// MATTERS OF GRAVITY

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Editor

Jorge Pullin
Center for Gravitational Physics and Geometry
The Pennsylvania State University
University Park, PA 16802-6300
Fax: (814)863-9608
Phone (814)863-9597
Internet: `pullin@phys.psu.edu`
WWW: `http://www.phys.psu.edu/~pullin`

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Editorial

Not much to report here. The newsletter is a bit late (it was due September 1st) due to last minute updates (TAMA and TOCO). I felt like a real editor for a little while! The next newsletter is due February 1st. If everything goes well this newsletter should be available in the gr-qc Los Alamos archives under number gr-qc/yymmnnn. To retrieve it send email to gr-qc@xxx.lanl.gov with Subject: get yymmnnn (numbers 2-15 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

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Cosmic microwave background anisotropies: tantalizingly close to expectations

Sean Carroll, University of Chicago
carroll@theory.uchicago.edu, http://pancake.uchicago.edu/~carroll/

Ever since the detection of temperature anisotropies in the cosmic microwave background (CMB) by the COBE satellite in 1992, cosmologists have anticipated that information about the amplitude of these fluctuations across a range of angular scales could be an extraordinarily powerful constraint on cosmological models (see for example [1]). Now a series of new experiments — the TOCO98 run of the MAT ground-based telescope in Chile [2], the balloon-borne Boomerang experiment flown both in Texas [3] and Antarctica [4], and the balloon-borne Maxima experiment flown in Texas [5] — have turned these expectations into reality.

The figure shows the new results combined with previous experiments, presented as amplitude of fluctuation vs. multipole moment l in a spherical harmonic decomposition. Angular size

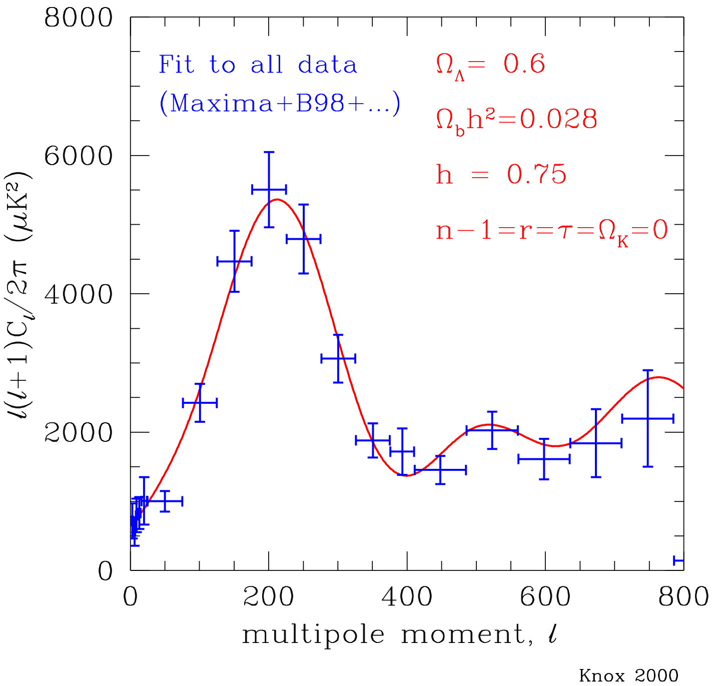

Figure 1: Amplitude of CMB temperature anisotropies, as a function of multipole moment l (so that angular scale decreases from left to right). The data points are averaged from all of the experiments performed as of Summer 2000. The curve is a theoretical model with scale-free adiabatic scalar perturbations in a flat universe dominated by a cosmological constant, with a slightly higher baryon density than implied by big-bang nucleosynthesis. Courtesy of Lloyd Knox.

decreases from left to right in the figure, as multipole moment is related to angular scale roughly by $\theta \sim 180°/l$. This plot manifests three crucial features:

1. A well-defined, narrow ($\Delta l/l \sim 1$) peak in the power spectrum. This is strong evidence in favor of "inflationary" primordial perturbations.

2. Location of the peak at $l \sim 200$. This is strong evidence in favor of a nearly flat spatial geometry ($\Omega_{\rm tot} = 1$).

3. A secondary peak ($l \sim 500$) which is rather small, if one is indicated at all. Previous best-fit models predicted a noticeable peak at this location; this might be evidence of tilt in the perturbation spectrum, a higher-than-expected baryon density, or more profound physics.

Let's consider each of these features in turn.

