MATTERS OF GRAVITY

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

Number 20 **Fall 2002**

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ISSN: 1527-3431

Editorial

Not much to report here. This newsletter ended a bit long, due to the large number of conference reports, just reflecting the increasing number of meetings that are taking place in our field. It is also a bit late, also due to the large number of articles involved. I apologize for this.

The next newsletter is due February 1st. If everything goes well this newsletter should be available in the gr-qc arXiv archives (`http://www.arxiv.org`) under number gr-qc/yymmnnn. To retrieve it send email to gr-qc@arxiv.org with Subject: get yymmnnn (numbers 2-19 are also available in gr-qc). All issues are available in the WWW:
`http://www.phys.lsu.edu/mog`

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

A hardcopy of the newsletter is distributed free of charge to the members of the APS Topical Group on Gravitation upon request (the default distribution form is via the web) to the secretary of the Topical Group. It is considered a lack of etiquette to ask me to mail you hard copies of the newsletter unless you have exhausted all your resources to get your copy otherwise.

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

Jorge Pullin

Correspondents

- John Friedman and Kip Thorne: Relativistic Astrophysics,
- Raymond Laflamme: Quantum Cosmology and Related Topics
- Gary Horowitz: Interface with Mathematical High Energy Physics and String Theory
- Beverly Berger: News from NSF
- Richard Matzner: Numerical Relativity
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- Warren Johnson: Resonant Mass Gravitational Wave Detectors
- Gary Sanders: LIGO Project
- Peter Saulson: former editor, correspondent at large.

Einstein Prize update

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The American Physical Society has formally established the Einstein Prize in Gravitational Physics as a biennial prize, for outstanding achievement in theory, experiment or observation in gravitational physics. Fundraising for the prize continues, however, with the goal of reaching an endowment of \$200 K, so that the prize could be awarded annually. David Lee continues to match every dollar raised for the prize. For information, contact Clifford Will (cmw@wuphys.wustl.edu) or check http://wugrav.wustl.edu/People/CLIFF/prize.html. A prize selection committee was established by the APS, with the intention of awarding the initial prize in 2003, at the April APS meeting. To nominate somebody for the prize, follow the guidelines that can be found at http://www.aps.org/praw/nomguide.html.

World year of physics 2005

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The year 2005 will be the centenary year of the 1905 Einstein miraculous year, in connection with this, UNESCO has declared 2005 a World Year of Physics. Each country would plan its own events and perhaps there will be an international meeting in Switzerland. The European Physical Society is leading the way and heading the European side of things.

The APS plans to be part of this, and they are thinking about outreach activities under the tentative title “Einstein in the 21st Century.” Although Einstein’s 1905 achievements really had nothing to do with the G of TGG, we do have a special claim on Einstein (the Einstein prize, for example). The role we will play in 2005 is now being considered.

We hear that...

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Robert Wald has been elected to the National Academy of Sciences (I incorrectly reported this in the fall 2001 issue, at that time he had been elected to the American Academy of Arts and Sciences).

Matt Choptuik was chosen among the top 20 researchers 40 years of age and under by the Canadian Insitute for Advanced Research (CIAR).

Patrick Brady and Amanda Peet have been awarded Sloan Fellowships. Brady also received a a Cottrell Science award from the Research Corporation.

Raphael Bousso and Fotini Markopoulou were chosen as the winners of the young researchers competition associated with the "Science and ultimate reality" symposium in honor of John Archibald Wheeler.

The Perimeter Institute in Waterloo Canada has received a major commitment from the Canadian Government. It will contribute $25 million over five years. Additional $11 million will be contributed towards the building. Prime Minister Chrétien spoke at the groundbreaking ceremony for the new building.

Hearty congratulations!

R-mode epitaph?

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For the past few years, because the growth time of the gravitational-wave driven instability (CFS instability) is short for r-modes, it has seemed likely that the instability limits the spin of rapidly rotating, newly formed neutron stars - and possible that it limits the spin of old, accreting neutron stars as well. Because most of the initial angular momentum of the star could be radiated, the gravitational waves emitted by sources as close as the Virgo Cluster might be observable by detectors with the expected sensitivity of advanced LIGO. In the past year, however, studies of two mechanisms – rapid cooling and high viscosity associated with a hyperons in neutron-star cores, and amplitude saturation by nonlinear coupling to stable modes have sharply decreased the likelihood that the waves from nascent neutron stars will be detectable. Whether the instability limits the spin of neutron stars remains an open question. And, surprisingly, the hyperon studies may have increased the chance of detecting gravitational waves from old accreting stars.

One of the major questions about the r-mode instability was whether nonlinear couplings would sharply limit its amplitude. The first studies of this problem were numerical evolutions of the nonlinear equations: First, Stergioulas and Font [1] carried out a numerical evolution of the exact relativistic Euler equations on a background spacetime, with the initial data of a large-amplitude r-mode. They found, surprisingly, that there was no apparent energy transfer to daughter modes until the perturbation's amplitude was substantially larger than unity. Next was a numerical time-evolution of the full Newtonian perturbation equations by Lindblom, Tohline and Vallisneri [2]. Because the actual growth time from radiation-reaction is impractically long, they looked at the maximum amplitude for a perturbation driven by a greatly enlarged radiation-reaction term. They again found saturation only at amplitude large compared to unity; the limit appeared to be set by a shock wave, a dramatic breaking on the star's surface.

A clear implication of these numerical evolutions was that coupling to low-order modes did not set a stringent limit on the r-mode amplitude – not, at least, within a time of about ten rotational periods, and with the small initial daughter-mode amplitudes and numerical viscosity of the simulations. These evolutions can examine the full nonlinear coupling, but they were limited in their resolution and evolution time. The complementary way to address the question is in 2nd-order perturbation theory - by omitting higher-order couplings, one reduces the nonlinear evolution to a set of coupled ordinary differential equations. But the second-order perturbation theory of a rotating star had not been developed, and it is was a major undertaking, completed this year by Arras, Flanagan, Morsink, Schenk, Teukolsky, and Wasserman [3]. The implication of their work is opposite to the indications of the fully nonlinear evolutions: Nonlinear couplings sharply limit the amplitude of an unstable r-mode.

Their work is consistent with the fully nonlinear numerical evolutions, because the coupling they find to low-order modes is consistent with a saturation amplitude of order unity. It is, instead, the coupling to many short-wavelength modes with frequencies comparable to that of the r-mode, that saturates the mode at an amplitude smaller than 10^{-2}. (And the most recent fully nonlinear numerical evolution, by Gressman et al.[4], finds that increasing the resolution yields rapid nonlinear decay of the mode at decreased amplitude.) Nevertheless, r-modes may set the limit on rotation of young rapidly rotating neutron stars (this is less likely if the actual saturation amplitude is 10^{-4}); and the r-mode instability may account for the maximum rotation period observed in old neutron stars spun-up by accretion (i.e., in x-ray binaries).

Exotic particles in the core of a neutron star lead to a significantly stronger viscous damping than assumed in the first studies of the unstable r-modes. Of particular relevance is the presence of hyperons and non-leptonic weak reactions. Hyperon-mediated damping of neutron-star oscillations was proposed by Langer and Cameron in 1969 and by Peter Jones in 1970, but the minimum density expected for hyperons was apparently 10^{15} g/cm^3 (see, for example, Zel'dovich and Novikov, v. 1, Sect. 11.5, in paragraphs written by Thorne). Spurred by Jones' recent reminder [5] that the r-mode instability would be completely suppressed in stars with a significant hyperon fraction, Lindblom and Owen [6], in a tour-de-force calculation using fully relativistic cross sections, found the bulk viscosity coefficient for non-leptonic reactions. Independently Haensel, Levenfish and Yakovlev [7] considered superfluid hyperons and obtained a set of approximate formulas for various bulk viscosity coefficients. These results show that, when hyperons are present, the dissipation due to direct URCA is overwhelming. In fact, the hyperon cooling is so rapid that, even without the enhanced hyperon bulk viscosity, no mode of a nascent neutron star would have time to grow before it was stabilized by viscous damping.

There is, however, significant uncertainty in the critical density at which hyperons appear and in the central density of neutron stars. Even for the equation of state (due to Glendenning) that Lindblom and Owen consider, the central density of a 1.4 $M_\odot$ star is near that needed for hyperons to appear when the rotation reaches its maximum value. The averaged measured mass of neutron stars is somewhat smaller than this; and the compressibility consistent with our knowledge of matter above nuclear density ranges over a factor of 5 or more for a 1.4 $M_\odot$ star, an error bar easily large enough to prevent our knowing whether or not neutron stars have hyperon cores.

The possibility that gravitational waves from unstable modes could balance the accretion torque, and hence halt the associated spin-up, was first discussed by Papaloizou and Pringle and Wagoner for the f-modes. The analogous scenario for the r-modes was analyzed in detail by Andersson, Kokkotas and Stergioulas and Bildsten a few years ago. Should this happen, neutron stars in LMXBs would be promising sources for detectable gravitational waves. In independent work, Spruit and Levin pointed out that this scenario may not work: The unstable mode will heat the star up (via the shear viscosity), and, if the viscosity gets weaker as the temperature increases, the mode-heating will trigger a rapid thermal runaway during which the star will spin down. This mechanism would seem to rule out r-modes in galactic LMXBs as a source of detectable gravitational waves, because they will only radiate for a tiny fraction of the system's lifetime.

Interestingly, the recent results indicating a small saturation amplitude and strong "exotic" bulk viscosity may imply that r-modes in these systems would be relevant gravitational-wave sources after all. Very recently, Wagoner [8] reported work showing that old, accreting neutron stars with a hyperon core will not undergo a thermal runaway, but will reach a the quasi-equilibrium state in which gravitational wave emission balances accretion spin-up *and cooling balances shear viscosity heating.* Andersson, Jones and Kokkotas [9] had previously found the same balance for strange stars, and it might also characterize accreting neutron stars with quark cores. Most importantly, in these scenarios the r-mode amplitude required to balance the accretion torque is orders of magnitude smaller than the saturation amplitude estimated by Arras et al. Finally, Heyl [10] has investigated the effect of a small saturation amplitude on the thermal runaway in a "normal" neutron star. His results show that the phase during which the r-modes radiate gravitationally is significantly extended if the modes cannot grow to a large amplitude (as long as the modes are not wiped out by the saturation mechanism).

One must place hyperon damping and nonlinear saturation at the top of the list of mechanisms that may kill or maim unstable r-modes [11], but reports of their demise may be premature.

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10. J. Heyl, *LMXBs may be important LIGO sources after all* astro-ph/0206174

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Gravitational waves from bumpy neutron stars

Benjamin J. Owen, Pennsylvania State University

It has often been overlooked in the recent fuss about unstable oscillation modes, but there is another way of getting gravitational waves out of single neutron stars. You might even say a more solid way: A crystalline crust might not be symmetric about the rotation axis of a star, giving the star a time-varying quadrupole moment.

This lack of symmetry could come either in the form of localized bumps (mountains), or a "bump" covering most of the star if the crust is symmetric about an axis different from the rotation axis. One problem is that, due to the nuclei having such low charge-to-mass ratios (being neutron-rich isotopes) and being so tightly packed, the so-called solid crust has essentially the same mechanical properties as Jell-O: It doesn't support bumps very well. Worse than Jell-O, neutron stars are expected to support bumps no higher than 10^{-7} times the star's radius. (For the derivation of this number, and other details and background, see the recent review by Ian Jones [1].)

