# MATTERS OF GRAVITY

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

**Number 17** **Spring 2001**

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ISSN: 1527-3431

# Editorial

Not much to report here. If you are burning to have Matters of Gravity with you all the time, the newsletter is now 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. The next newsletter is due September 1st. If everything goes well this newsletter should be available in the gr-qc Los Alamos archives (`http://xxx.lanl.gov`) under number gr-qc/yymmnnn. To retrieve it send email to gr-qc@xxx.lanl.gov with Subject: get yymmnnn (numbers 2-16 are also available in gr-qc). All issues are available in the WWW:
`http://gravity.phys.psu.edu/mog.html`
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

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## APS Prize on gravitation:

Clifford Will, Washington University St. Louis cmw@howdy.wustl.edu

The Topical Group on Gravitation and the APS have established a Prize in Gravitational Physics, and have begun a campaign to raise $200,000 to endow the prize. Through the generosity of Dr. David Lee, a 1974 Caltech Ph.D. in gravitational physics, a challenge gift of up to $100,000 has been promised, to match every dollar raised from other sources.

The prize was established to recognize outstanding achievements in gravitational physics, both theoretical and experimental. The APS plans to name it the *Einstein Prize in Gravitational Physics*. As of January 2001, we have raised $100,000 ($50,000 from Dr. Lee, $50,000 from TGG members).

*Please give generously to support this new TGG Prize!*

You may make a lump sum contribution, or pledge an amount to be spread over some years. The APS will send a reminder when each installment is due. Contributions are tax deductible as a charitable donation, and can be sent to

Gravitational Physics Prize c/o Darlene Logan, Director of Development American Physical Society One Physics Ellipse College Park MD 20740-3844

## TGG Elections

David Garfinkle, Oakland University garfinkl@oakland.edu

The nominating committee of the Topical Group on Gravitation has put together the following slate of candidates.

For Vice Chair: John Friedman, U. of Wisconsin, Milwaukee, Bill Hamilton, Louisiana State U.

For Members-at-large: Ted Jacobson, U. of Maryland, Pablo Laguna, Penn State, Don Marolf, Syracuse U., Jennie Traschen, U. Mass. Amherst

The purpose of this message is to ask for any nominations from the general membership of the Topical Group on Gravitation. If any member is nominated by at least 5 percent of the membership of the topical group then that member will be added to the ballot. Please send your nominations to me at garfinkl@oakland.edu and give the name of the person you are nominating and the office (Vice Chair or Member-at-large). Nominations must be received by Feb. 15.

## We hear that...

Jorge Pullin, Penn State pullin@phys.psu.edu

TGG members James Isenberg, James Hough, and William Unruh have recently been selected to be APS Fellows. Congratulations!

# Experimental Unruh Radiation?

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Experimental detection of Hawking radiation from real general-relativistic black holes seems a close to hopeless proposition. Even the detection of the Hawking radiation that is expected to arise from condensed matter analog models for general relativity, while much more accessible than that from true gravitational black holes, is also currently far from laboratory realization. Given this, perhaps the next best thing to do is to attempt an experimental verification of the existence of Unruh radiation. This is the hope of Pisin Chen (Stanford) and Toshi Tajima (Austin) who have analyzed the possibility of using intense lasers to accelerate electrons extremely rapidly [1].

Recall that the Unruh effect implies that a uniformly accelerating particle will find itself surrounded by a thermal heat bath of temperature

$$kT = \frac{\hbar a}{2\pi c}. \qquad (1)$$

More precisely, uniform acceleration through the usual quantum vacuum (Minkowski vacuum) of the electromagnetic field will distort the two-point function of the zero-point fluctuations (ZPF) in such a way that

$$\langle E_i(-\tau/2) E_j(+\tau/2)\rangle = \frac{4\hbar}{\pi c^3}\,\delta_{ij}\,\frac{(a/c)^4}{\sinh^4(a\tau/2c)}. \qquad (2)$$

Here $\tau$ is the proper time as measured at some fixed position in the accelerated frame, while $a$ is the acceleration. As $a \to 0$

$$\langle E_i(-\tau/2) E_j(+\tau/2)\rangle = \frac{64\hbar c}{\pi \tau^4},$$

which recovers the usual unaccelerated Minkowski space result.

In the setup considered by Chen and Tajima [1], they use a laser-driven classical EM field to accelerate a single electron. Because they are not accelerating the entire detector, just a single electron, searching for an Unruh temperature as in equation (1) is meaningless. Instead, they suggest looking for the effects due to equation (2): The acceleration of the electron through the Minkowski vacuum state modifies the correlations in the zero-point fluctuations of the vacuum, which causes an additional jitter in the electron's motion, which then modifies the radiation emitted by the electron — over and above the classical Larmor radiation. This additional acceleration-related radiation has a characteristic acceleration dependence (a distorted thermal spectrum) and a characteristic angular dependence, which should in principle be measurable in the not too distant future. In particular there is a "blind spot" in the angular dependence of the classical Larmor radiation [1,2], and if you sit in this blind spot any radiation you see should be traceable to this distortion of the zero-point fluctuations.

There are two tricky points to keep in mind, one of physics and one of sociology/linguistics:

(1) There is a maximum electric field beyond which the QED vacuum falls apart due to copious production of electron-positron pairs (Schwinger effect). This vacuum breakdown occurs for

$$eE_{max} \approx \frac{m_e c^2}{\lambda_e} = \frac{m_e c^2}{\hbar/(m_e c)} = m_e^2 c^3/\hbar,$$

and corresponds to a maximum acceleration

$$a_{max} \approx m_e c^3/\hbar \approx 10^{29}\ m/s^2 \approx 10^{28}\ g_{earth}.$$

The accelerations posited by Chen and Tajima are up to $10^{25}\ g_{earth}$, so they are approaching but not quite over this vacuum breakdown limit. Thus if you succeed in building the experiment suggested by Chen and Tajima you are close to ultimate limits on this type of experiment — there's not much extra maneuvering room.