The adjective "inflationary" refers to adiabatic perturbations that have been imprinted with (nearly) equal amplitudes on all scales (both greater and less than the Hubble radius H^{-1}) before recombination. "Adiabatic" means that fluctuations in each species are correlated, so that the number density ratios of photons/baryons/dark matter are spatially constant. (Here, "baryons" is cosmology-speak for "charged particles.") These are the kinds of perturbations predicted by inflationary cosmology; it is entirely possible that a mechanism other than inflation could generate perturbations of this type, although no theories which do so have thus far been proposed. When we observe temperature fluctuations in the CMB, on scales which are larger than the Hubble radius at recombination the dominant effect is the gravitational redshift/blueshift as photons move through potential wells (the Sachs-Wolfe effect), while on smaller scales the intrinsic temperature anisotropy is dominant. An adiabatic mode of wavelength λ (which grows along with the cosmic scale factor) will remain approximately constant in amplitude while $\lambda > H^{-1}$, after which it will begin to evolve under the competing effects of self-gravity (which works to increase the density contrast) and radiation pressure (which works to smooth it out). The result is an acoustic wave which oscillates during the period between when the mode becomes sub-Hubble-sized and recombination (when radiation pressure effectively ends). As the wave evolves it is also damped as photons dissipate from overdense to underdense regions. We therefore expect to see a series of peaks in the CMB spectrum, with the largest peak corresponding to a physical length scale equal to that of the Hubble radius at recombination. A crucial point is that the sharpness of this peak is evidence for the temporal coherence of the waves — the evolution of a wave at any one wavelength is related in a simple way to that at other wavelengths, which enables the spectral features to be well-defined (see [6] for a discussion). In models where the perturbations are continually generated at all times (such as with topological defects), or models of "isocurvature" fluctuations in which different species are uncorrelated, this coherence is absent, and it is very difficult to get a sharp peak. The new observations thus strongly favor primordial adiabatic perturbations.

As mentioned, the location of the first peak corresponds to the Hubble radius at the last scattering surface, $H_{\rm LS}^{-1}$. In a spatially flat universe, the observed angular scale of the peak would be the ratio of $H_{\rm LS}^{-1}$ to the angular diameter distance r_θ between us and the surface of last scattering. It turns out that, in a Friedmann-Robertson-Walker cosmology with plausible values of the various cosmological parameters, both $H_{\rm LS}^{-1}$ and r_θ depend on these parameters in roughly the same way: they are each proportional to $H_0^{-1}/\sqrt{\Omega_{\rm M0}}$, where $\Omega_{\rm M}$ is the ratio of the matter density to the critical density and subscripts 0 refer to quantities evaluated at the present time. The ratio $H_{\rm LS}^{-1}/r_\theta$ is thus approximately independent of the cosmological parameters. The observed angular scale of the first peak therefore depends primarily on the spatial geometry through which the photons have traveled; in a positively/negatively curved space, a fixed physical size corresponds to a larger/smaller angular size. The spatial geometry can be quantified by the total density parameter $\Omega_{\rm tot}$, and the angular dependence of the peak turns out to be $l_{\rm peak} \sim 200\Omega_{\rm tot}^{-1/2}$. Thus, the observed peak at $l \sim 200$ provides excellent evidence for a flat universe. The most recent data are sufficiently precise that sub-dominant effects become relevant, and more careful analyses are necessary [7]. The quantitative results depend somewhat on which parameters are allowed to vary and which additional data are taken into account; the CMB data alone are actually best fit by a universe with a very small positive spatial curvature, but a perfectly flat universe is within the errors, while an open matter-dominated universe with $\Omega_{\rm tot} < 0.5$ is strongly ruled out. Taking existing data on the Hubble parameter and large-scale structure distribution into acount implies the need for a positive cosmological constant, thus providing some independent confirmation for the striking supernova results [8].

The most unexpected feature of the observed CMB power spectrum, from the point of view of previously favored cosmological parameters, is the absence of an easily distinguishable secondary peak. It turns out that the expected peak can be suppressed in two straightforward ways: by "tilting" the primordial spectrum so that there is slightly less power on small scales, or by increasing the baryon-to-photon ratio. The tilting option, while plausible, is hard to accommodate within simple inflationary models, as a sufficient tilt is necessarily accompanied by additional tensor fluctuations on large scales [9], ruining the rest of the fit. The baryon density is most conveniently expressed in terms of $\Omega_{\rm b}h^2$, where $\Omega_{\rm b}$ is the density parameter in baryons and $h = H_0/(100\ {\rm km/sec/Mpc})$. The CMB data [7] imply $\Omega_{\rm b}h^2 = 0.032 \pm 0.009$, while big-bang nucleosynthesis [10] implies $\Omega_{\rm b}h^2 = 0.019 \pm 0.002$ (at 95% confidence), with an "extreme upper limit" [11] of $\Omega_{\rm b}h^2 \leq 0.025$. Hence, consistency is just barely preserved at the edges of the allowed values. It would seem at this point most likely that some combination of slight tilt and ordinary experimental error have combined to create this apparent tension, but there remains the possibility of interesting new physics. (Note that the *upper* limit on the baryon density provides additional support for the necessity of non-baryonic dark matter.)

The new CMB data are in a sense the idea experimental result, in that they provide useful constraints within the context of a successful theory while raising questions about aspects of that theory that can only be addressed by future experiments. The near future will see a number of new balloon, ground-based and satellite measurements of the CMB power spectrum on even smaller angular scales (including the presumed location of the third peak and beyond), which should reveal whether we are seeing a spectacular confirmation of the standard cosmology or the first signs of important deviations from it.