Numerous mechanisms have been proposed since the 1970s for producing bumps or misaligned axes including strong (10^{16}G) magnetic fields, *Magnus forces* due to superfluid vortex pinning, and just plain settling as an aging star spins down and loses its centrifugal bulge. Until recently, however, there wasn't much hope of detecting gravitational waves from any bumpy neutron stars with LIGO or a comparable interferometer [2].

The revival of interest in bumpy neutron stars as gravitational-wave sources started about the same time as for unstable modes, when in 1998 Lars Bildsten [3] suggested that *electron capture* could make large mountains on the accreting neutron stars in low-mass x-ray binaries. The density of a neutron star crust doesn't increase smoothly as you go down towards the core, but rather in discrete jumps. The result is layered like an onion: At the bottom of each layer, a proton in each nucleus captures an electron due to the intense pressure and turns into a neutron (inverse beta decay). This changes the chemical composition in the next layer and allows the now less positively charged nuclei to come closer together. Since the pressure of each electron capture falls strongly with rising temperature, a rain of hot accreting matter falling unevenly around the star can create buried mountains many layers deep.

Bildsten revived an old argument by Wagoner [4] to show that, if there's a bump, you can work out the gravitational wave strain from the observed x-ray flux—assuming that torque-up from accretion is balanced by torque-down from gravitational waves. Some rapidly-accreting x-ray binaries, particularly Sco X-1, would produce gravitational wave strains as high as a few times 10^{-26} provided the assumption of torque balance holds.

Brady and Creighton [5] examined the details of data analysis and detection. Sco X-1 would be quite detectable by advanced LIGO (or a comparable interferometer) if its orbit and the small fluctuations of its spin about the torque-balanced value were precisely known, e.g. by radio observations. Sco X-1 and most of its cousins are seen only in x-rays, where the timing and orbital data are less precise. The need to search a large parameter space of possible data demodulations increases the minimum observable strain by 2.5, meaning that a broadband advanced LIGO configuration could barely detect Sco X-1 above the noise. A narrow-band signal-recycling configuration such as prototyped by GEO600 could get a signal-to-noise ratio several times higher. A good detection above the noise would allow the extraction of interesting physics of the crust such as breaking strain and probable thickness, which in turn tells us something about the equation of state.

Is torque balance a reasonable assumption? Ushomirsky *et al.* [6] checked by combining nuclear physics with geology. The bad news is that mountains settle into the mantle as well as poke up into the sky, reducing the quadrupole. The good news is that on an accreting neutron star the mountains extend over many layers, which brings the quadrupole back up. If a star has a 5% temperature variation over the surface and if the breaking strain of the crust is 10^{-2}, even the fastest-accreting binaries such as Sco X-1 can achieve torque balance. More good news is that the crust won't smooth out a 5% temperature variation by conduction if the accretion is that irregular (and constant). More bad news is that 10^{-2} is on the very high end of predicted breaking strains, much higher than for terrestrial materials.

Another way of getting gravitational waves out of even axisymmetric neutron stars is *free precession.* If the crust's symmetry axis is tilted away from the rotation axis, both will precess about the fixed angular momentum vector. This free precession will radiate gravitational waves and tend to get damped both by radiation and by internal dissipation—the latter fairly quickly—and so the topic has been pretty quiet since the 1970s.

Free precession got a lot more notice recently when Stairs *et al.* [7] discovered a pulsar that shows the expected modulation in its radio signal. The star spins far too slowly for gravitational radiation to be significant, but it shed some light on the physics of precession (if there are vortices in a superfluid core they can't be pinned to the crust). Jones and Andersson [8] then systematically inventoried all known pumping mechanisms that could encourage rapid free precession and strong gravitational waves. Unfortunately the resulting signals are too faint even for advanced interferometers. Cutler and Jones [9] got excited briefly by the prospect of precessing neutron stars being unstable to gravitational radiation like the r-modes, but on closer inspection it turns out that an old result was wrong and radiation reaction always damps precession.

Stairs *et al.* aren't the only ones with a detection paper. Middleditch *et al.* [10] also claim to have observed a freely precessing pulsar with a 2ms spin period in the remnant of supernova 1987A. They also claim that its period derivative is consistent with spindown due to gravitational radiation! Obviously this is really hot if true, but there are some problems. Like the electron-capture scenario for Sco X-1, Middleditch's SN1987A would need a breaking strain of 10^{-2}—tough but conceivable. Furthermore, the extra moment of inertia due to the bump would have to have changed by a factor of 2 in a few years while somehow maintaining a constant precession angle, which is much harder to believe. Finally, the pulsar has been seen only by Middleditch's team, and then only sporadically in the 1990s despite close observation.

Very recently the old mechanism of bumps through strong magnetic fields got a new twist from Curt Cutler [11]. It has been rediscovered several times since the 1970s that a magnetic field of more than a few times 10^{12}G—a reasonable value for some young neutron stars—is secularly unstable in a neutron star with an elastic crust. That is, if the magnetic field axis is misaligned with the star's rotation axis, flexing of the crust due to free precession will let the field move into its lowest energy configuration. This happens to be one where the field axis is perpendicular to the rotation axis. Cutler points out that an internal toroidal field can be made quite strong by differential rotation in a young neutron star while keeping the external dipole magnetic field low, consistent with observations. This also means that gravitational radiation braking dominates electromagnetic braking. As a result stars in various scenarios—x-ray binaries, recycled millisecond pulsars, even (briefly) newborn neutron stars—could then be detectable by advanced interferometers.

To sum it up: The goods may be odd, but the odds are pretty good that within a few years we'll be seeing gravitational-wave signals from some known pulsars with big bumps on them.

The old bumping mechanisms from the 1970s have been pepped up considerably, and with the observation of at least one precessing pulsar hopes are high for more to come.

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LIGO science operations begin!

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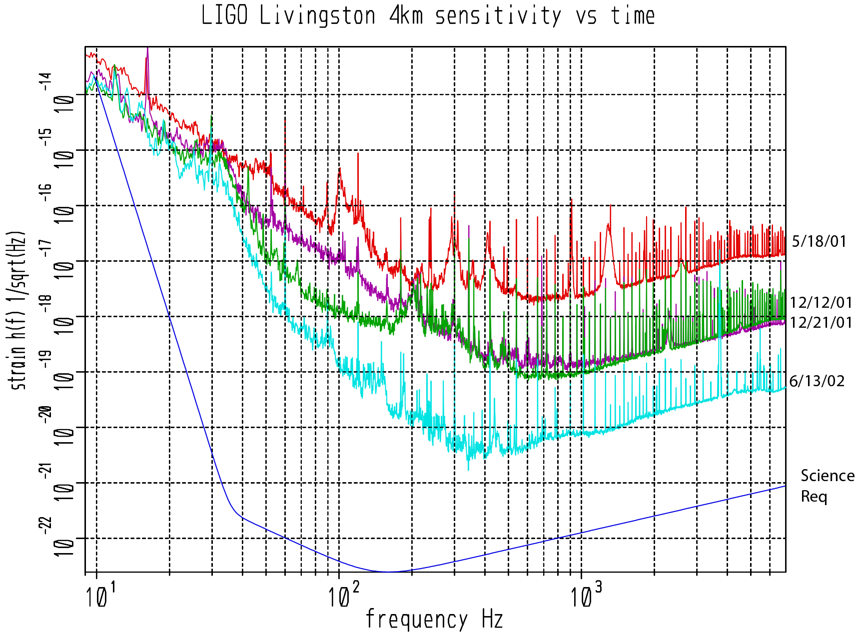
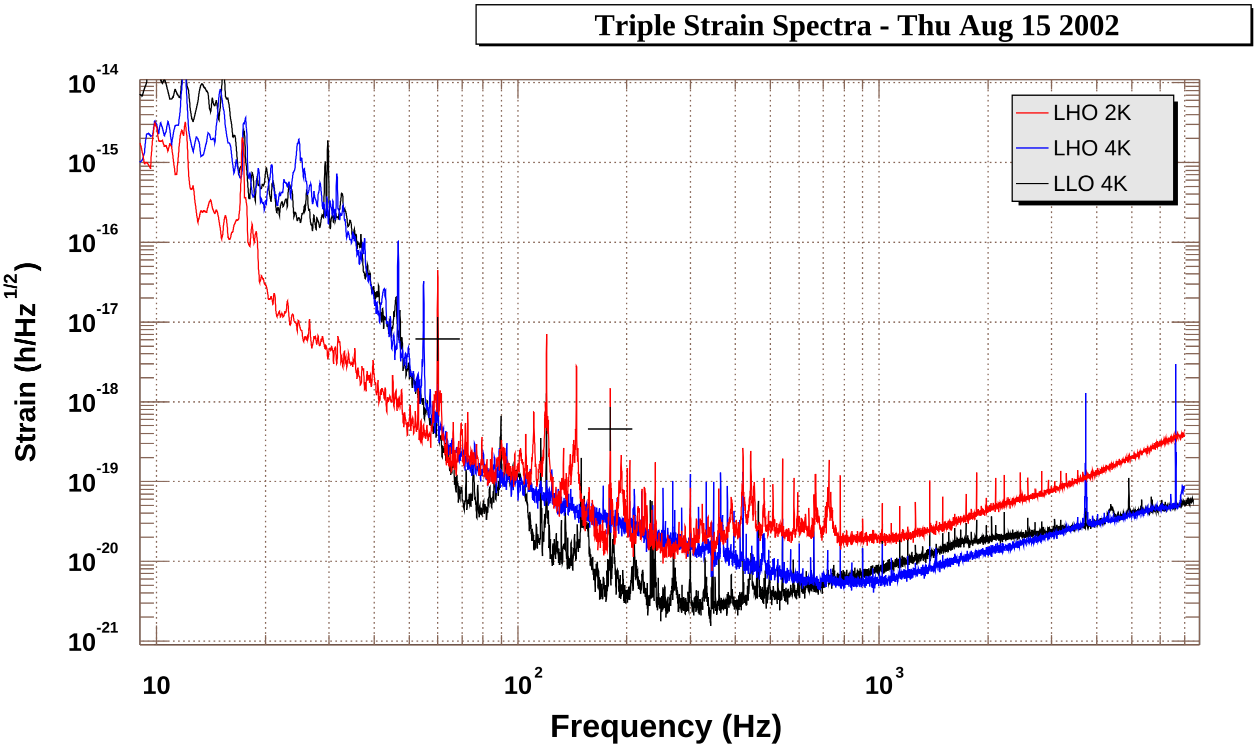
At 8:00 am Pacific time on August 23, LIGO began its first science run, dubbed S1. As the S1 run draws to a close on September 9 it appears to have succeeded in delivering a large data set from which the first analysis effort for scientific results now departs.

