invariance, gauge symmetries and also a dynamic metric are all emerging.

Renate Loll presented exciting new results in causal dynamical triangulations. Having worked their way up from two and three dimensions they have now arrived at four dimensions. The results so far are promising in that they show the correct dimensionality of four emerging at large scales. A very curious feature of the approach seems to be that at Planck scale the dimensionality becomes effectively two. The significance of this observation is not yet clear.

A presenter that stayed clear of quantum gravity proper was Xiao-Gang Wen. His presentation focused on the other pillars of our current understanding of fundamental physics: fermions and gauge interactions. Wen showed how these objects could emerge from a fundamental theory made up of simple quantum spins. A ground state of the system called spin-net condensate has excitations that are fermionic and have interactions described by a gauge theory.

Fotini Markopoulou described her attempt to deal with the conceptual problems of quantum gravity. For her the spacetime should emerge from the interactions of persistent degrees of freedom. To define such degrees of freedom she introduced noiseless subsystems, a notion borrowed from quantum information. The persistent degrees of freedom are noiseless with respect to the evolution of the system.

A connection between solid state physics and string theory was shown by Peter Horava. The Fermi points introduced by Grigori Volovik also appear in the physics of D-branes. The formulae describing the behavior near a Fermi point used by G. Volovik turn out to be a special case of the Atiyah-Bott-Shapiro construction in K-theory. Peter Horava proceeded to use these constructions for a new kind of emergent spacetime in string theory.

A completely new approach to quantum gravity was presented by Seth Lloyd. His model is based on a quantum computer. He showed how every quantum computation can be viewed as a superposition of histories and how every such history can be viewed as a spacetime with matter. The quantum computation is thus a quantum superposition of spacetimes.

The most interesting outcome of the workshop is the path that a number of participants have chosen to address the conceptual part of the emergence problem. They have made progress by assuming a fiducial time. The interesting question is: Does this step invalidate the progress that has been made? The final discussion showed that it is still too early to decide. Crucial steps still remain to be taken. In the approach presented by Renate Loll recent results have shown that the dimensionality of the emergent spacetime is correct but it is still not clear whether gravity is correctly described.

Another thing that became clear during the workshop is that the time frame for quantum gravity is beginning to change. Quantum gravity research has been going on for more then sixty years and has not had much success. With such a time frame the expectations tend to erode and nobody seems to be rushed. With the results presented by Renate Loll and Seth Lloyd though this situation seems to change. These programs might be able to produce quantum theories of gravity in a time frame of a couple of years rather then decades.

The situation we would be facing then would be a new and welcome one. Instead of having no theory of quantum gravity we would have several competing ones. One would then have to decide which one of these is the correct theory. A task that will require the competing theories to make observable predictions. What a thrilling prospect.

Quantum gravity subprogram at the Isaac Newton Institute

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The Isaac Newton Institute programme "Global Problems in Mathematical Relativity", which spanned close to 5 months in the autumn of 2005, contained in October-November a four-week subprogramme on quantum gravity, organized by Abhay Ashtekar and Piotr Chruściel. While quantum issues did feature throughout the mathematical relativity programme, and especially during the black holes theme weeks in August-September, the purpose of the quantum gravity subprogramme was to focus on loop quantum gravity and related topics.

There were two formal and three informal seminars each week. The formal seminars were pedagogical, targeted at a classical relativity audience, while the informal seminars were more specialized. Questions raised at a formal seminar would typically set the agenda for the next informal seminar or two. In my perception this organization worked well in stimulating interaction between participants from different backgrounds, and the informal seminars often drew a substantial non-specialist audience. Outside the official activities there were numerous informal discussions on specific topics, and the celebrated layout of the institute building encouraged all interested to join these discussions. Several postdocs and research students from the Department of Applied Mathematics and Theoretical Physics (University of Cambridge) participated in the activities on a regular basis.

A main theme was the dynamics of loop quantum gravity, including the mathematical structure of the associated Hilbert spaces and the concomitant quantization ambiguities. Talks on these topics were presented by Jerzy Lewandowski, Alejandro Perez, Hanno Sahlmann and Thomas Thiemann. Abhay Ashtekar and Martin Bojowald gave talks on spacetime singularity avoidance in loop quantum gravity, mainly in the context of quantized cosmological models but with a view to black hole singularities. Carlo Rovelli's talk addressed the semiclassical limit of n-point functions in loop quantum gravity.

John Barrett reviewed spin foam models of quantum gravity in three and four dimensions. Jorma Louko addressed group averaging techniques in quantization.

Among the informal seminars, Chris Fewster gave a pedagogical introduction into algebraic quantum field theory in curved spacetime and discussed recent work on energy inequalities. Ian Moss and David Jennings talked about quantum field effects on accelerated brane worlds.

The London Mathematical Society organized an afternoon of three talks aimed at the general mathematical community. Abhay Ashtekar gave here an overview of loop quantum gravity, and Karsten Danzmann reviewed the status of gravitational wave observatories. Roger Penrose presented a new perspective on the Weyl curvature hypothesis, suggesting that the future infinity of a spacetime dominated by a positive cosmological constant could be conformally reinterpreted as the initial singularity of a new spacetime.

The subprogramme was intensive and will undoubtedly prove valuable. It was also fortuitous in overlapping with a Cambridge production of Carl Djerassi's play "Calculus", which dramatizes events around the Royal Society Committee that passed judgment on the Newton-Leibniz priority dispute. A number of participants went to see the play; however, none were to my knowledge among those audience members who were invited to the stage to become, if only momentarily, members of the Royal Society.