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LISA Project Update

W. M. Folkner, Jet Propulsion Laboratory, Caltech
william.folkner@jpl.nasa.gov

The last 18 months have been very important for the Laser Interferometer Space Antenna project. Several advisory panels have made very positive recommendations regarding the prospects for a gravitational-wave observatory in space. NASA has begun serious planning for funding the LISA project and associated technology development starting in 2002 while continuing mission studies. The European Space Agency has continued technology development in key areas and funded a Phase A study under a contract led by Dornier Satellite Systems (now part of Astrium). Informal discussions on a partnership arrangement between NASA and ESA have continued and are about to transition to a more formal working arrangement. The prospects for achieving a launch of LISA towards the end of the decade are very good.

In 1999 NASA Office of Space Science conducted a series of meetings for the purpose of updating its Strategic Plan. (These updates are held approximately every three years.) A key meeting of the Structure and Evolution of the Universe Subcommittee was held in February 1999 to consider future missions within the SEU theme. Following that meeting the SEUS recommend that LISA be included in the 2000 OSS Strategic Plan as a candidate for a New Start in the 2005-2008 time frame. The SEUS recommendations are published in the SEU Roadmap (http://universe.gsfc.nasa.gov/roadmap.html). The recommendation of the SEUS was forwarded for consideration by the NASA's Space Science Advisory Committee. At a meeting held in November 1999 (in Galveston) the SSAC endorsed the SEUS recommendation of LISA for inclusion in the 2000 OSS Strategic Plan, which will be reflected in the Plan when published in the upcoming months. Outside NASA two panels commissioned by the National Research Council have given LISA high priority for future missions. The Committee on Gravitational Physics, chaired by Jim Hartle, gave a low-frequency gravitational-wave observatory its highest priority for space missions in gravitational physics (http://www.nap.edu/books/0309066352/html/). The Astronomy and Astrophysics Survey Committee, chaired by Joe Taylor and Chris McKee, ranked LISA as second highest priority among moderate-scale projects for the coming decade (http://books.nap.edu/catalog/9839.html).

NASA funding for the implementation of moderate missions has historically been provided by specific congressional line items in the NASA budget for each project. More recently congress has approved several continuing line items for multiple missions (e.g. Origins, Mars Exploration). NASA has decided to request a new continuing line item, called Cosmic Journeys, for the SEU theme to cover multiple future missions including LISA. If approved, significant advanced technology development for LISA would begin in 2002 with a nominal launch date in 2010.

Prior to approval for construction of the mission, the technology needed to achieve the science goals must be demonstrated to a suitable level. For Technology Plan for LISA has been developed and reviewed by an advisory group. One of the key technology issues for LISA is for the test masses to be free of unwanted forces that would cause motions larger than those cause by gravitational waves. For the frequency and sensitivity desired for LISA the disturbances are required to be less than $10^{-16}G$ for times scales of 100 to 10,000 seconds.

This level of performance seems achievable, and detailed calculations of expected forces for some designs indicate that the requirements can be met. But the required performance is far beyond any experiment done so far. Furthermore it seems unlikely that the required performance can be demonstrated on Earth. Therefore it is desirable to consider a space experiment to demonstrate the required level of performance.

Several concepts have been proposed for a mission to demonstrate technologies needed for LISA. In 1999 NASA's New Millennium Program supported a Phase A study of such a mission concept. The Disturbance Reduction System would have included two test masses and a laser interferometer to measure the distance between them. If the forces on each test were small enough then the distance between them would change very little, showing that the level of force noise was near the LISA requirement. The DRS concept was studied along with two other mission concepts for demonstrating technologies for future space science missions. DRS was not selected for implementation, primarily because the estimated cost the achieve the DRS goals exceeded the cost cap. (The selected mission was the Nanosat Constellation Trailblazer: http://nmp.jpl.nasa.gov/st5/).

Because of the high priority status of LISA with NASA and NRC reviews, there are continuing efforts to find the best way to implement the desired technology demonstration. One possibility being very actively studied is the possibility of adding a LISA Test Package to the ST3 Separated Spacecraft Interferometer mission (http://origins.jpl.nasa.gov/missions/st3.html). The ST3 mission is planned for launch into an Earth-trailing orbit in 2005. An Earth-trailing orbit is very desirable for a LISA technology demonstration because the thermal, magnetic, and gravitational environment is much more stable than for an Earth-orbiting mission. The environmental stability is key for achieving the low level of forces needed for the LISA demonstration. At this time, the possibilities for allocating the required funding from NASA, and for forming a partnership arrangement with ESA, for this option are being actively pursued.