In the previous report in MOG, Stan Whitcomb described the dress rehearsal for S1, the engineering run E7. Since E7, the LIGO Scientific Collaboration (LSC) upper limits analysis groups have labored over the data, exercising the analysis codes, developing algorithms and characterizing instrumental properties. The interferometer commissioning teams, consisting of personnel from the LIGO Laboratory and the LSC, have learned much from E7 and incorporated the insights into further development of the interferometers in the march to design sensitivity and to sustained predictable detector operation. To benchmark the progress in interferometer sensitivity, Figure 1 displays the progress in approaching LIGO design sensitivity for the Livingston 4 km interferometer. The December 2001 curves mark the sensitivity



before E7. As LIGO began S1, the three LIGO interferometers were much improved and roughly equally matched in sensitivity and this is displayed in Figure 2.



All three interferometers have operated in the power-recycled mode with individual interferometers operating in good "science" configuration roughly between 50% and 70% of the time. Intersite coincidences in lock have been logged typically about 1/3 of the time. Triple coincidences are logged in the data about 20 - 25% of the time.

As in E7, LIGO and GEO have coordinated their running and the GEO 600 interferometer has been operating with high reliability much of the time. LIGO and GEO have also been joined in coincidence with the veteran TAMA 300 interferometer which skirted construction disturbances at the TAMA site by running in coincidence with LIGO and GEO over the August 30 to September 2 weekend. Arrangements have been put into place between LIGO and GEO, and LIGO and TAMA for coordinated analyses of the data sets.

The LIGO Scientific Collaboration is planning to complete a scientific analysis of the S1 data by the end of the year, prior to S2, the next in the series of progressively more sensitive science runs. S2 and S3 should be carried out at much improved sensitivity, and these runs will extend for progressively longer periods.,

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

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

Fourth international LISA symposium

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The 4th International LISA (Laser Interferometer Space Antenna) Symposium was held at Penn State on July 20-24, 2002. It followed earlier Symposia at the Rutherford Appleton Laboratory near Oxford (1996), at Caltech (1998), and at the Albert Einstein Institute in Golm, Germany (2000).

The present status of LISA is that it is being planned as a joint mission of ESA and NASA. It officially is a Cornerstone Mission in the ESA program, but with the time schedule to be determined in consultation with NASA. From the NASA side, LISA is in the 5 Year Strategic Plan of the Office of Space Science, which means that the OSS hopes to obtain approval for the mission within 5 years. For planning purposes, a possible launch date of about 2011 is being considered.

The Symposium had 9 half-day sessions. The first gave a broad view of gravitational wave astronomy in the LISA epoch, and started with a talk on Science with LISA by Bernard Schutz. Next, Karsten Danzmann described LISA Technology and the Future. The last two talks were by David Shoemaker on Ground-Based GW Interferometers in the LISA Epoch, and by Massimo Cerdonio on Acoustic GW Detectors for the 2012 Timeframe.

Three of the remaining sessions covered LISA Sources and Source Science. One talk by Gijs Nelemans discussed galactic binaries, including their abundance and what can be learned from their signals. The main topic, however, was massive black holes, and their important role in astrophysics.

One important issue is how black holes grow to the roughly $10^5 M_{\rm Sun}$ or larger range, or whether they form with high masses by sudden collapse of large gas clouds or supermassive stars. Another issue is whether information about galaxy formation can be obtained from coalescences of massive black holes already present in pregalactic or galactic structures that merge. Existing and new information relevant to these topics was given in a number of talks by astrophysicists, that were among the highlights of the Symposium. As an example, Tom Abel discussed calculations of the probable mass distribution of the first stars to form, with the mass range up to about $300 M_{\rm Sun}$ appearing to have been favored. Thus many roughly $100 M_{\rm Sun}$ black holes may have formed early from rapid stellar evolution, and some could have gotten into galactic nuclei where massive black holes were being formed.

Another topic discussed in some detail was coalescences of stellar mass black holes and compact stars with massive black holes. Such highly unequal mass coalescences occur when compact objects in the density cusp around a massive black hole get scattered in close enough to start losing substantial energy by gravitational radiation. Sterl Phinney and Steinn Sigurdsson described both recent and earlier work in this area. In addition, the strong tests of general relativity that can be obtained from observing such events or more equal mass coalescences were discussed by Cliff Will.

Some of the other theoretical and data analysis topics included modeling binary black hole coalescence, radiation reaction in strong fields, formation of neutron stars and stellar mass black holes, templates for highly unequal mass coalescences, analysis of galactic binary signals, and the higher harmonic GW content of black hole binary inspiral signals. Tom Prince finished up the sessions on sources by reviewing the LISA science requirements and science challenges.

The highlights of the experimental and technology development sessions were the detailed discussions of the gravitational reference sensors, which also can be described as free mass units. Each of these devices provides a freely floating test mass inside a housing with capacitive electrodes on its inside to detect any relative motion. What gives LISA its high sensitivity, even at frequencies below $10^{-4}Hz$, is keeping the spurious accelerations of the test masses extremely low.

The three LISA spacecraft will be in solar orbit roughly 20 deg. behind the Earth, and form a nearly equilateral triangle 5 million km on a side. Micronewton thrusters are used to keep the spacecraft nearly motionless with respect to the test masses, despite solar radiation pressure and other non-gravitational forces on them. Laser distance measurements are made continuously between the test masses in the different spacecraft, and extremely small GW changes in the distances at periods of roughly a day to a second can be detected.

Almost all aspects of the mission can be tested on the ground. However, it does not appear possible to ground-test the gravitational reference sensors for spurious accelerations to the desired level. Thus ESA is planning a technology validation mission called SMART-2 for a 2006 launch, with demonstrating the gravitational reference sensor performance and the micronewton thrusters as the main objective of the mission. A European LISA Technology Package will be carried to accomplish this, as well as a NASA-provided package called the Disturbance Reduction System. The decision was made recently to provide the US package under the NASA New Millennium Technology Validation Program, since the principles demonstrated will be valuable for a number of other US missions besides LISA.

Two of the major talks were by Stefano Vitale and by William Folkner on the ESA and NASA test packages respectively. They laid the groundwork for additional talks on the detailed design of the units, and on the analysis of the noise sources for them. These included discussions of interferometric measurements of the tiny residual motions of the test masses, control of charging of the test masses due to cosmic rays, mechanisms for caging the test masses during launch, flight experience with accelerometers having many similarities to the gravitational reference sensors, and overall modeling of the expected performance.

Other LISA experimental and technology development talks included two by John Armstrong and Jean-Yver Vinet on the “time-delay interferometry” approach that will be used in LISA. This method has been developed for cancelling out the effects of phase noise in the lasers and some other undesired effects. Plans for making the required phase measurements on the laser signals also were described, and European work on development of the micronewton thrusters was reviewed. In addition, reports were given on the modeling of the motions of the coupled spacecraft and test mass systems, and on modeling of the whole LISA mission.

One other session was included to review progress on the design and construction of ground-based GW detectors. This included interferometric detectors such as LIGO, VIRGO, GEO-600, and TAMA, and also acoustic detectors. TAMA already is operating fairly frequently, and the first science run for LIGO is scheduled for starting in August, with parallel operations planned by GEO-600 and TAMA. Progress also is continuing with the acoustic detectors, including the development of the first spherical detectors, MiniGRAIL and two others, in The Netherlands, Brazil, and Italy.

The Symposium was sponsored by the National Science Foundation Center for Gravitational Wave Physics at Penn State. Co-sponsors included NASA’s Jet Propulsion Laboratory, and travel assistance for some European attendees was provided by the European Space Agency and the new Albert-Einstein-Institute for Experimental Gravitation. The very efficient and helpful Chair of the Scientific Organizing Committee was Sam Finn from Penn State.

Initial Data for Binary Systems

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The *Center for Gravitational Wave Physics* at the Pennsylvania State University held its first *Focus Session* on March 29–30, 2002. The topic was "Initial Data for Binary Systems". Organized by Pablo Laguna and myself, the meeting hosted eight invited speakers and thirty participants. The primary goal of the workshop was to foster discussion on current open questions and possible future directions related to the construction of astrophysically relevant initial data representing binary systems containing black holes and neutron stars. This is a very difficult standing problem for the LIGO/LISA source-modeling community. There are currently a number of different approaches that can be used to construct compact-binary initial data. Unfortunately, the only thing we are sure of is that, in one way or another, all of these current methods fall short of the goal of representing astrophysical systems with sufficient fidelity. With these initial data serving as the starting point for full numerical simulations of the plunge and coalescence of compact binaries, it is clear that, at the very least, the quality of the initial data needs to be well understood.

Why is it so hard to construct realistic initial data for compact binary systems? A combination of factors come into play. The initial value problem of general relativity is a *constrained* hyperbolic system. At any given instant of time, the gravitational fields must satisfy four constraints that can be posed as a set of elliptic boundary-value equations. Solving these equations represents the primary computational difficulty in constructing initial data, and this aspect of the problem has received considerable attention. However, solving the constraints only fixes one-third of the degrees-of-freedom of the gravitational fields. The remaining degrees-of-freedom are divided evenly between the gauge freedom of the theory and the freely specifiable initial dynamical content of the gravitational fields. Historically, the choices for these latter degrees-of-freedom have been based largely on what would simplify the problem of solving the constraints, not on what would produce the most realistic data. There are of course additional problems. The exact definition of *astrophysically realistic* initial data is not fully understood. Furthermore, given only the initial data for a gravitational system, it is impossible (except for special cases) to determine its full physical content. This requires evolving the data.

The schedule for the *Focus Session* was designed to foster active discussion. There were four sessions over two days. Each session was limited to two half-hour invited talks, with each talk followed by an hour of discussion. Participants were encouraged to prepare one or two transparencies and to ask the session chairs for time to present these at an appropriate time during the discussion sessions. The first day offered talks by Peter Diener, Philippe Grandclément, Richard Matzner and myself.

Philippe Grandclément and I each presented new approaches for constructing binary black hole initial data. These approaches are very similar and try to extend to black holes an approach that has been very fruitful for the case of neutron stars. They incorporate an approximate helical Killing vector, or a notion of quasi-equilibrium, into the process of constructing the data. The most important feature of these approaches is that they employ a much different method for fixing the extrinsic curvature. For black holes, essentially all approaches for constructing initial data have used an analytic solution of the momentum constraints (the Bowen-York solution) to fix the extrinsic curvature. Recent attempts to improve black hole data have used superpositions of the extrinsic curvature of a boosted Kerr black hole as a foundation for the extrinsic curvature. A difficulty with either of these approaches is that they incorporate an unknown contribution to the freely specifiable dynamical content of the data. Loosely speaking, some amount of unphysical junk is built into the data. In the new approaches discussed, the only assumption built into the extrinsic curvature is that it should, at least instantaneously, lead to a stationary geometry. (Technically only the conformal three-geometry is instantaneously stationary.) This new approach for specifying the initial data for black-hole binaries in quasi-circular orbits seems to yield results that are in better agreement with post-Newtonian results.

Richard Matzner presented a talk on using a superposition of boosted Kerr geometries as background data for solving the constraints. He also discussed many issues related to the physics of close binaries: the meaning of the innermost stable circular orbit (ISCO), the effects of spin and frame dragging, and tidal forces. This use of superposed boosted Kerr geometries as background data for solving the constraint equations is among the first attempts to employ more realistic choices for the freely specifiable initial dynamical content of the initial data.