Global problems in Mathematical Relativity at the Isaac Newton Institute

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Appropriately coinciding with last year's centenary of Einstein's great papers, the Isaac Newton Institute in Cambridge, England, sponsored and hosted during 2005 a nearly 5 month long programme on "Global Problems in Mathematical Relativity". The programme (organized by Piotr Chrusciel, Helmut Friedrich, and Paul Tod) was remarkably rich, extensive, and varied. Included were weeks of concentration on each of the following topics:

–the analysis of hyperbolic PDEs, including Einstein's equations

–numerical relativity

–black holes

–Einstein's theory as a dynamical system

–applications of Riemannian geometry in general relativity

–applications of Lorentzian geometry in general relativity

–global analysis and global techniques

–quantum aspects of gravity

–asymptotic structures in general relativistic spacetimes

–the application of inverse scattering techniques to the studies of solutions of Einstein's equations

–static and stationary solutions

–the Einstein constraint equations and their solutions

Each of these concentration periods attracted researchers from all over the world. In addition to the 7 mathematical relativists plus 2 graduate students who were there for the entire programme from early August until the end of December, there were roughly 10 to 15 shorter term visitors during any given time. With a light schedule of 3 or 4 talks per week, the emphasis was on concentrated collaborations among the participants. It was not unusual to see intense black board sessions occurring at all hours from 7 in the morning until well past midnight. By last count, at least 26 papers submitted for publication have resulted from collaborations carried out during the programme.

In addition to the weekly schedule of talks included in the programme, there were 4 special conferences. One of them was held as a satellite meeting at Southampton University. It focussed on numerical relativity, and reported on some of the breakthroughs for binary black hole simulations that have happened just this past year. The other special conferences were held at the Newton Institute. The first of these, the week long Euroconference on "Global General Relativity", included talks on a very wide range of topics, from recent developments on quasilocal mass to the latest observational data pertaining to astrophysical black holes, and from numerical simulations of classical solutions to recently developed ideas on quantum field theory in curved spacetimes. This conference was very popular, attracting over 100 participants. Equally popular was the one day "Spitalfields Day" (co-sponsored by the London Mathematical Society), which consisted of three lectures on the general theme of "Einstein and Beyond". These less technical lectures, delivered by Abhay Ashtekar, Roger Penrose, and Karsten Danzmann, attracted standing-room-only audiences for discussions of gravitational radiation detection, quantum gravity, and the nature of the universe at late times. The five month long Newton Institute programme was capped by a week long Euroconference in December which focussed on studies of the Einstein constraint equations and on a number of related mathematical and physical themes. This conference particularly highlighted the very important symbiotic relationship between geometrical analysis and mathematical relativity.

In addition to publicizing some of the particular recent triumphs which have occurred in mathematical relativity (including gains in understanding the nature of gravitational fields near cosmological and black hole singularities, as well as the rapid development of powerful new techniques for studying the stability of black hole spacetimes), and in addition to providing a perfect environment for the development of collaborations among workers whose home bases are widely scattered around the globe, the Newton Institute programme served as an important notice to the community of mathematicians and physicists that mathematical relativity is a very healthy discipline, which has had a great impact on both physics and mathematics, and will continue to do so. As the programme broke up just before the end of the Einstein centenary year of 2005, the participants all hoped to soon have another opportunity to collaborate and to share ideas in such an ideal setting.

Loops '05

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In the Einstein year, the almost annnual conference on background independent approaches to quantum gravity took place at the Albert Einstein Institute in Potsdam, close to Berlin, Germany. The official title of the conference was 'Loops 05', however, not only Loop Quantum Gravity (LQG) researchers were present but also practitioners of the other non – perturbative approaches. Plenary talks were distributed among the following topics: 1. Asymptotically Safe Quantum Gravity, 2. Causal Sets, 3. Dynamical Triangulations, 4. Generally Covariant Algebraic Quantum Field Theory and 5. Loop Quantum Gravity. Almost all the leaders in those fields were present at the conference, in particular, 1. Reuter, 2. Sorkin and Dowker, 3. Loll, 4. Verch, 5. Ashtekar, Baez, Barrett, Corichi, Freidel, Gambini, Lewandowski, Perez, Pullin, Rovelli and Smolin. There were also talks on background independent aspects of string theory (Dijkgraaf and Theisen), Supergravity (Julia), Emergent Quantum Gravity (Morales – Tecotl) and Quantum Cosmology (Maartens).

There were 20 plenary talks and 63 afternoon talks which, for the first time, had to be distributed over two parallel sessions. We had more than 150 official registrations but the lecture theater was sometimes filled close to capacity (210 seats). This was certainly the biggest quantum gravity conference focusing on background independent approaches so far. It is pleasing to observe that the number of participants at this kind of meetings is rapidly increasing. From my own memory I recall the following conferences and rough participant numbers respectively: Banach Center, Warsaw, Poland, 1995 (50); Punta Del Este, Uruguay, 1996, (40); ESI, Vienna, Austria, 1997, (60); Banach Center, Warsaw, Poland, 1997 (60); ITP, Santa Barbara, USA, 1999, (70), Banach Center, Warsaw, Poland, 2001 (60); IGPG, State College, USA, 2003 (90); CPT, Luminy, France, 2004 (110).