An update on the r-mode instability

Nils Andersson, University of Southampton, UK
N.Andersson@maths.soton.ac.uk

In the last two years the r-modes in rotating neutron stars have attracted a lot of attention. The main reason for this is that they are unstable due to the emission of gravitational waves via a mechanism that was discovered by Chandrasekhar, Friedman and Schutz more than 20 years ago. Until recently the r-modes —which are essentially horizontal currents associated with very small density variations— had not been considered in this context. Hence the discovery that they are unstable at all rates of rotation in a perfect fluid star [1] came as a slight surprise. And even more of a surprise was the subsequent realization [2] that the unstable r-modes (which radiate mainly through the current multipoles) provide a much more severe constraint on the rotation rate of viscous stars (viscosity tends to counteract mode-growth due to gravitational radiation) than the previously considered f-modes (which are dominated by the mass multipoles). A direct comparison shows that the f-mode becomes unstable when the star is spun up to roughly 95% of the mass-shedding limit, while the dominant r-mode becomes unstable already at 5% of the maximum spin rate (at some temperature). With these early estimates, the r-mode instability emerged as a potential agent for spinning nascent neutron stars down to rotation rates similar to the initial period inferred for the Crab pulsar ($P \approx 19$ ms), in the process radiating an amount of gravitational waves that should be detectable with LIGO II for sources in the Virgo cluster [3]. It was also suggested [4] that the instability could operate in older, colder neutron stars and perhaps explain the clustering of spin periods in the range 260-590 Hz of accreting neutron stars in Low-Mass X-ray Binaries (LMXB) indicated by the kHz QPOs.

Understandably, these possibilities created some excitement among workers in this field and some 50 papers discussing the r-mode instability have since appeared. My intention here is to provide an update on the current status of this discussion without going into too much detail. The interested reader is referred to an exhaustive review on the subject [5] (and the original papers, of course). My main aim is to describe how our understanding of the r-modes and the associated instability has changed since the first studies. To some extent this is a simple task, because all the original ideas remain relevant. No one has yet provided a demonstration that the mechanism cannot work or that our original thinking was seriously flawed. This is, of course, good news. Less comforting is the fact that the questions that need to be addressed to make further progress are very hard and involve a lot of essentially unknown physics.

A natural point of departure for this survey is the case for r-modes in hot young neutron stars emerging from supernova explosions. A newly born neutron star should cool to the temperature at which the dominant r-mode goes unstable (a few times 10^{10} K) in a few seconds. Provided that the star spins fast enough the r-mode will then grow with an "e-unfolding" time of a few tens of seconds until it enters the nonlinear regime and... then what? In the first studies of the problem it was assumed that nonlinear effects (e.g. coupling to other modes) would lead to the mode saturating at some large amplitude [3]. The mode would continue to radiate away angular momentum and the star would spin down from the mass-shedding limit to a period of 15-20 ms in a year or so [2]. In these models a crucial parameter is the amplitude of saturation. In order for the instability to have a dramatic effect on the spin-evolution of a young neutron star, the r-mode must be allowed to grow to a reasonably large amplitude. Intuitively, one might expect non-linear effects to become relevant at much smaller mode-amplitudes than those considered in the early work. However, the indications are now that the mode will be able to grow surprisingly large. This is demonstrated by very recent 3D time-evolutions (using a fully nonlinear relativistic hydrodynamics code with the spacetime "frozen") of Stergioulas and Font [6]. The first results of investigations into the nonlinear coupling between r-modes and other modes seem to point in the same direction [7]. There are no signs of mode-saturation until at very large amplitudes. It should, of course, be noted that much work remains to be done on this problem before we can draw any firm conclusions.

The original spin-down scenarios were based on the assumption that the star evolves along a sequence of uniformly rotation equilibrium models as it loses angular momentum. Recent work indicates that this is unlikely to be the case. One might expect that a large amplitude unstable mode will lead to differential rotation in the stellar fluid. It is well-known that this is the case for the bar-mode instability in the Maclaurin spheroids. Once spun up to the point where the bar-mode becomes unstable, the Maclaurin spheroids evolve through a sequence of differentially rotating Riemann S-ellipsoids. One might expect an analogous evolution for stars governed by the r-mode instability. Evidence in favor of this possibility have been presented by Rezzolla, Lamb and Shapiro [8]. They argue that the r-mode leads to a nonlinear differential drift of the various fluid elements. Their calculation is based on inferring higher order (in the mode-amplitude) results from established linear results, and may not be quantitatively reliable, but it provides an indication that nonlinear effects will severely alter the fluid motion. This result is supported both by the time-evolutions of Stergioulas and Font [6] and a shell toy model studied by Levin and Ushomirsky [9]. In the latter case the nonlinear effects can be determined exactly, and they lead to the anticipated differential drift. Furthermore, the shell toy-model shows that, once radiation reaction is implemented, another source of differential rotation comes into play. Thus it would seem almost certain that differential rotation will play a key role in any realistic r-mode scenario. Differential rotation immediately brings magnetic field effects into focus. While effects due to electromagnetic waves generated by an oscillation mode are typically small [10], differential rotation may lead to a twisting of the field lines and a dramatic increase in the field strength. In the case of the r-modes the instability scenario may lead to the generation of a very strong toroidal magnetic field [8].