Another theme of the meeting was to explore the possibility of incorporating, into initial data, information from post-Newtonian solutions for binaries in circular orbits. Peter Diener presented what may be the first attempt to use this information in fixing the background fields for both the metric and extrinsic curvature. This approach relies on using post-Newtonian solutions in the "ADM transverse-traceless" gauge. It seems that a major difficulty with the idea of incorporating post-Newtonian information is that different parts of the post-Newtonian solution are only well defined in certain regions (near-zone, wave-zone, far-zone).

These issues were explored again on the second day of the *Focus Session* when talks were given by Bala Iyer, Thomas Baumgarte, Kōji Uryū, and Olivier Sarbach. Bala Iyer gave an overview of how waveforms for inspiralling compact binaries are computed in post-Newtonian formalisms. This led to an extensive discussion about what information from the various post-Newtonian calculations could be incorporated into a background metric for use in solving the constraints. The consensus was that much of the wave information cannot be taken directly from current post-Newtonian calculations. One suggestion, however, was to use some kind of numerical post-Minkowski approach to obtain wave information that could be incorporated into a background metric.

Thomas Baumgarte and Kōji Uryū each presented approaches that used sequences of individual initial-data sets to model the inspiral of a neutron-star binary system. While their approaches were rather different, both made the assumption of a quasi-adiabatic inspiral and computed the gravitational waveforms being produced. In Thomas Baumgarte's approach, each initial-data configuration was evolved in a full dynamical code, with the restriction that the neutron-star matter sources were "frozen" in the corotating frame. After several orbits, the configuration reached a steady state and the gravitational waves being emitted were extracted. Kōji Uryū's approach differed in that it solved for a perturbation of the initial metric, evolved a linearized system, and expanded the perturbation in spherical harmonics. Although they followed different approaches, they both computed the gravitational-wave luminosity and then estimated the radiation reaction timescale in order to produce waveforms. These approaches seem to be promising avenues for computing the gravitational waveforms down to a point near the ISCO, and for providing corrections to the background metric which can be used to improve initial-data computations.

In the final talk, Olivier Sarbach presented results for a rather new approach for constructing black hole initial data. This approach differs from others in that it constructs initial data that is strictly of the Kerr-Schild type. While it isn't clear if this restriction will allow for constructing astrophysically realistic binary initial data, it is well suited for constructing data that can be used in “close-limit” perturbative evolutions. Such computations are especially useful for comparison with full nonlinear evolution codes.

I want to close by offering my thanks to the directors and staff of the *Center for Gravitational Wave Physics* for their support in running this *Focus Session*. They did a great job. Especially enjoyable was a wonderful banquet, hosted by Abbay Ashtekar, held Friday evening at a local Indian restaurant. A great time was had by all.

A full listing of the talks, along with copies of the speakers’ slides, can be found at http://cgwp.gravity.psu.edu/events/InitialData.

Joint LSC/Source Modeling Meeting, 20-24 March 2002

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In parallel with the March meeting of the LIGO Scientific Collaboration (LSC), there was a workshop to discuss formation of source working groups for interferometric gravitational-wave detectors. The workshop was motivated by the growing need for a tighter coupling of the gravitational-wave source-analysis community to the experimental gravitational-wave projects. The meeting took place at the LIGO Observatory in Livingston, Louisiana over three days interlaced between the LSC meeting. Many of the presentations are available from the LSC web site [1].

On the evening of the first day, the source analysts gave a series of short (15 minute) presentations about the state of source modeling as a field. Over the course of a long evening from 4pm until 10pm, attendees were shown the breadth of ongoing work. The presentations covered inspiral of compact binaries, binary black hole mergers, binary neutron star mergers, neutron-star black-hole mergers, stellar collapse and neutron star vibrations. Despite the short time available for each presentation and the long evening, presenters attempted to give a flavor of their work, where it stands, and where it is going.

The second day of the meeting was given over to the formal sessions of the LSC in the morning, and to presentations about how source analysts might interface with data analysts in the afternoon.

The third day of the meeting began with a series of presentations/panel discussions by data analysts. These presentations were intended to initiate the discourse on the need for information about sources. Considerable emphasis was placed on data analysis techniques other than matched-filtering, which the source analysis community is already familiar with. The discussion focused on the use of time-frequency methods in the detection of gravitational waves, emphasizing how information from the source analysts can be used to develop data analysis algorithms even in the absence of knowing the full waveform. Two examples of urgent needs for the ground-based detectors are: (1) Information on the phase evolution of waves from the late ("IBBH") stage of compact binary inspiral (where post-Newtonian expansions fail). (2) Information from numerical relativity simulations of black-hole merger waveforms which can be used in applying the excess-power algorithm. During the session on LISA data analysis, the needs were shown to be somewhat different at this time. For example, the first urgent need is to acquire sufficient science information to firm up LISA's noise curve by December 2003.

By the end of the session, it was clear that source analysis should be guided by the data analysis needs, and the development of data analysis algorithms will be more effective if source analysts participate to some degree. As the community moves from the goal of first detection of gravitational waves toward gravitational-wave astronomy, interpretation of the data will inevitably lead to closer coupling between source analysts and data analysts; when that happens, those with experience will benefit most from the mutual give and take

Separate from this meeting, NASA and NSF have been discussing a possible new initiative to fund source modeling efforts in the gravitational wave community. Members of a joint NASA/NSF panel, chaired by Saul Teukolsky, were present at the meeting and took the opportunity to obtain feedback for their report. An open discussion, in which Teukolsky explained the panel's mandate[1] took place on the afternoon of the second day. The discussion was animated and helped to identify the needs of the community. The report from the Teukolsky panel is now available [2].

The third day finished with a discussion of how to coordinate the efforts of the two communities more coherently. Several different methods were advocated: closer connection with the experiments [for example, through the Astrophysical Source Identification and Signatures (ASIS) group of the LSC], groups organized by source and led by their members. Once again, the discussion was animated and brought out problems with each of the possible ways to organize. In many cases, the purpose of such organization was called into question. In the end, however, it was clear that those involved in target-source data analysis had a strong desire to bring the source analysis community closer to the data analysis activities. Moreover, there is a community which wants a closer connection to the gravitational-wave experiments without direct obligation to provide deliverables to the LSC or another collaboration. The outcome of the discussions was the formation of several source groups to facilitate communication among its members with two goals:

1. The data analysts should educate the source analysts about gravitational-wave data analysis, and most especially about what kinds of source-analysis information will be useful, and in what ways, in data analysis.
2. The source analysts should educate the data analysts about source analysis and simulations, and most especially about what kinds of information it will be possible to supply for the data analysis and on what timescales.

Following the workshop in March, five source groups have formed. (In fact, another group centered on sources of stochastic gravitational waves is also forming.) At least two facilitators have been identified within each group (one data analyst and one source analyst) in the hope that they can help the groups get started. The facilitators' roles may become less important as the groups begin to self-organize. Information about the groups can be found at http://www.lsc-group.phys.uwm.edu/gwawg along with links about membership and to mailing lists for each group. Anybody interested in participating should join the mailing list which will be the venue for preliminary discussion/organization. The five existing groups are listed here with a descriptive paragraph adapted from the web site:

Inspiral of Comparable Mass Binaries This group will focus on the late stages of inspiral, up to the final plunge and merger, for BH/BH, NS/BH, and NS/NS binaries. Source analysis is currently being carried out via post-Newtonian methods, resummation methods, and numerical relativity methods. Data analysis is currently via matched filters using post-Newtonian (or kludged) waveforms, and by the fast chirp transform.

Source Analysis Facilitators: Bala Iyer and Thomas Baumgarte
Data Analysis Facilitator: Jolien Creighton

Binary Black Hole Mergers This group will focus on plunge from the innermost stable circular orbit and the final merger of binary black holes. Source analysis is currently by numerical relativity techniques. Data analysis is currently via various time-frequency techniques.

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[1] The panel's mandate was to identify the most urgent needs for LIGO and LISA in the area of theory involving large-scale computing and, if necessary, to identify the level of additional resources required to deal with those needs.

Source Analysis Facilitators: Bernd Bruegman and Luis Lehner
Data Analysis Facilitator: Patrick Brady

NS/NS and NS/BH Binary Mergers This group will focus on plunge induced by combined general relativity and tidal couplings, bar formation and evolution, oscillations of neutron stars. It will also focus on tidal disruption of the neutron star by the black hole in NS/BH binaries. Source analysis is currently by numerical simulations (Newtonian, post-Newtonian, and fully relativistic). Data analysis is currently via various time-frequency techniques.

Source Analysis Facilitators: Fred Rasio and Masaru Shibata
Data Analysis Facilitator: Ben Owen

Stellar Collapse This group will focus on core collapse at end of stellar evolution to form a neutron star, a centrifugally hung-up protoneutron star, and/or a black hole; accretion-induced collapse of a white dwarf; collapse of a supermassive star for LISA; dynamical or secular instabilities of neutron stars. Source analysis is currently by numerical simulations (Newtonian, post-Newtonian, and fully relativistic), and by study of stability and dynamics of equilibria models. Data analysis is currently via time-frequency techniques.

Source Analysis Facilitator: Tony Mezzacapa
Data Analysis Facilitator: Warren Anderson

Inspiral of Compact Objects into Supermassive Black Holes This group is already rather far along in its organization and work, and is attached to LISA Working Group 1. It focuses on white dwarfs, neutron stars, and stellar mass black holes captured into small-periastron orbits around a supermassive black hole in a galactic nucleus; evolution of the orbits under radiation reaction and via perturbations of other orbiting objects and via interaction with accretion disks; transition to plunge and capture. Source analysis is via black-hole perturbation theory and N-body simulations for capture computations as input for estimating capture rates. Data analysis is expected to be by hierarchical techniques that involve mixed coherent (matched-filter) and incoherent methods. Data analysis work includes separating the strongest sources from the background of weaker inspiral waves and WD/WD binary waves.

Source Analysis Facilitator: Scott Hughes
Data Analysis Facilitator: Curt Cutler

Most of these groups are embryonic and all interested parties are encouraged to join in and help define their activities.

References:

[1] LIGO Scientific Collaboration web site:
http://www.ligo.caltech.edu/LIGOweb/lsc/lsc.html.

[2] *Preliminary Report of the Task Group for an NSF/NASA Computational Initiative on Gravitational Wave Science* is available from http://gravity.phys.psu.edu/~tggweb/ or http://astrogravs.gsfc.nasa.gov.

Greek Relativity Conference, NEB-X

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The 10th Greek Relativity meeting has been hosted by the Thessaloniki group in Kallithea, Chalkidiki, an idyllic sea resort near Thessaloniki, from May 29 till June 2, 2002. The series of meetings of the Greek relativity community, named NEB (New Developments in Gravity), was initiated by Basilis Xanthopoulos in 1984. Since then, every second year Greek Relativists working either in Greek universities or abroad meet to present their research work and to discuss recent developments in gravity.