The conference was subsidized by the Max Planck Gesellschaft (MPG) and The Perimeter Institute for Theoretical Physics (PI). While PI sponsored the conference poster, the money from the MPG and about 60% of the conference fee (EUR150,-), which was cashed only from non – students, was solely used in order to enable students to participate. I would like to take the opportunity to thank the plenary speakers once again for not asking for reimbursement which would have down-sized the student participation by an order of 40 people.

Due to the help of the marketing company 'Milde Marketing', the conference also had quite some impact on the German press. Major articles appeared for instance in the Frankfurter Allgemeine Zeitung and the television company RBB interviewed some of the participants and intends to broadcast parts of the conference. Also, Lee Smolin spoke in the 'Urania', a world famous institution in Berlin, which focuses on mediating science to the public through popular talks.

The scientific contributions to the conference can be downloaded, in many cases both audio and video, from the conference website http://loops05.aei.mpg.de. It is difficult to single out particular highlights but maybe one of the lessons to take home from the conference is that all afore mentioned approaches start deriving results relevant for quantum cosmology which is very important in view of the fact that precision cosmological measurements such as WMAP and later PLANCK might be able to detect quantum gravity fingerprints in the CMB.

Personally, I would be very pleased if somebody took the energy to organize Loops06: Let us keep up the momentum and make this meeting an annual forum of our small but growing community.

Numrel 2005

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This workshop was organized by Dr. Joan Centrella, the Leader of the Gravitational Astrophysics Laboratory of the Exploration of the Universe Division at NASA/Goddard. The presentations at the workshop are available on line at: http://astrogravs.gsfc.nasa.gov/conf/numrel2005/presentations/

The workshop offered attendees an excellent overview of cutting-edge research throughout the field. Representatives from most of the major numerical relativity groups (AEI, Austin, Baton Rouge, Brownsville, Caltech, Goddard, Penn State...) were present and presented new research results. We heard about remarkable new progress in being able to simulate binary black hole interactions and to extract waveforms. Some of this work (by Pretorius, and a collaboration including Pollney and Diener) had been previously presented and/or posted at gr-qc, but two of the presentations (by Zlochower, representing a collaboration led by UTB, and by Choi representing a collaboration led by NASA/Goddard) had been previously unpublished in any form.

The opening was given by Dr. Nick White, the Director of the Exploration of the Universe Division at NASA/Goddard. We immediately went into a presentation by Joan Centrella: "Gravitational Wave Astrophysics, Compact Binaries, and Numerical Relativity". Centrella began with a discussion of the fundamental aspects of gravitational radiation. She followed with a discussion of the sensitivity of the LIGO detectors, which are at essentially full sensitivity as the Science Run S5 begins. Real gravitational wave science has begun. Even higher sensitivity (in a much lower frequency band) is expected for the proposed space-borne detector LISA.

What are the expected sources for gravitational wave detectors? LISA will be sensitive to supermassive black hole mergers. "Every" galaxy has a central supermassive black hole; "every" galaxy has undergone a merger. "X-type" radio sources (in disturbed galaxies) show sudden changes in jet direction, which is assumed to lie along the spin direction; a merger could lead to a flip of the spin, producing such a change, so these are considered supporting evidence for the existence of mergers. For LISA and (perhaps) for LIGO, intermediate mass black holes (hundreds of solar masses) are possible sources of gravitational radiation. Here there is fairly strong evidence from X-ray sources in active star forming galaxies. Stellar mass black holes can result from the explosion of high mass stars, and there is a chance that binary black holes can form by this method. This is of course the underlying assumption in computational gravitational waveform prediction from binary black hole mergers. Finally, there is recent evidence, from observations of the short gamma ray bursters GRB 050509b, GRB 050724, suggesting they are mergers (neutron star/ neutron star or neutron star/black hole) that leave a black hole which shows evidence of accretion-driven X-rays after the merger. These could be sources for Advanced LIGO.

Deirdre Shoemaker discussed "Complexity in Gravitational Waveforms from BH mergers". Her point was that in fact we are seeing little complexity. How do we understand the relative similarity of all gravitational waveforms obtained via numerical simulations? Shoemaker put forth a few ways in which "complexity" could be added to (and ultimately of course, extracted from) the waveforms. Shoemaker began by noting that there is beginning to be a strong convergence of results in binary black hole simulations, at least for simple configurations. She presented head-on simulations from Zlochower et al, Fiske et al., and from Sperhake et al. The waveforms are very similar, and are rather smooth with a rapid onset to apparent ringdown behavior. For the existing orbit-and-plunge simulations, the agreement is not especially tight. However they too show fairly smooth behavior and fairly rapid onset of ringdown.

Shoemaker raises the question: why is there so little complication in the waveforms? She points out that this is in contrast to the case with matter present, as in neutron-star binaries. She gives several examples (Duffert et al., Faber et al., Duez et al.) which have more structure near the end of the merger than occurs in the binary black hole case. A core collapse waveform shows quite complicated behavior (Zwerger and Mueller). Shoemaker presented one aspect of complexity in nonequal mass head-on collisions. "Kicks" occur in these cases, and the waveforms have somewhat more structure, but still show early onset of ringdown.