Following an original suggestion by Bildsten and Ushomirsky [11], much work in the last eight months or so has been focussed on the interface between the fluid core and the solid crust in a slightly older neutron star. Given that the crust is likely form already at a temperature of the order of 10^{10} K this discussion is relevant for all but very young neutron stars. Bildsten and Ushomirsky showed that a viscous boundary layer at the crust-core interface would lead to a very strong dissipation mechanism that would prevent the instability from operating unless the rotation period was very short. The original estimates seemed to suggest that the r-mode instability would not be relevant in the LMXBs and that it would not be able to spin a newly born neutron star down to spin periods beyond a few milliseconds. With more detailed studies these suggestions have been revised [12], and it now seems as if the instability could well be relevant for the LMXBs (perhaps leading to a cyclical spin-evolution [13]). But the uncertainties are large and many issues remain to be explored in this context. The crust-core discussion has led to suggestions that the heat released in the viscous boundary layer may, in fact, melt the crust. An interesting possibility, suggested by Lindblom, Owen and Ushomirsky [14], is that the final outcome is a kind of mixed state, with "chunks of crust" immersed in the fluid. To estimate the mode-dissipation associated with such a situation is, of course, very difficult. Also worth mentioning in this context are the results of Wu, Matzner and Arras [15]. They argue that the crust-core boundary layer is likely to be turbulent which would provide a mechanism for saturation. However, one can infer that the resultant saturation amplitude is of order unity for rapidly rotating stars. This could well indicate that the modes saturate due to some alternative, as yet unspecified, mechanism.

Progress on all these issues is somewhat hampered by the lack of detailed quantitative results. It may be appropriate to provide a contrast by concluding this discussion by emphasizing two particular cases where hard calculations have provided relevant results. The first of these concerns r-modes in superfluid stars. This is an important issue since the bulk of a neutron star is expected to become superfluid once it cools below a few times 10^9 K. At this point some rather exotic dissipation mechanisms come into play, and it turns out (somewhat paradoxically) that a superfluid star is more dissipative than a normal fluid one. The most important new mechanism is the so-called mutual friction which has been shown to completely suppress the instability associated with the f-modes. The initial expectations were that mutual friction would also have a strong effect on the r-modes [2,3]. Detailed calculations by Lindblom and Mendell [16] have shown that this is not necessarily the case. The outcome depends rather sensitively on the detailed superfluid model (the parameters of the so-called entrainment effect), and only in a small set of the models considered by Lindblom and Mendell do mutual friction affect the r-modes in a significant way. It would thus seem as if the r-mode instability may prevail also in superfluid stars.

Another important issue regards r-modes in fully relativistic stars. After all, the instability is a truly relativistic effect (being driven by gravitational radiation) and a relativistic calculation is required if we want to understand radiation reaction "beyond the quadrupole formula". And it should be recalled that the quadrupole formula leads to a significant error (it deviates from the true result by 20-30% already for $M/R \approx 0.03$) in estimates of the gravitational wave damping of the f-mode [17]. Furthermore, it is known that relativistic effects tend to further destabilize the f-modes [18]. While the quadrupole f-mode does not become unstable below the mass-shedding limit in a Newtonian star it does so in the relativistic case. For all these reasons the modeling of relativistic r-modes is a crucial step towards improved estimates of the instability timescales. It turns out that relativistic modes whose dynamics is mainly determined by the Coriolis force generally have a "hybrid" nature. This makes the calculation rather complicated, but significant progress on determining the relativistic analogue of the Newtonian r-modes has been made recently. These results are detailed in Lockitch's PhD thesis [19], as well as a recent paper [20] where the post-Newtonian corrections to the $l = m$ r-modes of uniform density stars are calculated. Estimates of the growth rate of the unstable modes in the fully relativistic case are currently being worked out as an extension of this work.

At this point I hope it is clear that, despite some recent progress, the uncertainties regarding the astrophysical role of the r-mode instability remain considerable. This is obviously somewhat disconcerting since it means that our understanding of this mechanism is not detailed enough to provide reliable theoretical templates that can be used to search for the associated gravitational waves in data taken by LIGO, GEO600, VIRGO or TAMA. In fact, I think it is quite unlikely that theorists will be able to provide this kind of information any time soon. After all, a detailed understanding of the involved issues demands a successful modeling of a regime where many extremes of physics meet. In view of this, I believe the challenge is to invent a pragmatic detection strategy based on general principles rather than detailed theoretical information. After all, would it not be quite exciting if an actual detection would provide us with some of the missing pieces of this pulsar puzzle, and help improve our understanding of general relativity, supranuclear physics, magnetic fields, superfluidity etcetera?

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Laboratory Experiments: A 14 ppm G measurement, a new sub-mm gravity constraint, and other news from MG9