(2) The linguistic problem is this: If you ultimately succeed in seeing this ZPF-induced modification to Larmor radiation, should you really call it the Unruh effect? [2,3] Or should you just call it basic quantum field theory? After all you are not directly measuring the Unruh temperature itself. [To add to the confusion there is a subspecies of physicist that still does not believe in quantum field theory (QFT), and instead goes through quite contorted gymnastics to try to interpret all of quantum physics in terms of a classical stochastic background of zero-point fluctuations. I do not expect this subspecies to be convinced by the experiment, regardless of the outcome.]

I think it fair to say that most of the relativity and quantum communities would view a successful experiment along these lines as a beautiful verification of the basic ideas of flat-space QFT. The connection with curved-space QFT is tenuous at best, but this does not reduce the interest in performing this type of experiment.

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# Why is the Universe accelerating?

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One of the most important discoveries of the late 20th century was the evidence from Type Ia supernovae (SNe-Ia) that the expansion of the Universe is accelerating [1]. If this result holds up, it will have fundamental significance for gravitation and cosmology.

Of course, the historically honored mechanism for the gravitational repulsion needed to provide the acceleration is the cosmological constant, $\Lambda$, originally proposed (and then retracted) by Einstein. A competing explanation, originally proposed by Caldwell *et al.* [2], is quintessence, a mechanism to obtain a time dependent cosmological constant with a scalar field $\phi_Q$ and a potential $V(\phi_Q)$. However, quintessence models have a large number of adjustable parameters and are *ad hoc* in the sense that there is no underlying quantum theory for $\phi_Q$. Both the cosmological constant and quintessence are added to "standard" cold dark matter (CDM) Friedmann-Robertson-Walker (FRW) cosmologies. With suitable adjustments of parameters, both $\Lambda$CDM and QCDM models can fit the SNe-Ia data.

Another important and recently discovered constraint on cosmological models is the angular dependence of the cosmic microwave background fluctuations (CMBF) initially detected by COBE and more accurately extended to smaller angular scales by BOOMERANG and MAXIMA [3]. Assuming the scale invariant spectrum of initial adiabatic fluctuations and flat spatial geometry of inflationary models, a series of peaks are predicted to occur in the CMBF data. The detailed predictions of the $\Lambda$CDM and QCDM models are remarkably consistent with the observations.

To many in gravitational physics, however, the cosmological constant is repulsive in more than one way. We should therefore welcome a scenario proposed by Leonard Parker and Alpan Raval (PR) of the University of Wisconsin at Milwaukee. The PR scenario agrees at least equally well with both the SNe-Ia and CMBF data as the $\Lambda$CDM and QCDM models with no more adjustable parameters than $\Lambda$CDM, need not be "fine-tuned" to have the desired properties, and is, in several ways, less *ad hoc* than its competitors. They call their scenario the VCDM model since the vacuum energy of a quantized scalar field provides negative pressure to accelerate the Universe.

The PR proposal, described in detail in [4, 5], adds a non-minimally coupled ultra-low-mass free scalar field to (e.g.) the FRW-CDM model. The required mass $m \approx 10^{-33}$ eV might be reasonable for a pseudo-Nambu-Goldstone boson or even for the graviton. Given such a scalar field, $\varphi$, standard techniques of quantum field theory in curved spacetime may be used to construct the effective action for the scalar field coupled to gravity by integrating out the quantum fluctuations of the scalar field. PR discovered that it is possible to perform a non-perturbative (i.e. infinite number of terms) sum of all terms in the propagator with at least one factor of the scalar curvature $R$. It is the non-perturbative effects which become dynamically important on gigayear timescales when $R \approx m^2/(-\bar{\xi})$ where $\bar{\xi} = 0$ indicates conformal coupling and $\bar{\xi} = 1/6$ is minimal coupling and $m$ is the mass of the scalar field. The single parameter $\bar{m} \equiv m/\sqrt{\bar{\xi}}$ replaces $\Lambda$ in the VCDM scenario. In [5], PR give a solution for the FRW scale factor $a(t)/a(t_j)$ for a VCDM model containing vacuum energy, nonrelativistic matter, and radiation. It is close to power law in $t$ for $t < t_j$ (as expected for zero cosmological constant) and close to exponential in $t$ if $t > t_j$ (as expected for non-zero cosmological constant). The non-perturbative vacuum energy effects cause the transition at $t_j$ when the pressureless matter density at $t_j$, $\rho_j = \bar{m}^2/(8\pi G)$. With this solution, it is possible to construct the equation of state for the vacuum from the Einstein tensor. The ultra-low-mass gives transition times corresponding to cosmological redshifts of $z \approx 1$.

Due to the mass scale, the non-perturbative effects are dynamically negligible in the early universe. (In [4c], PR point out that particle creation—which is part of the non-perturbative effective action—might be used to solve some current problems with the inflationary scenario.) At late times, with the transition time controlled by the mass of the scalar field, the vacuum energy dominates the dynamics. Vacuum energy typically violates the energy conditions—in this case with a negative pressure (but positive energy density). The FRW scale factor responds as if there were a cosmological constant. Since $t_j \approx H_0^{-1}/2$ for $H_0$ the present value of the Hubble parameter, the effective cosmological constant turns on very late in the history of the universe.