In order to examine the mechanism of early ringdown onset Shoemaker considered scalar field ringdowns, carried out in a sequence of fixed spacetimes which constitute a sequence of quasi-circular initial data (Pfeiffer et al 2004). The ringdown is Fourier transformed, and the frequency identified in the scalar ringdown. For a single black hole the frequency of the ringdown is related to the mass (in Schwarzschild) by $M_{BH} = 0.29293/\omega$. In these data, the ADM mass measures the total system mass, roughly twice the horizon mass of one hole.

If the holes are well separated (corresponding to a time well prior to the merger in an evolution), M_{BH} determined from the ringdown will be the mass of one of the two equal masses. As one considers holes close enough together (in principle corresponding to later time in the merger), the system acts as if it has a single effective ringdown potential with a mass equal to the ADM mass. For her survey Shoemaker finds the transition occurs roughly at the "ISCO", with a horizon separation of $8m$. This again support s the idea the merger forms a common potential and quickly moves into the final black hole ringdown, fairly early in the evolution (when the ISCO is reached).

Yosef Zlochower, from The University of Texas at Brownsville, discussed "Accurate Binary Black Hole Evolutions Without Excision". This previously unpublished work caused quite a stir. Zlochower gave an introduction to the BSSN method with punctures. In the puncture method, one sets data for black hole evolution by using modified Brill-Lindquist data. These data have r^{-1} singularities in the conformal factor, at the coordinate centers of the black holes. Previous to this workshop, known approaches either used excision, to cut the singular region out of the computational domain (obviously not specific to puncture data), or held the punctures fixed at their initial coordinate positions, treated the singular parts analytically, and computationally evolved only the subdominant nonsingular part of the conformal factor. (Work by Bruegmann and collaborators, reported at the workshop by Tichy, uses corotating coordinates to evolve a black hole binary for one orbit in a system where the punctures are at fixed coordinate position, though Bruegmann *et al.* also considered excised evolution.) However Zlochower then showed inspiral and merger results in which the full punctures were evolved and traveled across the computational grid! This was so unexpected that it led to a flurry of questions, and many points were only partially explicated before the next presentation had to start. However the work has now been posted on arXiv.org: gr-qc/0511048. That publication explains that the code is designed to evolve the inverse of the conformal factor. That, and some care to the behavior of the lapse, allows evolution of the full system, including the "singular" conformal factor. Second order convergence is shown. The data correspond to late inspiral. The holes perform about half an orbit before a common apparent horizon forms. A waveform is extracted, and the energy radiated is of order 2.8%, argued to be accurate to about 10% of this value. About 14% of the total angular momentum was radiated. The domain represented in the evolution extends to approximately 60M (where M is the total mass), via the use a a multiple step "fisheye" transformation.

The next presentation, by Dae-Il Choi from Goddard Space Flight Center: "Gravitational Waveforms from Coalescing Binary Black Holes", presented very similar results by very similar methods. This work has also been posted on arXiv.org: gr-qc/0511103. (Apparently the two groups were unaware of the others' work until these presentations.) Choi's presentation described a numerical regularization of the conformal factor singularity, which does not involve introducing the inverse of the conformal factor. Instead, straightforward finite differencing, together with a careful choice of the lapse allows the evolution of the puncture system. The initial data put the holes, and hence the punctures, on the z = 0 plane. The Goddard code uses a cell centered formulation, so no point at which quantities are evaluated actually contains this plane. For nonspinning holes, the orbits stay in the $z = 0$ plane and thus every computed quantity is finite. The Goddard code uses fixed mesh refinement with eight levels of factor of two steps. The outer boundary is at $128M$, and the inner box resolution in three different resolution simulations is $M/16$, $M/24$, and $M/32$. Second order convergence is shown. The simulation yields a waveform and the total radiated energy is $0.0330M$, where M is the total mass of the system. The angular momentum radiated is $J = 0.138M^2$. Further, the radiated energy was computed in two ways. The first computation was by integrated gravitational radiation flux across a sphere at radius equal to 25 times the horizon radius of the final black hole. Then this was compared to the difference of the initial and final ADM mass. The loss of mass-energy closely checks between these two methods. In fact the two measures of the wave energy loss agree to better than 5% (of the $\approx 3\%$ of the total energy that is radiated), showing at least 3−digit accuracy.

Alessandra Buonanno of the University of Maryland discussed "Predictions for the last stages of inspiral and plunge using analytical techniques". She described a method (the *Effective One Body* (EOB) method), to resume post-Newtonian expansions, in a way that appears to converge better than the straightforward PN expansions. Within analytical calculations the EOB is the only method which can approach a description of the dynamics and the gravity-wave signal beyond the adiabatic approximation. It can also provide initial data (g_{ij}, K_{ij}) for black holes close to the plunge to be used by numerical relativity. The real difficulty in carrying out these processes lies in understanding how accurate the EOB method really is, since it is an expansion in a PN-like parameter. At some point must we use more accurate (presumably computational) description. Current results indicate good agreement between numerical and analytical estimates of the binding energy without spin effects. Already in its current state the method can be used as a diagnostic for (or to fit) numerical relativity results, and can also suggest parameters to vary in templates to provide more complete coverage of the space of possible waveforms.