Riley Newman, University of California, Irvine
rdnewman@uci.edu

G to 14 ppm. An elegant new G measurement by Jens Gundlach and Stephen Merkowitz of the U. Washington "Eöt-Wash" group was reported at the April APS meeting in Long Beach, and at the Marcel Grossmann meeting (MG9) in Rome this summer. The reported result, $G = (6.674215 \pm 0.000092) \times 10^{-11} m^3 kg^{-1} s^{-2}$, carries an assigned uncertainty two orders of magnitude smaller than the 1500 ppm uncertainty associated with the current recommended "CODATA" G value (the CODATA uncertainty reflects large discrepancies in G values reported in the last decade – see MOG Number 13). Gundlach's measurement has a number of novel features. A PRL paper in press and available in preprint form [1] describes the experiment. At the heart of the apparatus is a torsion balance placed on a turntable located between a set of attractor spheres. The turntable is first rotated at a constant rate so that the pendulum experiences a sinusoidal torque due to the gravitational interaction with the attractor masses. A feedback is then turned on that changes the rotation rate so as to minimize the torsion fiber twist. The resulting angular acceleration of the turntable, which is now equal to the gravitational angular acceleration of the pendulum, is determined from the second time-derivative of the turntable angle readout. Since the torsion fiber does not experience any appreciable deflection, this technique is independent of many torsion fiber properties, including anelasticity, which may have led to a bias in previous measurements. The attractor masses revolve around the pendulum on a second turntable whose constant angular velocity differs from that of the pendulum's turntable. This motion of the attractor masses makes their torque on the pendulum readily distinguishable from torque due to ambient lab-fixed gravitational fields. Another key feature described in the forthcoming paper and earlier papers [2,3] is a pendulum in the form of a thin rectangular plate. The gravitational torque on the pendulum is dominantly determined by the ratio of its quadrupole moment to moment of inertia – a ratio which is independent of the shape and mass distribution of the pendulum in the limit that it has negligible width. This greatly eases the metrology requirement for the pendulum, in contrast to earlier experiments where pendulum metrology has been a limiting factor.

G at MG9. A session at MG9 was devoted primarily to G measurements, several of which target accuracy comparable to that of Gundlach and Merkowitz. Gundlach reported the measurement described above. Tim Armstrong reported measurements made at the New Zealand Measurement Standards Laboratory using a torsion pendulum in two modes: one in which a servo system and rotating platform ensured that there was no significant fiber twist, yielding $G = (6.6742 \pm 0.0007) \times 10^{-11} m^3 kg^{-1} s^{-2}$ [4], and a more recent one using the dynamic ("time-of-swing") method yielding $G = (6.675 \pm 0.01) \times 10^{-11} m^3 kg^{-1} s^{-2}$. The latter value has much larger uncertainty but is consistent with the former, and both values are consistent with that of Gundlach and Merkowitz. Jun Luo described a new G measurement being developed by his lab in China, which should improve on his measurement published recently [5]: $G = (6.6699 \pm 0.0007) \times 10^{-11} m^3 kg^{-1} s^{-2}$. Stephan Schlamminger gave a progress report on the University of Zürich G measurement using a beam balance and mercury-filled steel tank source masses. This experiment [6], which has been troubled in the past by systematic error, shows encouraging progress toward a 10 ppm measurement. Jim Faller reported progress of a G determination based on measurement of the differential deflection of a pair of suspended masses which form a Fabry-Perot cavity; this experiment expects 50 ppm G accuracy, significantly improving on an earlier G measurement by Faller's group [7]. Michael Bantel reported progress of the UC Irvine G measurement using a high-Q cryogenic torsion pendulum operating in the dynamic ("time-of-swing") mode. Ho Jung Paik described his proposed cryogenic G measurement in which a set of four magnetically suspended test masses would be located symmetrically on the periphery of a slowly rotating turntable. Paik's determination of G would be made by measuring the turntable rotation speed required to keep the masses at a fixed radius when an attracting mass is lowered into the center of the array of test masses. Paik's proposed experiment targets 1 ppm accuracy. In the one non-G talk of the session, Andrej Čadež with Jurij Kotar described the University of Ljubljana inverse square law test, in which two pairs of source masses rotate continuously about a torsion pendulum – one pair at opposite 971 mm radii and another at 383 mm radii along an axis perpendicular to that of the first pair. The masses of the pairs are chosen to produce null pendulum excitation at twice the rotation frequency for a Newtonian force law. The group expects to improve on their previous limit [8] which constrained a Yukawa interaction term to be $(-0.2 \pm 6) \times 10^{-3}$ relative to gravity over a distance range 0.2 m to 0.45 m.

It seems increasingly clear that the anomalous PTB G measurement [9] must be in error. However, new measurements have yet to converge satisfactorily. At the "CPEM2000" metrology conference in Australia in May this year, a BIPM group led by Terry Quinn reported (<u>preliminary</u>) results of G measurements using a torsion pendulum suspended by a strip fiber. Such a pendulum is minimally subject to systematic error associated with fiber anelasticity, because the dominant part of its effective torsion constant is gravitational in origin and hence lossless. The measurements were made in two modes: an unconstrained static measurement, yielding $G = (6.6693 \pm 0.0009) \times 10^{-11} m^3 kg^{-1} s^{-2}$ and a static measurement in which the pendulum was servoed to zero displacement with a calibrated electrostatic force, yielding $G = (6.6689 \pm 0.0014) \times 10^{-11} m^3 kg^{-1} s^{-2}$. The two methods yield consistent results which are however more than 5 of their own standard deviations from the G value obtained by Gundlach and Merkowitz.

Sub-mm gravity at MG9. The highlight of the MG9 session on short-range tests of gravity was preliminary results of the "Eöt-Wash" group's test, reported by Jens Gundlach. The instrument of this experiment is a torsion pendulum in the form of a horizontal disk with ten holes arranged symmetrically azimuthally, suspended above a rotating attractor, with a thin copper electrostatic shield between. The attractor is in the form of two copper disks, each with a set of ten holes. The lower of these rotating disks has a fixed angular displacement relative to the upper and is more massive, arranged so that for a particular pendulum-attractor separation the pendulum experiences no torque modulation at the signal frequency of ten times the attractor rotation frequency if gravity is Newtonian. Gundlach presented preliminary results in the form of a sketched plot indicating a one sigma limit on the order of 2% of gravity at a range of about 1.5 mm. The test is expected to yield still better constraints soon.