Things to note about the PR scenario compared to the competition are that given the existence of such an ultra-low-mass scalar field, there are no more *ad hoc* assumptions. The VCDM equation of state results from a wide range of values of $\bar{m}$. The current fits to SNe-Ia and CMBF data by PR use preferred values of cosmological parameters ($\Omega_{\mathrm{CDM}} = 0.50$, $\Omega_{\mathrm{B}} = 0.06$, and $h = 0.7$ for the CDM and baryon fractions and the current Hubble parameter in units of 100 km/s/Mpc). Should these change, it is still probable that a value of $\bar{m}$ can be found to fit the data.

PR compare their VCDM model to a $\Lambda$CDM model with the same cosmological parameters. The fits to the CMPF data are almost indistinguishable. This is not true for the SNe-Ia data which has information only back to $z \approx 1$. The VCDM model predicts significantly fainter supernovae near $z \approx 1$ than does the $\Lambda$CDM model. The VCDM prediction seems to follow the trend in the data more closely. However, the current quality of the data does not allow either model to be ruled out. Improved data might be able to choose between these models.

Caldwell has recently argued [6] that the key ingredient in the dependence of luminosity on redshift is $w$, the ratio of vacuum pressure to vacuum energy density. Quintessence models appear to require $-1 < w < 0$ while PR's VCDM scenario yields $w < -1$. Caldwell demonstrated that the latter behavior yields better fits to the SNe-Ia data but could only generate a very contrived model with that property. The PR scenario yields this behavior naturally.

Detailed properties of the PR scalar field scenario may be found in [4] and references therein. Graphs showing the comparisons to the SNe-Ia and CMBF data may be found in a very recent *Physical Review Letter* [5]. An even more recent discussion of this work as a plausible explanation of the accelerating universe may be found in *Nature Science Update* [7].

Leonard Parker and Alpan Raval have discovered a scenario which might represent the first observation of an effect predicted using quantum field theory in curved spacetime as well as a new quantized field. In their own words [5]: "If the universe is indeed acting, through its own acceleration, as a detector of this very low mass quantized field, then there would be a wealth of implications for particle physics and cosmology."

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# The Lazarus Project: Numerical relativity meets perturbation theory

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Numerical relativity and gravitational wave detection exist in an entangled state. Though there are many opinions about this state, two things are probably not controversial. First, numerical relativity is required to compute the dynamics and gravitational radiation when inspiralling black holes merge, and second, that this is extraordinarily difficult. The difficulties prevent us from getting answers to questions that are not only crucial to determining the detectability of black hole mergers, but that are just plain interesting. Among these is the question of what happens when the binary pair, late in its inspiral, has too much total (spin plus orbital) angular momentum to form a Kerr hole. Does the inspiral stall? For inspiralling holes, is there a plunge or a gradual transition from slow inspiral to distorted final hole? Does the answer to this depend on such details as the spins? In the past year or two there has been a slow but steady advance of the frontier of the numerical relativity of binary black holes. True 3 dimensional runs have been successfully carried out for so-called grazing collisions [1,2] that describe non-axisymmetric collisions of two holes that start fairly close together with a fairly small impact parameter. Work is progressing in many centers of numerical relativity on a better understanding of the the outer boundary condition, how to excise the black hole (or avoid the need for excision), how to choose the numerical variables for greatest stability and/or accuracy, and much much more. This inspires confidence that it will not be too long before numerical relativity will be giving answers to astrophysical questions.

That confidence has taken a nice jump in the past few months. A group at the Albert Einstein-Max Planck Institute ("AEI") has taken an eclectic approach, called the Lazarus Project [3] to looking at black hole mergers, and has provided waveforms generated by motion and merger after the holes move inward from the "ISCO" (the Innermost Stable Circular Orbit). The underlying idea is simple: If straightforward numerical relativity is used, the code evolving the spacetime would become unstable before useful information could be extracted. The Lazarus group therefore only uses numerical relativity where it is indispensable: to evolve the gravitational field from the ISCO stage to the point at which an almost stationary Kerr horizon is formed. After this, relatively simple black hole perturbation theory is used to continue the evolution of the spacetime. Perturbation theory allows evolution to rise from its unstable grave and to live again, like the biblical Lazarus. Sort of.

The initial Lazarus idea was the work of Carlos Lousto, Manuela Campanelli, and John Baker, who were joined early in the project by Bernd Brügmann. A student, Ryoji Takahashi, has also recently been added to the team. But the "team" in fact is the whole numerical relativity group at the AEI, since the numerical relativity code of the AEI and the CACTUS numerical relativity toolkit [4] constitute the front end of the eclectic Lazarus approach. The back end is the code to evolve perturbations of Kerr holes [5] developed several years ago. Not only did those elements already exist, but the idea itself of doing late stage evolution with perturbation theory is not new. The basic scheme had been set down in the mid 90s [6] and applied to simple axisymmetric processes [7]. What the Lazarus group did was to provide the tools for matching in a full 3D problem in which the final hole is a rapidly rotating Kerr hole. The details and difficulty of that task were what made this "obvious" step a real achievement.