Wolfgang Tichy (Florida Atlantic University) gave a discussion of "Simulations of orbiting black holes" This work is a review of work done by Tichy, Jensen and Bruegmann (*Phys. Rev. Lett.* **92** 211101 (2004); gr-qc/0312112). This approach uses puncture initial data for two orbiting black holes, with a (fairly standard) modified BSSN (Baumgarte Shapiro Shibata Nakamura) evolution system which replace all undifferentiated $\tilde{\Gamma}$ by derivatives of the metric, and ensures the tracelessness of the traceless conformal extrinsic curvature by explicit subtraction of the trace of $\tilde{A}_{ij}$ from $\tilde{A}_{ij}$ after each time step. (The time integration is Iterated Crank Nicholson). The outer boundary is a "lego sphere", with Sommerfeld outer boundary conditions for all evolved quantities.

The evolution is run with the holes excised (comparable results were found with puncture evolution that analytically handled the singular part of the conformal factor). The excision was carried out on lego-spheres of the black holes inside the horizon by the process of copying the time derivative at next interior point onto excision boundary (simple excision). Singularity avoiding gauge (lapse) was used to prevent the slice from running into physical singularities. The code is based on the BAM infrastructure, using fixed mesh refinement (FMR) for efficiency. Seven levels of nested boxes were constructed around each black hole. Outer boundaries were compared at 24M, 48M, and 96 M. The code evolves equal mass non-spinning holes, and uses quadrant symmetry. Because of these settings, the code can be run on a laptop. Perhaps the most important innovation was the use of co-moving coordinates enforced via the shift vector, which compensate for black hole orbital motion. The dominant terms in the shift correspond to rigid rotation. However it is the case that the data do not describe exactly circular motion, so the black holes can drift from their coordinate location in a specific evolution. An interesting algorithm is used to modify the shift to center the value of the lapse function (a proxy for the apparent horizon location) at a fixed specific coordinate location. The evolutions can evolve up to about 125M, more than the orbital time-scale inferred from the initial data. However, no waveforms have been published from these runs.

Peter Diener (LSU) discussed “Recent developments in binary black hole evolutions”. The results were obtained with a large group of collaborators (M. Alcubierre, B. Bruegmann, F. Guzman, I. Hawke, S. Hawley, F. Herrmann, M. Koppitz, D. Pollney, E. Seidel, R. Takahashi, J. Thornburg and J. Ventrella) associated with the Max Planck Institute Albert Einstein Institute in Potsdam, Germany, and with LSU.

This is another example of the surprising gains that have been made in computation of binary black hole interactions. Diener presented work using fixed mash refinement, with corotating coordinates, and an active adjustment of the shift vector to keep the holes centered in the corotating coordinates. Developing this code was prompted by the earlier work by Bruegmann, Tichy and Jansen, reported above by W. Tichy. Very interestingly, in this code the gauge used had five adjustable parameters, which control the behavior of the lapse and the shift. The lapse and shift are determined by driver conditions that evolve them toward “1+log” lapse and co-moving shift (which follows the centers of the black holes). These parameters define the factor of the lapse in the time derivative controlling the shift, for instance.

Two sets of parameters were used: *Gauge Choice 1*, and *Gauge Choice 2*. It was found that the lifetime of the simulation depended on the gauge used (Gauge choice 1 ran longer, to about 140M; Gauge choice 2 ran to about 80M). Also the computed proper distance (at a given time) between the apparent horizons depended on the gauge choice. When the two gauges were run at various resolutions, however, one could do convergence on the proper separation, and Richardson extrapolation. The result is that the extrapolated separations from the two sets of simulations overlap very closely in the range where both are available (t ¡ $80M$). This is a very interesting result. It means that the code is definitely doing something right. It strongly suggests that the different implementations of the driver conditions are leading to very closely the same time slicing. It also indicates that quite fine discretization is needed to achieve the convergent regime, and to achieve reasonable accuracy.

Denis Pollney of the Albert Einstein institute in Potsdam, spoke on “Evolutions of Binary Black Hole Spacetimes in the Last Orbit” He broke his talk into two sections: 1. Evolutions of Helical Killing Vector Data; 2. Evolving Single Black Holes Using a Multi-patch Code.

In the binary orbit (helical Killing vector) work, comparisons were made of evolutions from data set in one of two ways: Punctures with parameters along an effective potential sequence developed by Cook (1994), and thin sandwich data using a *Helical Killing Vector* condition, constructed by Grandclement, Gourgoulhon and Bonnazolla (2002) Meudon data. This code is as described in Diener's talk above; in particular it is a rectangular coordinate code. A series of orbits and head-on collisions can be produced in this code, and in particular, results similar to those of the earlier work by Bruegmann, Tichy and Jansen were accomplished.

The second aspect of Pollney's presentation concerns patching to spherical domains, and in particular conforming surfaces for inner (excision) and outer boundary surfaces. The current work has concentrated on single black holes, and uses Thornburg's inflated cube coordinate system, which is multi-patch (six patches) and uses interpolation between adjacent grids. Angular coordinates are chosen so that adjacent patches share coordinates perpendicular to their mutual boundary so the method needs only 1D interpolations. The method was tested in a hydrodynamics code (Whisky) to show that shock propagation is correctly handled across the interfaces in a single hole background. Evolution of a single distorted black hole by this method showed inter-patch effects well below finite difference accuracy.