This year's meeting (http://www.astro.auth.gr/gravity/)attracted increased international participation with respect to the previous ones, in an attempt to promote NEB into a regional meeting for South-East Europe. Several of the world's top relativists were invited and delivered plenary talks in Cosmology, Mathematical Relativity, Relativistic Astrophysics, Gravitational-Wave Detection and Quantum Gravity

In the first session, the focus was on Cosmology and Brane Gravity. Roy Maartens gave a review talk on the geometry, dynamics and perturbations of brane-world models. The simplest of these models are able to reproduce the predictions of general relativity at low energies, while introducing interesting new features at high energies - for example in the very early universe, or during gravitational collapse to a black hole, or in cosmic ray showers. A new method for constructing branes of any dimensionality was presented by Nikolaos Batakis while Georgios Kofinas showed an analysis of the induced brane dynamics, when the intrinsic curvature term is included in the bulk action. The invariant description of Bianchi-homogeneous 3-spaces, by considering the action of the automorphism group in the configuration space of real, symmetric and positive definite 3×3 matrices, was the subject of the talk of Theodosios Christodoulakis. The session continued with Nicolaos Spyrou, who presented work on the conformal-invariance approach of hydrodynamical flows in cosmological models. Leandros Perivolaropoulos in his talk showed that the redshift of pressureless matter density due to the expansion of the universe, generically induces small oscillations in the stabilized radius of extra dimensions (the radion field); low-frequency oscillations lead to oscillations in the expansion rate of the universe, which could naturally resolve the coincidence problem. A dynamical systems approach to scalar field cosmologies has been presented by John Miritzis, who analyzed general mathematical properties of the differential equations describing the evolution of FRW models. Argyris Nicolaidis described how experiments may yield proof of the existence of extra dimensions of space, and Christos Eleftheriadis concluded the session with a presentation of the CAST experiment at CERN, aiming at the detection of axions.

The second session, devoted to Mathematical Relativity, opened with Jiri Bicak's in-depth review of exact models of radiative spacetimes. Sayan Kar argued that the Kalb-Raymond field, coupled gravitationally to the Maxwell field, can lead to a wavelength-independent optical activity in synchrotron radiation from cosmologically distant radio sources. Work aimed at finding interior, anisotropic fluid solutions, matched to the Kerr metric, was reported by Taxiarchis Papakostas, while the conditions under which the nonradial stresses might prevent spherical gravitational collapse were discussed by Petros Florides. Dimitris Tsoubelis presented a new family of integrable nonlinear systems that include the Ernst equation for colliding gravitational waves. Anastasios Tongas discussed geometrical aspects of integrable nonlinear equations of the Schwarzian type. Spyros Cotsakis reported on work with Y. Choquet-Bruhat in which they prove completeness theorems in general relativity under generic geometrical assumptions, while George Papadopoulos presented a talk on an alterative proof of the generality of the Kantowski-Sachs vacuum, based on general coordinate transformations that preserve spatial homogeneity. The definition of conserved quantities in general theories of gravity was discussed by Andreas Zoupas. The session ended with a presentation by Christos Tsagas on how gravitational waves can produce and sustain large-scale magnetic fields, strong enough to seed the galactic dynamo.

The next session was devoted to Astrophysical Relativity and the Detection of gravitational waves. Bernard Schutz gave a thorough introduction on the most promising astrophysical sources of gravitational waves for the new-generation detectors, while on the experimental side Gabriela Gonzalez updated us on the current status of the LIGO detectors. In the same session, Remo Ruffini gave a historical review of the gamma-ray burst puzzle and summarized the current theoretical understanding. 3-D numerical simulations of rotating relativistic stars and the first computation of their quasi-radial modes of pulsation in rapid rotation were shown by Nick Stergioulas, followed by a report by Theocharis Apostolatos on computations of differentially rotating relativistic stars and their pulsations. The effect of quasi-normal mode excitation on the detection of gravitational waves from neutron star binaries was discussed by Emanuele Berti. Kostas Kokkotas argued in his talk that, due to the r-mode instability, strange stars can be a good and persistent source of gravitational waves. Uli Sperhake talked about his studies on nonlinear radial oscillations of relativistic stars viewed as deviations from an equilibrium state, and Adamantios Stavridis reported on recent computations of r-modes in relativistic stars, showing that discrete modes exist in most cases, due to the coupling of axial and polar terms. Dimitrios Papadopoulos talked on acceleration and cyclotron radiation induced by gravitational waves, Sotirios Bonanos ended this session with a description of the capabilities of his "Riemannian Geometry and Tensor Calculus" package for Mathematica, which is freely available at http://www.inp.demokritos.gr/˜sbonano/RGTC/RiemannTensorCalculus.html.

The conference concluded with a special review by Jorge Pullin on the stability properties of various discrete versions of Einstein's equations, and their use in the canonical quantization of general relativity.

The next (11th) Greek Relativity meeting will take place in Lesvos, in the summer of 2004 http://www.astro.auth.gr/gravity/NEB.html.

Gravity, Astrophysics, and Strings @ the Black Sea

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The first international conference Gravity, Astrophysics, and Strings @ the Black Sea took place from June 10 till June 16, in a small town on the Bulgarian sea shore, called Kiten. Somebody suggested that if we rename the place by replacing the "K" with "W", the conference will have much greater success. Actually, a brief account of the lectures presented at the meeting, suggests that the endeavor achieved our main goal - to bring together experienced researchers from the title subjects with younger physicists and students, mostly from the South Eastern corner of Europe. The meeting was organized by the Joint Group in Gravity and Astrophysics, including researchers from various institutions in Sofia. The participants were representing local researchers, students, and scientists from major institutions in roughly equal proportions. As the title suggests, our idea was to gather researchers from relatively distant although related areas and explore the consequences of this diversity.

Edward Seidel (MPI) opened the Conference by giving his first lecture on the Numerical Relativity and Its Applications to Gravitational Wave Astronomy. In total of 4 hour-long lectures the foundations of numerical relativity ware described. The theoretical formulations of Einstein's equations, tools and techniques for analyzing black hole space-times, gravitational waves, boson stars, relativistic hydrodynamics, and other topics were covered. Gabrielle Allen (MPI) introduced the CACTUS Toolkit as a freely available, modular, portable and manageable environment for collaboratively developing parallel, high-performance multi-dimensional simulations. Jorge Pullin (Louisiana State U) presented some new ideas on consistent discretizations in classical and quantum gravity. A very interesting discussion on Supercomputing in Europe completed the first day program. No question about it: Indeed, there was a Welcome Party in the evening.

On the second day, D. Sasselov (Harvard U) acquainted the audience with the first atoms in the Early Universe and the cosmic wave background radiation. Before lunch, U. Sperhake (Aristotle U of Thessaloniki) presented a numerical approach, which enables us to evolve radial oscillations of neutron stars over large amplitude range with high accuracy. In the afternoon, K. Kokkotas (Aristotle U of Thessaloniki) started his series of lectures on the recent results on instabilities of different kind of relativistic stars, and especially of neutron stars. Many new numerical results of different scientific groups were reported. Also, R. Rashkov (Sofia U) gave a review for students on strings, brane worlds, and Ekpyrotic theory. In these lectures a brief but intense review was given of the progress in understanding String theory and its implications to gravity, cosmology and gauge theories.

The third day started with some of the follow-ups of the abovementioned series of lectures as well as a presentation by E. Guendelman (Ben Gurion U) on two measure gravity theories and cosmology, in which the possibility of using a measure of integration independent of the metric was studied. In the afternoon a relaxing excursion took place to the outfall of the nearby Ropotamo river. The remaining program of the day included an account of spherically symmetric braneworld solution given by E. Papantonopoulos (National Technical U of Athens). After reviewing the known black hole solutions on the brane, the induced gravity scenario was discussed, according to which an R(4) term is induced on the brane. To close the scientific program for the day, M. Vavoulidis (Aristotle U of Thessaloniki) gave a talk on rotating relativistic stars.

On the next day, right on time, M. Bander (U of California, Irvine) resurrected time in quantum gravity. By allowing for non zero vacuum expectation values for some of the fields that appear in the Hamiltonian constraint of canonical general relativity a time variable, with usual properties, can be identified; the constraint plays the role of the ordinary Hamiltonian. Before lunch time, E. Horozov (Sofia U) talked about the Weyl algebra and bispectral operators. In the afternoon, another entertaining event took place: The participants in the Conference visited the old towns of Nessebar and Sozopol. These are towns, settled for the first time by the ancient Greeks, with many churches from Byzantine times and old fisherman houses. The closure for the day was provided by the official dinner.

On Friday, M. Todorov (Technical U - Sofia) presented a joint work with T. Boyadjiev, P. Fiziev, and S. Yazadjiev (Sofia U), on a new numerical algorithm for solving a class of BVPs with internal free boundaries. An investigation of numerically models of the static spherically symmetric boson-fermion stars in the scalar-tensor theory of gravity with massive dilaton field was presented. The proper mathematical model of such stars is interpreted as a nonlinear two-parametric eigenvalue problem with an unknown internal boundary. After that, P. Fiziev (Sofia U) gave the first of his pair of lectures on the basic principles of 4D dilatonic gravity and some of their consequences for cosmology and astrophysics. E. Nissimov (Bulgarian Academy of Science) completed the morning session by presenting his work on strings and branes with dynamically generated tension. The properties of a new class of string and p-brane models free of any ad hoc dimensionful parameters were discussed.

P. Bozhilov (Shoumen U) started the afternoon session by presenting his work on probe brane dynamics in nonconstant background fields. A probe p-brane dynamics in string theory backgrounds of general type was considered, with an action, which interpolates between Nambu-Goto and Polyakov type actions. In his talk, B. Ivanov (Bulgarian Academy of Science) acquainted the audience with his work on the maximal bounds on the surface redshift of anisotropic stars. It was shown that for realistic anisotropic star models the surface redshift cannot exceed values, higher than 2, the bound in the perfect fluid case, when the tangential pressure satisfies the strong or the dominant energy condition, respectively. R. Rashkov (Sofia U) completed the program for the day, by presenting his talk on the physical states in vacuum string field theory.

In a spark of scientific enthusiasm, the Conference continued its work on Saturday. P. Fiziev (Sofia U) and R. Rashkov (Sofia U) completed their series of lectures and V. Gueorguiev discussed the subject of relativistic particle and its D-brane cousin. The properties of classical reparametrization-invariant matter systems, mainly the relativistic particle and its generalization to extended objects (D-branes) were presented.

All the organizers were very much satisfied with the overall results from the Conference. We concluded that there is a need for such meetings and started preparation for the next one. One of the main supporting arguments was the very convenient Sofia University Summer House, which hosted the Conference. In accordance with the suggestions from the participants, we are considering building a new Lecture Hall, which will be able to host bigger crowds. So, we hope to see you next year at the Black Sea.

Quantum field theory on curved spacetime at the Erwin Schrödinger Institute

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A program on “Quantum field theory on curved space times” was held at the Erwin Schroedinger Institute in Vienna, Austria from July 1 through August 31, 2002. The main goal of this program was to bring together researchers with expertise in general relativity and researchers with expertise in mathematical aspects of quantum field theory, in order to address some problems of mutual interest in quantum field theory in curved spacetime. Approximately 25 researchers in quantum field theory in curved spacetime and related areas participated in the program. The following is a brief summary of some of the main topics and results discussed during the program.