The essence of the problem is to assign spacetime coordinates that are in some sense almost

Boyer-Lindquist coordinates for the numerically evolved spacetime that is almost the Kerr spacetime outside the horizon, and in those coordinates to identify perturbations. There is, of course, no unique way of assigning coordinates and extracting perturbations. Small changes in the coordinates induce small changes in the perturbations. But the Teukolsky function, the quantity used in Lazarus perturbative evolution, is changed only to second order when small coordinate changes are made so the extraction process is insensitive if the spacetime geometry is really "almost Kerr." The best way of building confidence about the method is inherent in the method. The matching of numerical relativity and perturbation theory is done at some transition time (i.e., on some spacelike hypersurface). If that transition time is taken to be too early, the numerically evolved spacetime will not have achieved the point of being a perturbation of Kerr. If that transition time is too late the numerical code will become unstable and the perturbations that are extracted will be unrelated to the physical problem. If there is a reasonable range of transition times that are neither too early nor too late, then the Lazarus method should give the same results for all transitions within this range. If the results are the same for a wide range of transition times, then it is very hard to resist accepting the results.

During development, the Lazarus method passed many tests. Among them was a test that results varied little for a range of transition times. But these were results for small transverse momentum, and hence were grazing collisions. The big question is whether numerical relativity plus Lazarus is ready to tell us about mergers, and the answer is either "yes" or "very close." According to recent estimates [8,9], for puncture type initial data [10], the ISCO for equal mass, nonspinning holes, corresponds to a separation L of 4.8M (where M is the total ADM mass), a transverse momentum for each hole of 0.335M, and total angular momentum of $0.76M^2$. These initial data were used as the starting point for numerical evolution with an AEI code that uses maximal slicing, zero shift, and the standard ADM approach. The range of acceptable transition times was narrow, from about 10M to 12M, and the radiated energy generated was uncertain by a factor of around 2. It would be nice, of course, to hear of 10% accuracy, but a factor of 2 uncertainty is really quite respectable. Even with the limited accuracy the results carry some important astrophysical information. For one thing, there is an estimate of radiated energy 4-5%$Mc^2$, more than twice as large as any previous computation (though smaller than previous speculations), and a good omen for the detectibility of black hole mergers, and for the yet larger numbers that mergers of spinning holes may produce.) Aside from a welcome number, the results have an interesting qualitative lesson. There appears to be little radiation associated with the early motion of the holes; almost all the radiation can be ascribed to the dynamics of the distorted black hole that is formed.

It is possible, of course, that initial conditions that truly represent the ISCO will tell a rather different story (such as more orbital motion before the formation of a distorted horizon). To explore such questions what is needed is the ability to start evolution at an earlier time (or larger transverse momentum). This cannot be done at present; the numerical code used for evolution would go unstable before a perturbed Kerr hole is formed. But this will change, and that is perhaps the most exciting thing about the the addition of Lazarus to the set of numerical relativity toos. With Lazarus, the improvements in code stability that will be achieved in the coming months can quickly be turned into improvements in our understanding of black hole mergers.

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# LIGO locks its first detector!

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In a year filled with important milestones, perhaps the most exciting event for LIGO in 2000 was achieving first lock on its 2 km interferometer at the Hanford Observatory. To achieve the sensitivity required for searching for gravitational waves the mirrors in the LIGO interferometers must be held in the correct positions for the laser light to resonate properly, a process known as "locking the interferometer". The required accuracies range from 0.1 to 100 picometers depending on which optic, a formidable task when one realizes that the ground is continually in motion with an rms displacement of about 1 micron! Over the past year, we have been building toward the goal of locking the full interferometer by locking simpler configurations (for example a single arm cavity last spring) to test and tune the photodetectors, electronics and software that are the heart of the locking system. Finally, last fall we began attempting to lock the full interferometer. To make the task a little easier in the beginning, we introduced some additional losses into the optical path, either by misaligning the optics slightly or by using a gate valve to clip the beams in the arms. After successfully locking the interferometer with the added losses, we used the locked sessions to characterize the servos and finally in January we were able to lock the interferometer without the aid of the added losses. This marks an important transition in our commissioning effort–the beginning of working with a fully functioning interferometer, and not just subsets of the full instrument ( `http://www.ligo.caltech.edu/LIGO_web/firstlock/`).

Just a couple weeks after the final step in locking the 2 km interferometer, we achieved another important milestone, this time on the interferometer at the Livingston Observatory–the first 4 km arm cavity has been locked to the laser. This initiates the debugging and commissioning of the control systems for lengths and angles on the second interferometer.

Each of LIGO's three interferometers has a well-defined role in the commissioning. The 2 km interferometer is the pathfinder–the place where things are tried first and where problems are found. The Livingston 4 km interferometer is where systematic characterization and resolution of problems takes place. Installation of the Hanford 4 km interferometer (still on-going) is paced so that it takes maximum advantage of the experience with the other two interferometers, but is still completed on schedule for the Science Run.

To help the LIGO Laboratory staff move toward round the clock operation and to help the LIGO Scientific Collaboration (LSC) prepare to analyze the LIGO data, we are carrying out a series of "engineering runs". These runs have durations of a few days to a few weeks and can involve either or both sites, depending on the goals of a particular run. The interferometers and other measurement equipment are operated in a well-defined configuration, and the data taken are archived and made available to LSC members. In early November 2000, the second of these engineering runs was held, with the 2 km interferometer operating as a recombined Michelson interferometer with Fabry-Perot arms (but no recycling). The high percentage of time in lock, about 90third engineering run is scheduled for March. The data from these engineering runs both help us improve the detectors and prepare for the task of analyzing the full LIGO data to come.

The remainder of 2001 has a busy schedule, bringing the three interferometers into full operation at their design sensitivity. Everything is on track for the initiation of the LIGO Science Run in early 2002.