John Price reported a current sensitivity about 100 times gravitational strength at 0.1 mm, expected to improve to 1 times gravitational strength at that distance using his existing room temperature instrument and to improve still further with a planned cryogenic instrument.

Michael Moore discussed the short-range test he is developing with Paul Boynton, which uses a near-planar torsion pendulum suspended above a near-planar source mass, configured to give a nearly null signal for purely Newtonian gravity. The expected sensitivity of their apparatus to an anomalous force is about 0.25 of gravity at 0.25 mm and 0.01 of gravity at 1 mm.

Aharon Kapitulnik described his present cantilever-based instrument at Stanford, which has projected sensitivity better than .05 of gravity at 0.08 mm, and discussed possible future improvements.

Giuseppe Ruoso discussed the apparatus of the Padua group. Currently optimized for Casimir force measurements, the instrument does not yet have good sensitivity for short-range gravity measurements. When the Casimir tests are completed the group expects to optimize it for gravity tests, and expects sensitivity on the order of $\alpha = 10^7$ to 10^8 for ranges of a few microns, in a yet-unexplored region of the $\alpha - \lambda$ plane.

Ho Jung Paik reported the design of a cryogenic null test of the inverse-square law, with expected sensitivity at a level 0.0001 of gravity at 1 mm and 0.01 of gravity at 0.1 mm.

Ephraim Fischbach reviewed the motivations for short-distance gravity tests, and discussed prospects for very short range tests using atomic force microscopy. Dennis Krause as well as Ephraim discussed ways of dealing with the severe problems of molecular background forces in extremely short range tests.

Christian Trenkel reported the development of a torsion balance using a Meissner effect suspension, and this instrument's prospective applications in weak force physics such as a spin-mass coupling experiment.

A list including other current mm-scale gravity tests, with a little more detail on some of the projects reported above, is available in MOG number 15.

Laboratory equivalence principle tests at MG9. A session on equivalence principle tests, chaired by Ramanath Cowsik, included talks on both space and laboratory tests; I report here only on the latter.

Nadathur Krishnan reported the status of the TIFR equivalence principle experiment, which employs a torsion pendulum with a 3.6 meter long torsion fiber of rectangular cross section, operating in a chamber deep underground in a seismically very quiet region of India. The test operates in a Dicke mode, using the sun as acceleration source, targeting a sensitivity at a level of $\eta \approx 10^{-13}$. Continuous operation of the instrument is about to begin.

Paul Boynton discussed a novel mode in which a torsion pendulum may be used to measure anomalous forces, based on measurement of the second harmonic component of the pendulum's oscillatory motion. This method, introduced by Michael Moore in Paul's group, has the great advantage that it is extremely insensitive to variation of the fiber temperature, in contrast to force measurements based on measurement of a pendulum's oscillation frequency or static displacement.

I gave a short talk on prospects for improved terrestrial equivalence principle tests using a cryogenic torsion pendulum, taking advantage of the high Q and good temperature control achievable with such an instrument. In principle such an instrument should be capable of η sensitivities of 10^{-14} or better, although many practical difficulties are to be encountered.

Wolfgang Vodel gave a progress report on the Bremen Drop Tower test of the equivalence principle, in which a superconducting differential accelerometer falls 109 meters in an evacuated tube. This system is expected to be capable of η sensitivity at a 10^{-14} level, with a theoretical limit at a 10^{-16} level and a near-term result anticipated at a 10^{-13} level.

Cliff Will reviewed tests of the three ingredients of the Einstein Equivalence Principle – universality of free fall, local Lorentz invariance, and local position invariance – and discussed their theoretical implications.

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Progress toward Commissioning the LIGO detectors

Stan Whitcomb, LIGO Laboratory
stan@ligo.caltech.edu

This past year has seen great progress in two distinct detector activities: installation–defined as getting working subsystems into position–and commissioning–making the subsystems work together to operate as a complete detector with full sensitivity.

Our installation and commissioning plan has evolved into one where each of the three interferometers has a well-defined role, and the scheduling of the work on each one has been tailored to its role. The Hanford 2 km interferometer is the first in line and serves as a "pathfinder" to identify problems early. The Livingston 4 km interferometer follows about 6 months behind, and is used for problem resolution and detailed characterization. We will initiate coincidence testing as soon as the first two interferometers are operational, but we will deliberately delay installation of some elements of the Hanford 4km interferometer (primarily control electronics) to enable lessons learned from the first two interferometers to be realized in redesign before installation. The LIGO I science run will begin when reliable and calibrated coincidence data on three interferometers can be taken while keeping the configuration stable for substantial periods of time. The improvements to reach final design goals in sensitivity and reliability will be alternated with data running in a way that optimizes both the early running and obtains integrated high sensitivity data taking before the completion of the initial LIGO science run.