A great deal of progress has been made in recent years in characterizing the “ultraviolet divergences” of quantum fields in curved spacetime and developing renormalization theory for interacting quantum fields. Seminars by S. Hollands, K. Fredenhagen, R. Verch, and R. Wald reported on this recent progress. The difficulties resulting from the lack of a preferred vacuum state and a preferred Hilbert space representation of the canonical commutation relations for the free field have been overcome by formulating the theory within the algebraic approach. The difficulties associated with the lack of a global notion of a Fourier transform (so that the usual momentum space methods for renormalization cannot be used) have been overcome by the use of the methods of “microlocal analysis”. Finally, the difficulties associated with the absence of a notion of “Poincare invariance” (or any other symmetries) in general curved spacetime have been overcome by imposing the condition that the quantum fields of interest be constructed locally and covariantly out of the spacetime metric. The upshot is that perturbative renormalization theory for quantum fields in curved spacetime is now on as sound a footing as in Minkowski spacetime. Furthermore, theories that are renormalizable in Minkowski spacetime will also be renormalizable in curved spacetime, although additional “counterterms” corresponding to couplings of the quantum field to curvature will arise.

Although the Hawking effect was derived more than 25 years ago, there remains a difficulty with the derivation in that it relies on the properties of quantum fields in a regime where one has no right to expect quantum field theory in curved spacetime to be a good approximation. Specifically, consider the modes of the quantum field that correspond to “particles” that are seen by observers near infinity to emerge from the black hole at late times. When traced backward in time, these modes become highly blueshifted and correspond to “trans-Planckian” frequencies and wavelengths at early times. Thus, the Hawking effect appears to rely on assumptions concerning the initial state and behavior of degrees of freedom in the trans-Planckian regime. Similar issues also arise in cosmology when considering the “quantum fluctuations” responsible for the formation of large scale structure at late times. Seminars by Jacobson and Unruh explained the nature of the trans-Planckian issues and described some simple models where the effects of modifying dynamical laws in the trans-Planckian regime can be analyzed. These models support the view that the Hawking effect is robust with respect to changes in physical laws in the trans-Planckian regime.

It is well known that in quantum field theory in flat or curved spacetime, the expected energy density at a point can be made arbitrarily negative. However, during the past ten years, some global restrictions on negative energy have been derived. In particular, “quantum inequalities” have been derived, which put a lower bound on the energy density measured along the worldline of an observer with a (smooth, compact support) “sampling function” $f(\tau)$. Originally, such bounds were derived by non-rigorous methods in certain special cases, but recently a rigorous and completely general derivation of quantum inequalities has been given using the methods of microlocal analysis. Many issues remain open, however, such as the derivation of optimal bounds and whether some version may hold of the average null energy condition (which asserts the non-negativity of the integral over a complete null geodesic of the stress energy tensor contracted twice with the tangent to the null geodesic). These issues were explored in seminars by Ford, Fewster, Roman, Flanagan, and Pfenning. In research arising directly from discussions occurring during the program, progress also was made toward deriving quantum inequalities for quantities other than the stress-energy tensor.

The Bisognano-Wichmann theorem states that in Minkowski spacetime, the restriction of the vacuum state to a wedge region is a KMS state with respect to a 1-parameter subgroup of the Poincare group. (This result can be viewed as a mathematically rigorous version of the “Unruh effect”.) The mathematical theory underlying this result is the modular theory of Tomita and Takesaki. The computation of modular transformations was discussed in a seminar by Ynvason, and the determination of analogous wedge regions and states in deSitter spacetime was discussed by Guido. In Anti-de Sitter spacetime the wedges are in one to one correspondence with double cones in the Minkowski spacetime at spacelike infinity. One thus obtains an algebraic version of AdS-CFT correspondence which was discovered by Rehren. A seminar by Rehren discussed this correspondence in more detail by considering the relation between limits of fields at the boundary and the partition function for specified boundary values.

In the loop variables/quantum geometry approach to quantum gravity, one first defines a “kinematical Hilbert space” and then tries to define the action of the Hamiltonian constraint operator on these “kinematical states”. In this approach, the Hamiltonian constraint operator is not intrinsically well defined (i.e., “regularization” is needed), but the nature of this regularization appears to be very different from the usual regularization of “ultraviolet divergences” occurring in quantum field theory. One of the goals of our program was to explore the nature of renormalization in the loop variables/quantum geometry approach to quantum gravity and to understand its relationship to renormalization in ordinary quantum field theory. Seminars by Lewandowski, Perez, Ashtekar, Thiemann, Bojowald, Fairhurst, and Sahlmann described in detail various aspects of the loop variables/quantum geometry approach. The extended interactions between the researchers in the loop variables/quantum geometry approach and researchers in quantum field theory resulting from these seminars as well as from numerous private discussions were very fruitful. In particular, simple quantum field theory analogs of some of the constructions used in the loop variables/quantum geometry approach were obtained and explored.

Overall, the program appears to have been very successful in promoting considerable productive interaction between groups of researchers who generally have had only limited interaction with each other. One may hope that the “cross-fertilization” and new collaborations initiated by these interactions will bear fruit for many years to come.

School on quantum gravity in Chile

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For ten days in January, nearly 70 grad students and postdocs representing over 13 countries gathered at the Centro Estudios Cientificos (CECS) in Valdivia, Chile for the PASI school on quantum gravity. Supported by the U.S. NSF and DOE through a grant to Syracuse University, by Syracuse University funds, by the Millennium Science Initiative (Chile), and by a group of private companies that supports CECS, the school featured a series of lectures by renowned experts with ample time for questions and discussion. My co-organizer Andres Gomberoff and I were pleased to arrange lectures by Marc Henneaux, Ted Jacobson, Clifford Johnson, Juan Maldacena, Rob Myers, Washington Taylor, Claudio Teitelboim, Bob Wald, and Frank Wilczek. We were also looking forward to lectures by Abhay Ashtekar and Rafael Sorkin and, although both had to cancel due to last minute emergencies, both remained connected to the program. Sorkin was able to send a set of typed lecture notes that were widely read and discussed and questions and comments from several of Ashtekar's students ensured that their point of view was represented.

Though perhaps we are somewhat biased, Andres and I thought that the interactions between the speakers was excellent – in particular, between the string theorists and other quantum gravity speakers. Along with the excellent questions from students, public discussion among the lecturers helped to draw out the important but subtle points in each of the talks. Readers curious about the topics can still find the schedule posted at http://physics.syr.edu/˜pasi/sched.html, but suffice it to say that the range was broad and the quality was excellent. I am very much looking forward to the proceedings that speakers have promised to write (hint, hint!). They will no doubt become a valuable reference for the community.

We were also extremely please with how well the students mixed, though it is unclear whether this was due to the intellectual environment, the pool parties at the hotel, the local Cuban Salsa club, or the sheer joy of the North Americans experiencing summer in January. The contacts made with those from other countries or other perspectives on quantum gravity should serve these students well throughout their career. We are very grateful to CECS for providing a dynamic, stimulating, and lovely environment for the school. Thanks again to everyone who helped to make the event a success!!

"Apples with Apples no Oranges" Workshop on Formulations of Einstein's Equations for Numerical Relativity

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Late Spring saw a very successful workshop concentrating on formulations of the Einstein equations for numerical relativity. The workshop was held at Institute of Nuclear Sciences of the National University of Mexico (UNAM) in Mexico city on May 13-24, and was attended by some 25 people from Mexico, the U.S. and Europe (with a particularly large group from Germany). The purpose of the workshop was to gather a group of experts in the recent developments of the different formulations of the Einstein equations and their applications to numerical relativity. There was a focus in 3+1 formulations, though the conformal approach was also represented. One of the highlights of the meeting was our trip to Teotihuacan, where many a pyramid was climbed and where the god of rain was kind on us by throwing torrential rains during our bus trip to refresh the place, and stopping just as we arrived. But we also talked about physics, of course.

The workshop was motivated by the growing realization in the numerical relativity community that different forms of writing the evolution equations can have tremendous impact in the long term stability and accuracy of a numerical simulation. Some formulations have been show to be either simply ill-posed in a mathematical sense, or else such that well-posedness can not be proved. Such is the case, for example, of the standard ADM formulation. Formulations that can be shown to be well-posed, for example strongly hyperbolic ones, should clearly have an advantage.

During the workshop several key points became clear: hyperbolicity, though desirable, is not enough, as several groups reported that some strongly hyperbolic formulations are far superior than others. Also, hyperbolicity might not even be necessary for long-term stability, as some formulations that are not directly hyperbolic (as the BSSN formulation) have been shown to be remarkably robust. Moreover, recent developments, in particular the introduction of multiple-parameter families of strongly hyperbolic formulations by Kidder et all (the KST family), make it clear that simply comparing many formulations against each other in direct numerical experiments is a difficult task, and theoretical insights are badly needed to help us chose the more promising formulations from an everyday growing zoo.

The meeting lasted two weeks, and was organized with talks in the morning and working sessions in the afternoon during the first week, and informal discussions plus more working sessions the second week. It is difficult to discuss all contributions to the workshop here, but I will make an attempt to mention a few highlights:

On Monday, Lee Lindblom talked about the recent KST family of strongly hyperbolic formulations, and mentioned what I believe to be a very important development in the field, the realization that since symmetric hyperbolic formulations allow a norm to be constructed, one can in fact predict ahead of time the rate of growth of solutions on a given background. This has led to the discovery that this growth is essentially a linear phenomenon, so analysis of linearized equations around non-trivial backgrounds should be sufficient. Carles Bona then presented a framework under which many different formulations, from the ADM and BSSN formulations to the Bona-Masso and KST formulations can be studied under a unified approach.

On Tuesday, Hisaaki Shinkai showed the results of many tests he has carried out with many formulations, and presented the hypothesis that a Fourier mode analysis of linearized equations around specific backgrounds should be a good indicator of which formulation will behave better than others. Thomas Baumgarte presented a beautiful analysis of electrodynamics where he showed how one can construct an analogous of the BSSN formulation in relativity and see very clearly what the benefits of such a form of the evolution equations are. Erik Schnetter talked about ways in which different gauge conditions can and should be enforced during a numerical simulation. Finally, Deirdre Shoemaker talked about recent advances that Pablo Laguna's group at PSU has had in developing formulations based on BSSN, but where care is taken to eliminate some quadratic source terms. Their approach is to look systematically not only at the principal part, but also a lower order terms in the search for better stability.

Wednesday saw the talks representing the conformal approach, given by Christiane Lechner and Sascha Husa. Their approach, based on Friedrich's conformal equations is capable of evolving all the way to null infinity (and beyond), seems to have all the benefits of the Cauchy-characteristic matching and fewer of its problems. Still, at this time it also seems to have problems with long term stability. Wednesday also saw our trip to Teotihuacan.

On Thursday Jeff Winicour and Bela Szilagyi reminded us all of the importance of choosing adequate boundary conditions that are designed to satisfy the constraint equations. Their efforts on developing consistent boundary conditions are a model of what all other groups should be worrying about when writing Cauchy codes. The interaction of boundaries and interior should clearly be taken into account when thinking about the long-term stability of the different codes. Ryoji Takahashi also talked about gauge stability of different 3+1 formulations.

Friday saw a talk by Miguel Alcubierre presenting the stability analysis of BSSN in linearized gravity. Denis Pollney talked about the recent experience of the Potsdam group with BSSN in black hole simulations, and Ian Hawke gave a general talk on how to implement in a simple and systematic way a general method of lines algorithm within the Cactus framework.