# Progress on the nonlinear r-mode problem

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Since the recent discovery that the r-modes of rotating stars are unstable to the emission of gravitational waves [1], much effort has been directed towards improving the physical models of the r-mode instability. In the last issue of *Matters of Gravity*, Nils Andersson gave an update on some of this work [2] - reviewing such effects as neutron star superfluidity, the nonlinear evolution of the r-modes, the damping associated with the formation of the crust and the effects of general relativity on the spectrum and growth timescales of the modes. (More detailed reviews may be found in [3].) My purpose here is to report further on very recent progress that has been made specifically on the nonlinear r-mode problem.

Early work suggested that the r-mode instability may limit the spin rate of newly formed, rapidly rotating neutron stars and that the radiation emitted while the star sheds its angular momentum may be detectable by LIGO II [4]. The spin-down model on which these tantalizing estimates were based assumed that the most unstable r-mode (with multipole indices $l = m = 2$) would be able to grow to an amplitude of order unity before being saturated by some sort of nonlinear process. It was also assumed that the star would spin down along a sequence of stellar models each consisting of a uniformly rotating equilibrium star perturbed by the dominant r-mode.

The central issue is whether the instability found in idealized models survives the physics that governs a young neutron star: Will nonlinear coupling to other modes allow an unstable r-mode to grow to unit amplitude? Does the background star retain a uniform rotation law as it spins down or does a growing r-mode generate significant differential rotation? The importance of this last question was emphasized by Spruit [5] and by Rezzolla, Lamb and Shapiro [6] who argued that differential rotation would wind up a toroidal magnetic field and drain the oscillation energy of the r-mode. A number of different approaches have since been applied to the nonlinear r-mode problem in an attempt to address these questions.

One notable approach is the direct numerical evolution of the nonlinear equations describing a self-gravitating fluid. Stergioulas and Font [7] have performed 3-D general relativistic hydrodynamic evolutions in the Cowling approximation, and Lindblom, Tohline and Vallisneri [8] have performed 3-D Newtonian hydrodynamic evolutions with an added driving force representing gravitational radiation-reaction.

Stergioulas and Font [7] construct an equilibrium model of a rapidly rotating relativistic star and add to it an initial perturbation that roughly approximates its $l = m = 2$ r-mode. They then evolve the perturbed star using the nonlinear hydrodynamic equations with the spacetime metric held fixed to its equilibrium value (the relativistic Cowling approximation). They find no evidence for suppression of the mode on a dynamical timescale, even when the mode amplitude, $\alpha$, is initially taken to be of order unity. Because of the approximate nature of the initial perturbation, other oscillation modes are excited in the initial data. For a star with a barotropic equation of state, the generic rotationally restored mode is not a pure axial-parity r-mode, but an r-g "hybrid" mode with a mixture of axial and polar parity components [8]. Stergioulas and Font [7] find that a number of these hybrid modes are excited in their initial data with good agreement between the inferred frequencies and earlier results from linear perturbation theory [8]. In their published work, they find no evidence that the dominant mode is leaking its oscillation energy to other modes on a dynamical timescale.

Instead, a nonlinear version of an r-mode appears to persist over the time of the run, about 25 rotations of the star. In additional runs with amplitudes substantially larger than unity, however, one no longer sees a coherent r-mode. This may be evidence of nonlinear saturation, but further runs with more accurate initial data will be necessary to conclude this definitively [10].

These conclusions are consistent with preliminary results from studies of nonlinear mode-mode couplings at higher order in perturbation theory [11,12]. Other r-modes of a nonbarotropic star seem to give no indication of a strong coupling to the $l = m = 2$ r-mode unless its amplitude is unphysically large ($\alpha \gtrsim 30!$) [12]. Work is still in progress on the nonlinear coupling of the dominant r-mode to the g-modes of nonbarotropic stars [12] and to the hybrid modes of barotropic stars [11].

The results of Stergioulas and Font [7] have also been confirmed and significantly extended by the calculation of Lindblom, Tohline and Vallisneri [8]. In Stergioulas and Font's calculation the growth of the unstable r-mode does not occur because the spacetime dynamics have been turned off. However, it would be impossible to model this growth anyway even in a fully general relativistic hydrodynamic evolution, because the timescale on which the mode grows due to the emission of gravitational waves far exceeds the dynamical timescale of a rapidly rotating neutron star.

To simulate the growth of the dominant r-mode in a calculation accessible to current supercomputers, Lindblom, Tohline and Vallisneri [8] take a different approach. They begin by constructing an equilibrium model of a rapidly rotating Newtonian star and add to it a small initial perturbation corresponding to its $l = m = 2$ r-mode. They then evolve the perturbed star by the equations of Newtonian hydrodynamics with a post-Newtonian radiation-reaction force that drives the current quadrupole associated with the $l = m = 2$ r-mode.

By artificially scaling up the strength of the driving force, they are able to shorten the growth time of the unstable r-mode by a factor of 4500. In the resulting simulation the mode grows exponentially from an amplitude $\alpha = 0.1$ to $\alpha = 2.0$ in only about 20 rotations of the star.

With this magnified radiation-reaction force, Lindblom, Tohline and Vallisneri [8] are able to confirm the general features of the simplified r-mode spin-down models [4]. In their simulation, the star begins to spin down noticeably when the amplitude of the dominant mode is of order unity, and ultimately about 40% of the star's angular momentum is radiated away. The evolution of the star's angular momentum as computed numerically agrees well with the predicted angular momentum loss to gravitational radiation. If their model is accurate, however, gravitational radiation would not be emitted steadily at a saturation amplitude, but would die out after saturation and then reappear as the mode regenerates.