Frans Pretorius of the University of Alberta described his binary black hole simulations. [*Phys. Rev. Lett.* **95** 121101 (2005); gr-qc/0507014]. This work integrates several approaches which are not in wide use within the numerical relativity community — use of a second-order formulation of the Einstein equations, compactification of spatial infinity, adaptive mesh refinement, and a harmonic gauge. The code is based on generalized harmonic coordinates, so every component of the Einstein equations obeys a wave equation (with nonlinear source). Source functions are added to the definition of the harmonic gauge in order to be able to choose slicing and shift conditions. These equations are discretized directly into second-order in time finite difference equations. Adaptive mesh refinement follows http://www.perimeterinstitute.cathe holes and excision removes the singularities from the domain. Numerical dissipation is used to control instabilities that otherwise arise near the black holes. A final interesting point is that the spatial domain is compactified, which provides an "inexpensive" implementation of the outer boundary. In addition, Pretorius used *constraint damping* which adds a linear combination of the gauge constraints to the metric evolution, and which produces extended stable evolution. Initial data are set up using boosted field collapse. The initial data slice is conformally flat maximal. The harmonic condition gives the initial time derivatives of the lapse and shift. The Hamilton and momentum constraints are solved for the initial conformal factor and shift.

Data as set are equal mass components, in an approximately circular orbit (eccentricity of order 0.2 or less), with a proper distance between holes of approximately 16M (coordinate separation of 13M), where the initial ADM mass is 2.4M. Each black hole has a velocity of abut 0.16, and zero spin angular momentum. The evolution traces out about 2/3 of an orbit to one full orbit before the horizons merge. The final black hole has an angular momentum Kerr parameter $a = 0.7M_f$. Presumably because of dissipation and lack of resolution in the spatial compactification, the extracted waveform has a faster than r^{-1} falloff, though the shape is very well preserved at different wave extraction radii. Regardless of the falloff, one estimates about 5% of the total initial energy is radiated.

Mark Scheel (CalTech) discussed "Solving Einstein's Equations using Spectral Methods". He began with a description of the method, which provides exponential convergence as the number of basis functions is increased (though the *coefficient* in the exponential must be studied in each case). In the pseudospectral approach, analysis of the basis functions leads one to define specific collocation points x_n. Expansions to truncated series in terms of basis amplitudes and basis functions (truncated to a maximum number, N) can be inverted exactly to obtain the basis amplitudes by carrying out a weighted sum with N terms, over the function at the specified collocation points, multiplied by the basis functions at those points. This transformation between space and spectral representation is an algebraic process. In the nonlinear case derivatives are computed in spectral space, nonlinear terms are evaluated in physical space. Boundary conditions are imposed analytically on characteristic fields.

The method uses characteristic decomposition, and complicated domain decomposition; every domain maps either to a spherical region or to a sphere, where the basis functions are defined. An example for a single black hole had 54 sub-domains. Because of the fact that the sum over basis functions defined a function everywhere, no explicit interpolation is needed to transfer values between patches.

The KST code [Kidder, Scheel, Teukolsky, *Phys. Rev.* **D** 64 064017 (2001)] is a parameterized hyperbolic code. This was used with "quasi-equilibrium" conformal thin sandwich data to compute binary black hole interaction in a co-moving frame. By using characteristic decompositions, no boundary conditions are needed at the BH horizons (excision) and Sommerfeld-like outer boundary conditions were imposed at the outer $r = 320M_{BH}$. The was a free evolution, the constraints were solved only initially. For moderately short evolutions the constraints converged. However by $t \approx 20M$ the convergence was lost. A fix in the shift vector to keep the apparent horizons centered in coordinate location (and spherical) improved the behavior for about another $10M$, but convergence was then lost. Suggested fixes were to impose elliptic gauge conditions, or some sort of driver condition.

The final topic of Scheel's talk concerned an effort to construct a pseudospectral version of Pretorius code, necessarily adapted to a first order form, this code works extremely well for single Schwarzschild black holes. However, very strong instabilities are found when trying to do co rotation problems. with moderately large domains. Even flat space is unstable (when $R\Omega > 0.7$, with R the size of the domain an Ω the angular velocity). The KST system does not have this problem.

Harald Pfeiffer (CalTech) discussed "Quasi-equilibrium binary black hole initial data". The basic idea is that there is approximate time independence in a corotating frame; this implies an approximate helical Killing vector. Time-independence in corotating frame implies vanishing time derivatives. The idea is that the initial data for black holes in not too close orbit approximately satisfy these condition; construct data that exactly has these properties. The solution proceeds by a conformal solve of the resulting elliptic equations to obtain the lapse, the conformal factor and the shift vector The co rotation requires a boundary condition on the shift vector of $\beta^i = (\omega \times r)^i$. The boundary condition on the lapse at infinity is $N = 1$, and on the conformal factor $\psi = 1$. Inner boundary conditions on ψ and β are written at the apparent horizons, which are assumed in the data to be stationary and isolated (no shear of their generators). The so called extended conformal thin sandwich formalism also sets the time derivative of the extrinsic curvature on the initial slice to zero. This formalism leads to some curious double valuedness in the ADM energy as a function of wave amplitude in the conformal background. This apparently can be understood physically, and can be evaded by considering only the standard conformal thin sandwich approach.

One possible difficulty is that evolution codes typically evolve inside the apparent horizon, but these data are produced with the apparent horizon as its inner boundary.