Working sessions concentrated in getting the different codes working together under a similar framework. Whenever possible, different codes where ported into the Cactus framework to facilitate sharing initial data and analysis tools. The meeting was very successful, and people have continued to work together several months afterward trying to compare results of the different approaches in specific situations.

As a final personal comment I would like to add that the workshop had also an impact in the Institute of Nuclear Sciences in Mexico, where I work. Initially, a computer terminal room was booked for the working sessions, but it quickly became apparent that laptops and wireless networks could be used to transform our main lecture theater into a much better working environment. The sight of 20 plus people having claimed the main auditorium for two weeks solid, typing away at their laptop keyboards while simultaneously sharing data through the Internet was enough to impress everyone, and in my view showed what should probably become a standard in future numerical relativity workshops.

Radiation reaction focus session and the 5th Capra meeting

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One of the activities supported by the newly created Center for Gravitational Wave Physics at Penn State are *focus sessions*. These are intended to bring together a small group of experts in a single, narrowly defined technical topic in order to make progress (see the article by Sam Finn in Issue 19 of Matters of Gravity). One of the first such focus sessions was held at Penn State from May 24 to 30, dedicated to radiation reaction in general relativity, organized by Warren Anderson, Patrick Brady, Sam Finn and myself. It was followed by the fifth Capra Ranch meeting on radiation reaction, from May 31 to June 2.

Focus session on radiation reaction

One of the primary sources for the space-based gravitational wave detector LISA will be the inspiral of compact objects (neutron stars and solar mass black holes) into supermassive black holes. The last year of inspiral of these systems will typically consist of $\sim 10^5$ or so orbits deep in the relativistic regime near the black hole horizon (Finn and Thorne 2000). In order to compute the gravitational wave signal emitted by these systems, it is hoped to compute the deviations from geodesic motion to linear order in the mass ratio, using black hole perturbation theory. While conservation laws can be used to evolve certain classes of orbits (see, eg, Hughes 2000), the treatment of generic orbits will require the computation of the so-called self force that acts on the compact object.

Over the last few years, several research groups have been developing the mathematical and computational tools necessary for computation of the self force; see the accounts of the previous Capra Ranch meetings in Issues 14, 16 and 18 of Matters of Gravity. The foundations for this effort were laid by a pair of papers in 1997 (Mino, Sasaki and Tanaka 1997; Quinn and Wald 1997), which derived a general formal expression for the self force in an arbitrary vacuum spacetime. The challenge has been to translate this expression into a practical computational scheme for orbits in the Kerr spacetime. Such a computational scheme may also be useful for compact objects spiralling into middleweight black holes ($\sim 10^3 M_\odot$) which may be detected by ground based detectors (see the article by Ben Bromley in Issue 14 of Matters of Gravity). While several different computational schemes are being explored, the most developed and most promising contender at the moment seems to be "mode sum regularization", in which one (i) computes using black hole perturbation theory the contribution $f^\alpha_{lm\omega}$ to the self force on a point particle from the mode $lm\omega$; (ii) subtracts from this an analytically computed counterterm involving some regularization parameters; and (iii) sums over all the modes to determine the total self force (see, eg, Barack et. al. 2002 and references therein). This scheme has by now been implemented to compute gravitational self-forces in the Schwarzschild spacetime (Barack and Lousto 2002). The challenge now is to extend the analysis to the Kerr spacetime.

It was to address this challenge that Sam Finn instigated the focus session. We were fortunate to be able to attract most of the key researchers in the field to attend; eighteen people in all were given office space and internet connections for a week. The format and organization of the focus session was significantly different from traditional conferences based around presentations, and was aimed instead at promoting interactions and collaborations among the participants. While one or two black board talks/discussions were scheduled most days, a significant amount of time was left open.

Some of the highlights of the week were as follows. On the first day Yasushi Mino gave a detailed overview of the status of self-force computations, and Scott Hughes reviewed LISA Science objectives. One of the key technical issues that dominated the discussions of the week was the incomplete status of the theory of linear perturbations of the Kerr spacetime. Specifically, one needs to be able to reconstruct the metric perturbation from the Weyl scalars ψ_0 and ψ_4 for general non-vacuum linear perturbations. Bernard Whiting discussed a proposed method of completing the formalism of Chrzanowski (1975) as corrected by Wald (1978), and Amos Ori discussed another possible method. Steve Detweiler talked about how one might deal with the fact that the Teukolsky-Sasaki-Nakamura perturbation formalism does not include the the "$l = 0, 1$" modes which are needed for self-force computations. Another theme was the freedom of choice in the analytically computed counterterms that one uses to renormalize the self force due to a particular mode. Leor Barack discussed the details of one choice of counterterms, and Steve Detweiler discussed another choice that increased the speed of convergence in the sum over modes (Detweiler, Messaritaki and Whiting 2002) based on a definition of a regularized self-field that satisfies the homogeneous wave equation (Detweiler and Whiting 2002).

Eric Poisson discussed the necessity of going beyond the computation of the self-force to calculate the gravitational wave signal, and the problem that linear perturbation theory is strictly speaking insufficient to compute the gravitational wave signal from the inspiralling orbit that includes the backreaction. For the most general contexts, it will be necessary to use second order perturbation theory (Campanelli and Lousto 1999), a daunting prospect! However, in the adiabatic inspiral regime relevant to most of the observations, it seems likely that the linear perturbation formalism will be highly accurate, and there was some discussion of how one might justify this using a two-timescale expansion of the Einstein equations rather than a straightforward perturbation expansion.

One particularly useful talk was Bob Wald's review of the construction of Green's functions via Hadamard expansions, in which he debunked several myths that have appeared in the relativity literature. In particular, the radius of convergence of the Hadamard series can be zero for smooth Lorentzian metrics, and outside of a normal neighborhood one cannot in general compute a Green's function $G(x, x')$ by summing over the geodesics that join x and x'. Eric Poisson discussed how the Mino-Sasaki-Tanaka-Quinn-Wald self-force expression, when specialized to weak fields and slow motions, reproduces the standard post-1-Newtonian results wherein the self force has a conservative part but no dissipative part (Pfenning and Poisson 2002). A separate approach to computing self-forces would be to use a numerical, time-domain Teukolsky code rather than splitting the field into modes. Carlos Lousto reviewed the status of this field of research. Warren Anderson discussed computations with Adrian Ottewill and myself of a local expansion of the tail piece of the metric perturbation, which could be used as a foundation for a different type of regularization method.

There was an enthusiastic consensus by the end of the week that the format had worked very well, and that the intensive discussions that grew out of the blackboard talks were very useful. These discussions spilled over into the coffee breaks, the offices of the participants, and to the picnic hosted by Sam Finn one evening. The meeting was particularly useful because the people involved had already formed a small, closely knit group via the previous Capra Ranch meetings, and most of the group were focusing closely on a specific narrowly defined research area. I expect that many of the discussions at the sixth Capra meeting next summer will involve research projects and collaborations that were germinated at the focus session.

Fifth Capra Ranch Meeting

The primary focus of the meeting was radiation reaction of point particles, as in previous years, but there was also broader, forward-looking focus on radiation reaction effects in general and in particular in numerical relativity and astrophysics. We followed the informal format used in previous meetings where equal time was allotted to talks and discussions.

The meeting opened with a presentation by Amos Ori on a suggested method for computing the metric perturbation in the ingoing radiation gauge from the Weyl scalars ψ_0 and ψ_4 in the Kerr spacetime, based on working in the frequency domain. He described how this method could be used in principle to compute self forces (see Ori 2002 for details). Yasushi Mino described work in progress on a different approach towards computing the self force in Kerr, using the Regge-Wheeler gauge and an expansion in powers of the black hole's spin parameter a.

Leor Barack and Carlos Lousto discussed different aspects of their recent and ongoing work on computing gravitational self forces in the Schwarzschild spacetime (Barack and Lousto 2002), based on the method of Barack *et. al.* (2002). They described the analytic computation of all the regularization parameters needed for a generic orbit, completed computations for radial trajectories that agreed with the ζ-function regularization scheme of Lousto (2000), and ongoing work on circular orbits. Leor also described analytic computations of the large l behavior of the un-renormalized self force; this information was used to improve the speed of convergence of the sum over modes.

Lior Burko described computations of scalar field radiation reaction for particles in circular orbits about Schwarzschild black holes (Burko 2002), which incorporated corrections to the phasing beyond the leading order in an expansion in the mass ratio (corresponding to an accumulated phase correction of order unity during an inspiral). He discussed the fact that such higher order corrections may eventually be necessary for precision astronomy with LISA.

Steve Detweiler described the Green's function decomposition of Detweiler and Whiting (2002). The advantages of this decomposition over earlier decompositions is that the corresponding regularized metric perturbation is a smooth solution of the homogeneous wave equation, and the particle's motion is a geodesic of the regularized perturbed metric. He also described how the use of a particular normal coordinate system defined by Thorne and Hartle (1985) and extended by Zhang (1986) greatly simplifies the local computation of the singular piece of the metric perturbation that is subtracted, and related the construction to the derivation of the self force based on matched asymptotic expansions given in Detweiler (2001). He then described scalar self-force computations for particles in Schwarzschild (Detweiler, Messaritaki and Whiting 2002) and also new gravitational self-force computations, and showed how the use of the new decomposition speeded up the convergence of the sum over modes.

Saturday started with Eric Poisson describing ongoing work with Claude Barrabès in which he defined a coordinate system called retarded normal coordinates, which are closely related to Fermi normal coordinates except that the construction is based null geodesics rather than spacelike geodesics. He showed how the use of these coordinates rather than other types of normal coordinates greatly simplifies the computations in the classic papers of Dirac (1938) and DeWitt and Brehme (1960), and he anticipated that they would also simplify the computations of Mino, Sasaki and Tanaka (1997) and Quinn and Wald (1997).

Next, Manuela Campanelli described a formalism for computing second order perturbations of Kerr black hole in the time domain using the Weyl scalar ψ_4 (Campanelli and Lousto 1999). She described how to obtain second order quantities that are invariant under both coordinate transformations and tetrad rotations, and showed impressive numerical results comparing the second order gravitational waveform from binary black holes in the close limit with the waveform from full numerical relativity and with the first order waveform. She explained that the main roadblock to applying the code to compute self-forces is the necessity to regularize the formally infinite source terms representing the point particle. On a similar note, Karl Martel described numerical work in which he explored replacing a delta function source with a Gaussian profile, in the context of computing the scalar field sourced by a point particle in Schwarzschild. He compared the waveform obtained from the smeared source to that from the exact source for a point particle, for computations in both Schwarzschild coordinates and Painlevé-Gullstrand coordinates. He showed that good agreement between the waveforms was obtained when the width of the Gaussian profile was suitably chosen.

Bernard Whiting then gave a talk in which he discussed a number of issues, including the status of the problem of the $l = 0, 1$ modes in Kerr, the reason why increased smoothness of the regularized metric perturbation gives rise to improved convergence properties of the sum over modes, and analogous phenomena involving convergence and smoothness that arise in LIGO data analysis. He also discussed the prospects for generalizing to the Kerr spacetime the formalism of Lousto and Whiting (2002) for reconstructing metric perturbations from Weyl curvature perturbations in Schwarzschild, in which he emphasized the key role of the algebraically special solutions.