Again, there is no evidence of nonlinear saturation for mode amplitudes $\alpha \lesssim 1$. The growth of the mode is eventually suppressed at an amplitude $\alpha \simeq 3.4$, and the amplitude drops off sharply thereafter. Lindblom, Tohline and Vallisneri argue that the mechanism suppressing the mode is the formation of shocks associated with the breaking of surface waves on the star. They find no evidence of mass-shedding, nor of coupling of the dominant mode to the other r-modes or hybrid modes of their Newtonian barotropic model.

These various studies all provide evidence pointing to the same conclusion: the most unstable r-mode appears likely to grow to an amplitude of order unity before being suppressed by nonlinear hydrodynamic processes. It is important to emphasize, however, that the 3-D numerical simulations have probed nonlinear processes occurring only on dynamical timescales and that the actual growth timescale for the r-mode instability is longer by a factor of order $10^4$. It is possible that the instability may be suppressed by hydrodynamic couplings occurring on timescales that are longer than the dynamical timescale but shorter than the r-mode growth timescale. Further work clearly needs to be done before definitive conclusions can be drawn. Particularly relevant will be the results from the ongoing mode-mode coupling studies [11,12].

Turning to the question of differential rotation, deviations from a uniform rotation law are observed in both of the 3-D numerical simulations [7,8] It has been proposed that differential rotation will be driven by gravitational radiation-reaction [5] as well as being associated with the second order motion of the r-mode, itself [6]. In a useful toy model, Levin and Ushomirsky [13] calculated an exact r-mode solution in a thin fluid shell and found both sources of differential rotation to be present.

To address in more detail the issue of whether or not the r-mode instability would generate significant differential rotation, Friedman, Lockitch and Sá [14] have calculated the axisymmetric part of the second order r-mode. We work to second order in perturbation theory with the equilibrium solution taken to be either a slowly rotating polytrope (with index $n = 1$) or an arbitrarily rotating uniform density star (a Maclaurin spheroid). The first order solution, which appears in the source term of the second order equations, is taken to be a pure $l = m$ r-mode with amplitude $\alpha$.

We find that differential rotation is indeed generated both by gravitational radiation-reaction and by the quadratic source terms in Euler's equation; however, the latter dominate a post-Newtonian expansion. The functional form of the differential rotation is independent of the equation of state - the axisymmetric, second order change in $v^\varphi$ being proportional to $z^2$ (in cylindrical coordinates) for both the polytrope and Maclaurin.

Our result extends that of Rezzolla, Lamb and Shapiro [6] who computed the order $\alpha^2$ differential drift resulting from the linear r-mode velocity field. These authors neglect the nonlinear terms in the fluid equations and argue (based on an analogy with shallow water waves) that the contribution from the neglected terms might be irrelevant. Indeed, for sound waves and shallow water waves, the fluid drift computed using the linear velocity field turns out to be exact to second order [15]; thus, one may safely ignore the nonlinear terms. However, for the motion of a fluid element associated with the r-modes, we find that there is in fact a non-negligible contribution from the second-order change in $v^\varphi$. Interestingly, the resulting second order differential rotation is stratified on cylinders. It remains to be seen whether the coupling of this differential rotation to the star's magnetic field does indeed imply suppression of the r-mode instability.

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# Analog Models of General Relativity

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The workshop "Analog Models of General Relativity" was held in Rio de Janeiro from 16 October to 20 October 2000. The organizing committee consisted of Mario Novello, Grigori Volovik, and myself. Invited speakers talked about a wide range of issues concerning the use of condensed matter systems as analogues of (and analogs for) general relativity. Condensed matter analogs can be used to help us understand GR, or GR can be used to help us understand condensed matter physics. More boldly, you can use condensed matter analogs to suggest possible replacements for GR, physical systems that approximate ordinary GR in the appropriate limit. Among the invited presentations:

(1) The workshop started with an introductory survey, presented by myself, that set the basic parameters for the week.

(2) Bill Unruh talked about his acoustic black holes ("dumb holes"), illustrating the way that acoustics in a moving fluid leads to the notion of an "effective acoustic metric".

(3) Grigori Volovik discussed the use of $^3He$ as a model of, and indeed for, GR. (Low-energy quasiparticles near the Fermi surface can in certain circumstances generically exhibit a relativistic spectrum, and induced gravity a la Sakharov can then be argued to lead to an effective dynamics similar to Einstein gravity.)

(4) Brandon Carter carefully distinguished the notions of quasi-gravity from pseudo-gravity. (q-gravity: systems that mathematically simulate GR but are qualitatively different, e.g. acoustic geometries; p-gravity: systems that physically mimic gravitational fields, e.g. centrifugal force). He also discussed a model of how to use braneworld cosmologies to mimic gravity in a non-standard way.

(5) Ulf Leonhardt described his proposal for an "optical horizon" using "slow light" (resonance induced transparency in a Bose–Einstein condensate; a BEC).

(6) Renaud Parentani talked about quantum metric fluctuations and Hawking radiation. He argued that the near horizon propagation of outgoing quanta resembles that of photons in a moving random medium.

(7) Haret Rosu discussed a number of topics concerning exotic effects in the GR quantum interface.

(8) Mario Novello described nonlinear electrodynamics (for example, Born-Infeld, Schwinger, or Euler-Heisenberg electrodynamics) and the way it leads to the notion of an effective metric governing photon propagation.

(9) Ted Jacobson talked about a particular implementation of the notion of "analog horizon" in a $^3He$ superfluid system.