Greg Cook (Wake Forest)gave an update "Black-Hole Binary Initial Data: Getting the Spin Right". This was an update on the construction of quasi-circular binary black hole data. All of his results made use of the conformal thin-sandwich method. There are two approaches that yield a sequence of quasi-circular orbits. In one approach, the binding energy is plotted vs the orbital angular momentum, with fixed total angular momentum. The minimum of each of these curves defines an effectively circular orbit. The second approach makes use of the fact that in true quasi-circular motion all the fields should be constant in the corotating frame. one compares the value of the Komar mass (defined only for stationary spacetimes) with the ADM mass. Consider the corotating Black Hole case. By computing a number of test cases, Cook found a modification of the lowest-order corotating condition for the tidal field seen by a black hole at its horizon, in the presence of a second: $\beta^i = \alpha\psi^{-2}\tilde{s}^i + \Omega_{BH}\xi^i$ at the horizon, where $\tilde{s}^i$ is the spacelike normal to the horizon, and ξ^i is a spatial unit vector. The first term ($\alpha\psi^{-2}\tilde{s}^i$) is well established; it is an outward directed shift component that counteracts the inward fall of the coordinates. The second term had previously been taken as the angular rate Ω_0 measured at infinity. However Alvi (2000) pointed out that the rate at the horizon of the tidal rotation is given by

$\Omega = \Omega_0 - \eta M/b + ...$, where b is a measure of the separation, $\eta = m_1 m_2/M^2$, and M is the total mass. Cook expresses this completely in terms of the rotation rate and finds $\Omega = \Omega_0 - \eta(M\Omega_0)^{2/3} + ...$. With this correction for co rotation, Cook finds complete agreement between the helical Killing Vector and the effective potential methods.

Scott Hawley (University of Texas, Austin) gave a summary of some recent work (with Richard Matzner and Michael Vitalo) validating an efficient multigrid-with-excision code that produces binary black hole data. The code is a node centered code, and uses a particular way of defining the excision. The excised points are those on any grid which lie inside the excision radius. Consequently, except for very special choices of the parameters, the excised regions are *larger* on the finer grids. The code is parallelized, and exists in a fixed-refinement version. However Hawley spoke about the unigrid code. To test the code, Hawley compared the computed binding energy to predictions of a lowest-order spin-spin coupling due to Wald. For relatively close placement of the momentarily stationary holes in the initial data set (coordinate separation of $10m$, where each hole has mass parameter mass m), one obtains a binding energy variation with spin that has the dependence on angle suggested by Wald, and an amplitude about 10% higher. This latter difference is attributed to the closeness of the holes in these runs. (The binding energy is computed by assuming the horizon area determines the intrinsic mass, and subtracting that from the ADM mass.) More exploratory work will be carried out in the future, with the FMR version of the code.

Stu Shapiro (Illinois), "Binaries Containing Neutron Stars: The Merger Aftermath", described a number of results concerning neutron stars, and neutron star/neutron star and neutron star/black hole mergers. He began by showing computations indicating that certain rotating hypermassive stars are dynamically stable, but other physics (turbulent viscosity, magnetic braking, neutrinos/ gravitational waves) can lead to delayed collapse to black holes and delayed gravitational wave bursts. Shapiro described simulations of neutron-star binary systems mass ratio 0.9 to 1.0. The work found a critical mass approximately 2.5 to $2.7M_{solar}$ for the merged star. Exceeding this critical mass leads to prompt collapse; less than the critical mass leads to an hypermassive remnant and delayed ($100msec$) collapse. The associated gravitational wave frequency is in the 3 to $4kHz$ range, a possible target for AdLIGO. A theoretical question associated with rotating collapse concerns whether data with $J/M^2 > 1$ can collapse beyond the neutron-star stage. Computational experiments, some described by

Shapiro, do not do so. (Note that a Kerr solution with $J/M^2 > 1$ has a naked singularity.) The behavior of the matter in the simulations is a rotation induced bounce. Simple Newtonian arguments explain the results by angular momentum conservation preventing collapse to within a horizon. Shapiro also described new, more realistic simulations involving General Relativistic MHD, and including realistic shear viscosity. These effects may contribute to delayed collapse with a gravitational wave burst, enhanced collapse bounce shocks, and possible magnetic jets. These topics are some of the most astrophysically relevant things which computational physicists can approach, and suggest exciting AdLIGO connections: coincident (triggered) detection between GRBs and their associated gravitational radiation, with a reasonable event rate.

John Baker gave a summary and "future directions" talk Friday afternoon.

The work in this conference that produced waveforms (Zlochower, Choi and Pretorius) produced waveforms that are remarkably similar in general features. In particular, most of the waveform "looks like" a ringdown waveform, and this is where most of the energy is radiated. It does appear that we can define a "generic" waveform for black hole mergers, appropriate to template generation. One of the outcomes of the meeting was a brief meeting of an ad-hoc committee chaired by John Baker to define data standards for, and to collect, waveform data from simulations, ensure consistency with the standards, and to post them at a public website.

Apples With Apples Workshop in Argentina

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The third "Apples with Apples" workshop, which took place from March 14–25 2005 in Argentina, continued a series of roughly one two-week meeting per year to bring together numerical relativists in hands-on comparisons of formulations of the Einstein equations for numerical relativity. The meeting was organized by Oscar Reula in Villa General Belgrano, located in the beautiful Calamuchita Valley near Cordoba. The conference hotel that hosted all participants provided a very communicative setting for our purposes. Special thanks go to Oscar and the local students Florencia Parisi and Santiago Gomez for their help and support of the participants. The meeting followed the established patterns of previous apples with apples meetings, with talks and discussions in the first week, and working sessions and more discussions in the second week. Talks have been presented by Jeff Winicour, Osvaldo Moreschi, Tilman Vogel, Sascha Husa, Santiago Gomez, Bernd Reimann, Carles Bona, Bela Szilagyi, Yosef Zlochower and Pedro Maronetti, and all of these talks have been accompanied by rather lively discussions.