Ian Jones described an ongoing project at Southampton University aimed at including local radiation reaction forces in nonlinear Newtonian and post-Newtonian hydrodynamic codes. He discussed numerical difficulties involved involved in evaluating the local force expressions caused by the large number of time derivatives required. He reviewed a particular formulation of post-1-Newtonian hydrodynamics due to Blanchet, Damour and Schaeffer that eliminates the time derivatives, and which is well adapted to mass quadrupole radiation reaction, and indicated that they planned to use an extension of this formalism being developed by Faye and Schaeffer to incorporate current quadrupole radiation reaction.

Mark Miller described fully general relativistic, 3+1 dimensional simulations of binary neutron star inspirals, using the code described in Font et. al. (2001), and compared the orbital decay rate obtained to the decay rates obtained from post-Newtonian computations. The full GR code evolved the binary for 10 orbital periods. He explained that oscillations observed in the stellar separation suggested that the initial data used actually corresponded to a slightly eccentric binary. He also showed how to use Richardson extrapolation with several runs with different outer boundaries and grid sizes to estimate the computational error. Currently the error in the decay rate is comparable to the decay rate itself, but the errors will improve with time. He also described computations of binding energy curves for binaries obtained using the so-called conformally-flat, quasi-equilibrium approximation, and the orbital decay rates obtained by combining those binding energy curves with the quadrupole energy loss rate. To compute the binding energy curves, he advocated a new prescription in which one subtracts from the total ADM mass of the spacetime the sum of the ADM masses of isolated, *rotating* neutron stars with appropriately chosen angular momenta (rather than isolated non-rotating neutron stars as had been done in the past).

The Capra meeting, like the focus session, was supported by funds from the Center for Gravitational Wave Physics. Thanks are due to Sam Finn for his organizational skills. All of the presentations can be found online at http://cgwp.gravity.psu.edu/events/Capra5/capra5.html.

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Numerical Relativity Workshop at IMA

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The *Numerical Relativity (NR) Workshop* organized by the Institute for Mathematics and its Applications (IMA) at the University of Minnesota and jointly sponsored with the Center for Gravitational Wave Physics (CGWP) at Penn State, took place in IMA's facilities from June 24th to June 29th (the last week of the 2002 Soccer World Cup, a detail not ignored by many of the attendees).

As announced, the workshop effectively "brought together numerical relativists and mathematicians working in fields such as numerical analysis, scientific computation, partial differential equations and geometry, for an intense but informal period aimed at maximal communication and interaction between diverse researchers". Considerable effort was put in bringing these communities closer. Relativists tried to describe the status and problems of NR and differences between General Relativity (GR) and Maxwell theory or fluid dynamics. On the other hand, numerical analysts made their best to bring their expertises closer to our field. At the end of the workshop the latter were much more familiar with the problems of NR, while relativists got to learn and revisit a plethora of mathematical techniques that may help solve some of the problems.

On the first day mathematicians were introduced to GR by talks given by Doug Arnold (director of IMA), Alan Rendall (AEI), and Robert Bartnik (University of Canberra). Arnold gave a self consistent tutorial to Einstein's equations from a mathematician's point of view. Followed Rendall, discussing the $3+1$ decomposition and local existence and uniqueness to the Cauchy problem. Bartnik, in turn, explained slicing conditions, the constraint equations and gravitational radiation.

On Tuesday morning, Ralf Hiptmair (Universität Bonn) reviewed discretizations of Maxwell's equations, putting emphasis on coordinate- free methods. He included the finite volume approach, generalized finite differences, and finite elements. Later, Eitan Tadmor (University of Maryland) presented discretizations for nonlinear hyperbolic systems that preserve local and global invariants. Since these discretizations are motivated mainly by computational fluid dynamics, there were several discussions on how to make use of these techniques in Einstein's vacuum evolutions. On Thursday morning Tadmor continued the discussion with some remarks about hyperbolic formulations and giving some ideas to diminish the accumulation errors by trading some hyperbolic equations for elliptic ones.

Back on Tuesday, during the afternoon Oscar Reula (University of Córdoba) talked about the role of hyperbolicity in formulations of Einstein's equations. He discussed the weak-ill posedness of the standard ADM formulation and the "hidden" hyperbolicity of BSSN-like systems. He also mentioned the linear degeneracy of usual formulations of Einstein's equations. Markus Keel (IMA) on Thursday morning gave a talk further elaborating this point and others. Namely, he explained that usual formulations for Einstein's vacuum equations are not genuinely nonlinear and therefore one should not expect shocks. He also discussed the "stability problem" in NR (later in the workshop to be covered in more detail by Lindblom and Scheel), and a stability result by Kreiss, Ortiz and Reula for hyperbolic systems. Going back once again to Tuesday, after Reula's talk I gave one overviewing NR as an initial-boundary value problem, summarizing what is known about constraint preservation, well posedness, and numerical stability for finite difference schemes in the presence of boundaries.

On Wednesday morning, Jeff Winicour (University of Pittsburgh) gave a one hour and a half introduction to black holes (BHs), covering topics such as conformally compactified spacetimes, the notion of an event horizon and its intrinsic geometry, the no-hair hypothesis, and a description of gravitational collapse. Later in the morning, Matt Choptuik (University of British Columbia) talked about fundamental issues in NR. Among other things, he discussed BH excision, coordinate conditions, optimization, differences with other kind of numerical computations, adaptative mesh refinement, gravitational collapse, and boundary conditions. He pointed out something that was going to be mentioned by mathematicians several times during the workshop as well. Namely, that while the majority of NR implementations are obtained with free (unconstrained) evolution, there are schemes for solving elliptic equations (e.g. multigrid methods) where the number of operations scales linearly with number of gridpoints. As highlights, he discussed the issue of choosing good model problems, Brandt's golden rule that *the amount of numerical computation should be proportional to the amount of real physical changes in the computed system*, and that the situations for which we most need NR are those for which there is little a priori knowledge.

Pablo Laguna (PSU) gave the last talk on Wednesday afternoon, giving an overview of the state of the art in NR. He reviewed 3D evolutions of single BHs, BH-BH, BH-neutron stars (NSs), and NS-NS binaries, and 2D simulations of gravitational collapse. He explained what formulations of Einstein's equations are used in these simulations, and the available results.

Later in the afternoon there was a pizza dinner followed by computational demonstrations. Winicour presented numerical evolutions of a well posed initial-boundary formulation of vacuum GR using the harmonic gauge, and some comparison tests from the *Workshop on Formulations of Einstein equations for NR* [2] that showed improved stability in this formulation. Jincha Xu (Penn State) discussed problem-independent adaptivity and multigrid methods. Michael Holst (University of California at San Diego) presented the (finite element) Manifold Code (MC) developed at UCSD, designed to solve nonlinear elliptic systems. Bartnik showed quasi-spherical numerical evolutions of BHs via a characteristic formulation. Dennis Pollney (AEI) presented 3D simulations using new coordinate conditions that they applied to binary BH evolutions, with improved stability properties.

Thursday morning was devoted to the initial data problem, with two talks, given respectively by Greg Cook (Wake Forest University) and Holst. Cook reviewed the 3+1 decomposition, the conformal and physical transverse-traceless decompositions, and the conformal thin sandwich approach. Then, he described BHs and NSs initial data. He ended pointing out current trends, such as initial data with more astrophysical content and/or data for objects in quasi equilibrim. Holst's talk was a natural continuation of Cook's, this time addressing mathematical issues. For example, he overviewed existence results for the Hamiltonian constraint, as well as more recent techniques for the coupled Hamiltonian-Momentum equations. He gave a detailed discussion of well posedness, a priori and a posteriori error estimates, and then moved to numerical solutions, mainly using finite element methods. He also presented some specific results for BH initial data.

In the afternoon, Deirdre Shoemaker (PSU) talked about BH excision and apparent horizon tracking. She discussed different numerical methods for this tracking, as well as the different discretizations that are currently used for finite differencing at the inner boundary in the case of excision. As an application she presented the status of simulations of moving 3D Schwarzschild BH. Followed Mark Scheel's (Caltech) talk about pseudospectral evolution of BHs. He explained pseudo spectral collocation methods and then discussed the constraint

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[2] See the article by Alcubierre in this issue of MOG

violating problem in NR (namely, fast growing, non-physical modes excited by numerical errors). He showed several evolutions of a 3D Schwarzschild BH, emphasizing the dependence of the stability on the choice of the formulation of Einstein's equations. He also discussed a priori analytical energy estimates, a point that was later elaborated in more detail by Lee Lindblom (Caltech) on Friday. In his talk Lindblom explained their method to obtain sharp estimates, which can be used to a priori choose a formulation that optimizes the stability of a given background, and presented numerical results that confirmed their analytical predictions.

On Friday morning, Luis Lehner (University of British Columbia) gave the state of the art of outer boundary conditions in NR. He discussed standard and new ways of handling boundaries in Cauchy evolution, and the characteristic and conformal approaches. He also stressed that one can actually make use of Gustaffson-Kreiss-Sundstrum-Osher's theory in NR to construct stable boundary treatments. Richard Falk (Rutgers University) explained finite element methods for hyperbolic equations, how to parallel continuum estimates in the design of numerical methods, and different mesh constructions. Sascha Husa (AEI) summarized the conformal approach to NR, discussing previous work (e.g. constructing the whole spacetime describing weak gravitational waves) and some needs (for example, live gauges) and difficulties . He emphasized that many of these difficulties also appear in other, more standard, approaches to NR.

Sam Finn and Lee Lindblom closed Friday's presentations with two talks. During the week, computational scientists had asked how gravitational waves are related to solutions of Einstein's equations. Finn addressed these questions with a talk that explained the basics of laser interferometry, and generation and observation of gravitational waves. Lindblom talked about simulation of r-modes through pseudo-Newtonian models.

During the afternoon, there was a panel discussion on numerical methods. Topics such as adaptative mesh refinement and the possibility of general purpose tools were discussed. The possibility of explicitly solving the constraints during evolution was also brought up, especially given that several of the computational scientists present were experts in solving elliptic equations with advanced, efficient methods. The current lack of understanding in NR of boundary conditions for hyperbolic-elliptic systems was in turn presented by numerical relativists as one of the main obstacles in implementing such methods.

The workshop ended on Saturday noon, after a discussion lead by Richard Price. He presented the "many aspects of the elephant", and an original *yin-yang* summary of different opinions about to attempt obtaining gravitational wave templates in the short term (we are doing fine/we need a new idea, specific focus/all areas, careful analysis/computer experiments, more intuition/more math, big codes/model problems, etc) that was used to start a general discussion of what would be the best way to proceed.

People agreed on continuing the workshop in the future with other meetings. Doug Arnold suggested joining together smaller groups of people willing to collaborate or to discuss more specific aspects. Sam Finn, as director of the CGWP, offered the Center as another natural place for these future meetings. As one can imagine from the number of talks given and variety of topics discussed, the workshop was very intense. People went back home with new ideas, renewed hopes, and just in time to see Brazil win the final game of the World Cup.

The conference website is http://www.ima.unm.edu/nr