(10) Mike Stone presented a careful discussion of how notions of effective metric and the machinery of general relativity can help understand the concepts of pseudo-momentum and physical momentum in condensed matter systems.

In addition there were a number of contributed talks (Santiago Bergliaffa presented examples of gravity-like systems in non-linear electrodynamics, Jose Salim discussed closed spacelike photon paths in nonlinear electrodynamics, Nami Fux Svaiter discussed the rotating vacuum and the quantum Mach principle, and Carlos Barcelo presented a discussion of analog gravity based on Bose–Einstein condensates; BECs).

Additionally, approximately 50 graduate students and postdocs attended the workshop.

There was considerable animated discussion, aided by an open workshop format that left plenty of time for give-and-take. The most promising systems for experimentally mimicking "event horizons" seem to be based on (a) "slow light" in BEC systems with resonance induced transparency, (b) quasiparticles in superfluids, and (c) acoustic oscillations of the phase of the condensate field in BECs. Considerable enthusiasm and hope was expressed that one or more of these "analog systems" might be brought to laboratory fruition in the near (5 to 10 year) future.

Many of the transparencies from the presentations (plus some write-ups, web-links, and other technical information) is now available from the post-conference website: `http://www.lafex.cbpf.br/~bscg/analog/`

A mirror of this website is maintained in the USA at: `http://www.physics.wustl.edu/~visser/Analog/`

# Workshop on Astrophysical Sources of Gravitational Radiation for Ground-Based Detectors

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As the $21^{st}$ century begins, gravitational wave astronomy is poised for unprecedented expansion and discovery. Understanding the expected gravitational wave frequencies and other characteristics of astrophysical sources is essential to take full advantage of these opportunities, and to stimulate and influence detector development. To this end, gravitational wave experimentalists, relativists, astronomers, and astrophysicists met at Drexel University on October 30 - November 1, 2000 for a workshop focusing on gravitational wave sources for ground-based detectors.

The scientific sessions began with a series of talks on the detectors. Barry Barish presented a review of first generation interferometers. He was followed by Peter Fritschel, who described the current plans for LIGO-II, and Kip Thorne, who discussed issues involving thermal noise, optical noise, and quantum non-demolition for instruments beyond LIGO-II. Bill Hamilton then gave an overview of resonant bar detectors and the international bar detector community.

The data expected from the LIGO-I science run was addressed by Albert Lazzarini, who also discussed the GriPhyN project and its relevance to LIGO data. Patrick Brady discussed LIGO data analysis efforts, and Sam Finn followed with a description of LIGO's science reach.

New initiatives in astronomy and astrophysics provide rich resources and partnerships for gravitational wave astronomy. Tom Gaisser reported on the recommendations of the Particle, Nuclear, and Gravitational Wave Astrophysics panel from the recently completed decadal survey *Astronomy and Astrophysics in the New Millennium* (see, e.g., `http://www.nap.edu/books/0309070317/html/` ). He was followed by Tom Prince, who described the space-based LISA detector, and Bob Hanisch, who discussed the National Virtual Observatory; both of these projects received strong support from the decadal survey. Nick White gave an overview of NASA's future programs in high energy astrophysics, many of which focus on black holes and their environments.

Coalescing compact binaries constitute the "bread and butter" source for ground-based interferometers, and were addressed from a variety of directions. Vicky Kalogera began with a discussion of event rates for binary inspiral; she was followed by Steve McMillan, who described the formation of black hole binaries in globular clusters. The importance of large scale numerical simulations was highlighted by numerous speakers. Josh Faber and Fred Rasio presented new work on the hydrodynamics of neutron star mergers, and Max Ruffert underscored the importance of coalescing compact binaries for understanding gamma ray bursts. William Lee presented simulations of black hole-neutron star coalescence, and Richard Matzner discussed binary black hole collisions. Thomas Baumgarte concluded this session with a talk on the innermost stable circular orbit in compact binary systems.

Cosmological sources of stochastic gravitational waves were addressed by Arthur Kosowsky. David Spergel spoke on plans to use the CMB as a gravitational wave detector.

Stellar core collapse has long been proposed as a source of gravitational waves, and was

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discussed by Chris Fryer. Kimberly New described dynamical rotational instabilities that can arise in centrifugally hung compact cores, and David Brown discussed their occurrence during collapse. Gravitational radiation from secular bar-mode instabilities was addressed by Dong Lai.

In recent years, a number of exciting new developments have arisen in the study of rotating neutron stars. Jean Swank discussed X-ray observations of accretion instabilities on long and short timescales in low mass X-ray binaries. Tod Strohmayer described X-ray observations giving evidence for millisecond spins. Gravitational radiation produced by temperature gradients, and its importance for LIGO-II, was addressed by Lars Bildsten. Greg Ushomirsky discussed gravitational waves from r-modes in accreting neutron stars and young neutron stars.

Conference rapporteurs Rainer Weiss, Peter Saulson, and Joel Tohline provided thought-provoking and insightful overviews of the meeting.

This workshop proved to be a fruitful and enjoyable time for these different communities to interact with each other. Those who were unable to attend in person should visit `http://www.physics.drexel.edu/events/astro_conference`. At this website the transparencies of the talks can be viewed by going to the meeting program, and clicking on the title of each talk.

# Numerical Relativity and Black Hole Collisions at the 20th Texas Symposium on Relativistic Astrophysics

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In spite of the low general attendance to the 20th Texas Symposium on Relativistic Astrophysics last December in Austin, Texas, the parallel session on numerical relativity and black hole collisions was not only oversubscribed and had to be extended one hour beyond the allocated time limit, but it also attracted a large audience. Eleven ten minute talks were given and two one minute poster advertisements.