Jeff Winicour opened the meeting with a general introduction to the ideas and history of the project, and set the scene for the discussions to come. Carles Bona, Bela Szilagyi and Yosef Zlochower presented test results with their codes (the Z4 system, different versions of harmonic codes, and the LazEv BSSN code), and what they had learned from their tests and the discussions within the project. Sascha Husa presented results obtained with Calabrese and Hinder in [1] on second order in space hyperbolic evolution equations, and presented suggestions for revising the robust stability test. Bernd Reimann (see [2]) and Tilman Vogel (see [3]) discussed their promising approaches to deal with continuum instabilities. Pedro Marronetti presented his thoughts on setting up tests for binary neutron star evolutions, followed by a discussion on what could/should be done regarding tests for systems with matter. Santiago Gomez presented work of the Cordoba group on a new evolution system using components of the Weyl tensor as evolution variables, Osvaldo Moreschi talked about a new approach to the binary black hole problem, where interior and asymptotic region are matched with analytic methods. See [4] for abstracts and some slides.

The declared goal of the apples with apples project is to develop a hierarchy of testbeds which should eventually include binary black hole problems, and a natural hope is to progress rather quickly from the simple toy problems with periodic boundaries we had designed at the first meeting to actual black hole spacetimes – in particular since running 3D black hole simulations with advanced technology such as grid refinement or excision has become routine for several groups. However, another declared goal of this project is to significantly improve our level of actual understanding – believing that understanding is key to eventually develop robust simulation methods. More than for the previous meetings, the spirit of the Cordoba meeting has been one of digestion rather than accelerating the broadening of our scope – but this, I believe, has been achieved rather successfully! One of the main topics of the workshop was to incorporate recent theoretical progress into our practical program of designing test suites and in particular also into the interpretation of test results. Most notable here are the advances regarding the mathematical understanding of second order in space systems, of continuum instabilities (e.g. as signified in the talks of Reimann and Vogel), and in much work on particular evolution systems which has directly emanated from the apples project, such as the rather detailed studies of the Pittsburgh group.

Let me select a few points where our understanding has improved substantially: The instability exhibited for the ADM [5] system in the first "apples paper" [6] has finally been nailed down as an ordinary von Neumann instability. In order to properly understand this, progress with the theory of well-posedness and numerical stability for second order in space systems was required, see e.g. [1,7]. In fact, one of the misleading original ideas was to look for exponential growth in our "robust stability test", whereas weakly hyperbolic equations should be expected to only produce resolution dependent polynomial, e.g. linear, growth in the linear constant coefficient case (i.e. the robust stability test setup). This non-convergent behavior has in particular been verified for the ADM system.

Some confusion had been caused by the fact that numerical stability tests in the linear constant coefficient regime can show a rather complicated phenomenology due to the frequency dependent damping effects inherent in any finite difference scheme (with or without artificial dissipation). Depending on various parameters such as number of grid points, time step size or dissipation factor various effects with different inherent time scales may compete, and the proper interpretation of results may requires either extremely detailed and careful parameter studies – or some analytical modelling in addition to numerical tests. As should be expected on theoretical grounds, most codes do require artificial dissipation (e.g. of Kreiss-Oliger type) beyond the linear constant coefficient regime in order to avoid high-frequency instabilities. Particularly clarifying in this respect were Yosef Zlochower's runs with the LazEv BSSN code, and Christiane Lechner's runs with various symmetric hyperbolic codes. As shown in [1], it turns out that for second order in space formulations the situation is somewhat more subtle than for first order systems: while the second derivatives in these systems typically help to damp out high grid frequencies, a mixing of first and second derivatives in the principal part may result in a numerical instability with standard discretizations of certain well posed systems (at least without artificial dissipation).

Since the meeting has taken place, several phone conferences have been organized to further coordinate our work, for information on how to join, news and how to access our data repositories with results see our web site [4]. Finally, let me mention that the steaks *are* indeed fabulous in Argentina, and that they are preferably accompanied by a Malbec from Mendoza.

References:

[1] G. Calabrese, I. Hinder and S. Husa, Numerical stability for finite difference approximations of Einstein's equations, gr-qc/0503056.

[2] B. Reimann, M. Alcubierre, J. A. González and D. Núnez, Constraint and gauge shocks in one-dimensional numerical relativity, *PRD* **71**, 064021 (2005).

[3] J. Frauendiener and T. Vogel, Algebraic stability analysis of constraint propagation, *Class. Quantum Grav.* **22**, 1769 (2005).

[4] See the project website at `http://www.appleswithapples.org` and the web pages of the meeting at `http://www.appleswithapples.org/Meetings/Cordoba2005` http://www.appleswithapples.org/Meetings/Cordoba2005

[5] Here the term ADM refers to the system presented in J. W. York, in Sources of Gravitational Radiation (Cambridge University Press, Cambridge, England, 1979).

[6] M. Alcubierre et al., Toward standard testbeds for numerical relativity, *Class. Quantum Grav.* **21**, 589 (2004).

[7] For an overview, new results and further references see Carsten Gundlach, Jose M. Martin-Garcia, Hyperbolicity of second-order in space systems of evolution equations, gr-qc/0506037.