Bernd Schmidt (AEI/Germany) presented results on the numerical evolution of the Kruskal spacetime using the conformal field equations. Specifically, he addressed initial data sets for the conformal field equations which describe spacelike hypersurfaces in the conformally extended Kruskal spacetime. These are data sets that have been evolved using the code for the conformal field equations developed by P. Huebner. Schmidt showed results from these simulations.

Sascha Husa (AEI/Germany) reported recent progress toward the global study of asymptotically flat spacetimes with numerical relativity. The development of a 3D solver for asymptotically Minkowski extended hyperboloidal initial data has rendered possible the application of Friedrich's conformal field equations to astrophysically interesting spacetimes. As a first application, he presented the future development of a hyperboloidal set of weak initial data, including future null and timelike infinity. Using this example, he sketched the numerical techniques employed and highlighted some of the unique capabilities of the numerical code. Husa briefly mentioned the implications of these results for future work on (multi) black hole spacetimes.

Pedro Marronetti (Texas/Austin) presented the first full numerical solutions of the initial data problem of two black holes based on a Kerr-Schild spacetime slicing. These new solutions provides more physically realistic solutions than the initial data based on conformally flat metric/maximal slicing methods. The singularity/inner boundary problems are circumvented by a new technique that allows the use of an elliptic solver on a Cartesian grid where no points are excised, simplifying enormously the numerical problem. After this presentation, Richard Matzner (Texas/Austin) showed a video of the simulation of grazing collisions of black holes performed by the Texas-Pittsburgh-Penn State collaboration.

Deirdre Shoemaker (Penn State) gave a presentation pointing out first that recent experience with numerically evolving the space-time of grazing collisions of black holes have provided valuable lessons about the difficulties that one might face in the more important case of a collision when the holes start far apart. She stressed that some of the difficulties can be successfully modeled and studied in attempting to understand how to evolve a single black hole. She then presented results from several studies that the Penn State group have performed attempting to evolve the ADM equations with various lapse/shift conditions for this problem.

E. Seidel and R. Takahashi (AEI/Germany) presented results from the full 3D evolution of two colliding black holes, with angular momentum, spin, and unequal mass. They emphasized that the AEI group has for the first time computed waveforms a grazing collision. The collision can be followed through the merger to form a single black hole, and through part of the ring-down period of the final black hole. The apparent horizons are tracked and studied, and physical parameters, such as the mass of the final black hole, are computed. The total energy radiated is shown to be consistent with the total ADM mass of the spacetime and the final black hole mass. Finally, Seidel discussed the implications of these simulations for gravitational wave astronomy.

Miguel Alcubierre and D. Pollney (AEI/Germany) discussed a series of techniques required for the numerical simulation of black hole spacetime. These techniques include the choice of an adequate formulation of the evolution equations, the choice of lapse and shift conditions, the choice of boundary conditions, and the use of black hole excision. They presented also the results of the three dimensional simulation of a distorted black hole where these techniques have been applied successfully, allowing us to obtain long-term stable, accurate simulations.

Carlos Lousto, John Baker and Manuela Campanelli (AEI/Germany) presented results from the coalescence of binary black holes from the innermost stable circular orbit down to the final single rotating black hole under the Lazarus framework. The Lazarus approach combines the full numerical approach to solve Einstein equations, applied in the truly nonlinear regime, and linearized perturbation theory around the final distorted single black hole at later times. Their results indicate a significantly higher amount of energy radiated (up to 4 or 5They presented also waveforms lasting for over t 100M, and pointed out that their waveforms suggest an early nonlinear ringing.

Peter Diener (AEI/Germany) presented results from a work in progress on Binary black hole initial data, based on adding two Schwarzschild black holes in Kerr-Schild form. Using attenuation functions in order to force the constraint deviations to vanish near the singularities, he pointed out that it is possible to solve the constraint equations over the entire spatial grid.

S. Hawley (AEI/Germany) presented results of his study on critical phenomena in boson stars. Specifically, this study introduces a real field to perturb the boson star via a gravitational interaction which results in a significant transfer of energy. The resulting critical solutions not only are similar to those of unstable boson stars but also persist for a finite time before dispersing or forming a black hole.

John Whelan (Texas/Brownsville) presented results in which the quasi-stationary approximation is used to model a phase of the inspiral of a compact-object binary where the time scale for decay of the orbits is long compared to the orbital period, without imposing any weak-field approximations. These results were obtained by numerically solving for a stationary spacetime which approximates the slowly evolving one, maintaining equilibrium in the radiating system by imposing a balance of incoming and outgoing radiation at large distances. Such a radiation-balanced solution can serve as an alternative to existing techniques for constructing initial-value data for full-numerical "plunge" simulations.

Mark Miller (WashU) presented a new method for numerically constructing solutions to the constraint equations of general relativity that correspond to a single black hole in quasi-circular orbit with a single neutron star. By examining sequences of such solutions, he showed that it is possible to estimate the location of the innermost stable circular orbit for these systems, which will be used as the starting point for full 3D numerical simulations of binary black hole - neutron star coalescences.

Harald Dimmelmeier (Garching/Germany) reported on results from a new numerical relativistic hydrodynamical code for axisymmetric core collapse. He utilizes high-resolution shock capturing methods for the hydrodynamic equations, and Wilson and Mathews' approximation of a conformally flat spatial metric. The results presented were obtained from simulations of supernova core collapse and bounce, and rotating neutron star simulations. He showed gravitational radiation waveforms obtained by post-processing using the quadrupole formula.