On the installation front, the fabrication of the detectors was completed (with the exception of some electronics components), and most detector components have been delivered to the Observatories for installation. Installation of the Hanford 2 km interferometer was completed in May 2000. Installation of the Livingston 4 km interferometer is being completed as this Newsletter goes to press (September 2000). As mentioned above the Hanford 4 km interferometer installation has been intentionally delayed, but substantial progress has been made: the seismic isolation has been installed and the infrastructure (networking, data acquisition, monitoring equipment) has been installed and tested.

Commissioning the LIGO detectors began even before the installation was complete. On both the Hanford 2 km interferometer and the Livingston 4 km interferometer, the pre-stabilized laser has been integrated with the mode cleaner (a suspended cavity to stabilize the laser beam before it enters the interferometer). Initial characterization of the laser/mode cleaner system has been completed and show that the combination is already very close to meeting their performance requirements.

In December 1999, we began a four month test of the 2 km interferometer in which each arm of the interferometer was separately locked to the laser. This test was performed to measure optical properties of the arms, to test the interferometer sensing and control electronics, to gain information about the environmental noise sources and to exercise the data acquisition and control networks. Lock sections up to 10 hours were obtained and all planned investigations were successfully concluded. At the end of the testing, a 24-hour stretch of data was taken and archived for use by groups developing software and techniques for data analysis and detector characterization.

During the past summer, we have gradually begun to bring the entire 2 km interferometer on-line. We began by operating it in the recycled Michelson configuration, (without the long arm cavities). This simple configuration allowed us to test the control systems: verifying the myriad connections, measuring transfer functions, setting modulation/demodulation phases, all of the nuts and bolts of precision interferometry that must be in place before everything will work. Most recently, we have locked the power-recycled Michelson with one Fabry-Perot arm also locked on resonance. This initiated another set of control system measurements which should lead to locking the full interferometer early this fall.

Of course, a number of problems have been encountered along the way, but many have been solved, solutions to others are in the works, and none will jeopardize the performance or schedule significantly. We are on track to initiate the first triple coincidence science runs by early 2002.

160 Hours of Data Taken on the TAMA300 Gravitational Wave Detector

Seiji Kawamura, National Astronomical Observatory of Japan
seiji.kawamura@nao.ac.jp

The TAMA project, the Japanese effort for detecting gravitational waves using the 300m laser interferometer, successfully took 160 hours of data between August 21, 2000 and September 4, 2000. The best sensitivity of the detector was about $5 \times 10^{-21}\mathrm{Hz}^{-1/2}$ around 1 kHz in terms of strain, which gives a signal-to-noise ratio of 20 to 30 for gravitational waves emitted from a binary neutron star coalescence in the center of our galaxy. The interferometer was operated remarkably stably; the longest continuous locking time was more than 12 hours, and on one day it was locked for more than 23 hours out of 24 hours. The quality of the data was also drastically improved compared with our previous runs. First the non-stationary noise which appeared very often in the previous data runs was significantly reduced. Secondly approximately 100 signals including feedback and error signals of various control loops and environmental signals such as ground motion were also recorded so that any spurious signals in the interferometer output can be vetoed by correlating them with other channels. The obtained data are now being analyzed for gravitational wave detection as well as for diagnosis purposes of the interferometer. We will further improve the sensitivity and stability of the detector from now until in January 2001 we plan to hold a two-month data run.

Please have a look at our home page. http://tamago.mtk.nao.ac.jp/

Also the "Data treatment guideline of TAMA" can be found at the following web site. http://tamago.mtk.nao.ac.jp/tama/data-access.html

Kipfest

Richard Price, University of Utah
rprice@mail.physics.utah.edu

With the development of time machines apparently bogged down, Caltech's Kip Thorne had little alternative but to reach his 60th birthday on June 1, 2000. A large corps of relativity observers were on hand for the occasion to mark the moment, and to prevent Kip from relaxing and enjoying it. A set of Kip's former students organized a three day "KipFest" on June 1 –3 that included two days of scientific talks, a day of popular talks for the public, and a banquet.

The scientific talks, presented on June 1 and June 2, were not primarily conference-style reports on scientific news, but rather were talks emphasizing the scope of Kip Thorne's contributions to various branches of relativity and relativistic astrophysics. They included overviews of problems on which Kip had worked and reminiscences about Kip. The full two-day scientific program can be found linked to the KipFest website at

http://wugrav.wustl.edu/People/CLIFF/KipFest/kipmain.html

The list of topics is striking in its breadth of topics. Kip had been a driving force, or major contributor, to problems ranging from experimental approaches to gravity (e.g., the talks by Rai Weiss and Vladimir Braginsky) to wormholes (Eanna Flanagan's talk) and "real" astrophysics (talks by Roger Blandford and Anna Zytkow). Even with all the memorable moments of the two days, one moment stands out. Jim Hartle related how he had worked with Kip on slowly rotating stars more than 20 years ago, but then was lured away by the siren call of quantum gravity. (Jim suggested that he could be accused of "not having done a lick of honest work since.") The call interrupted work on a final Hartle-Thorne paper that Kip had started and Jim was to finish. The paper had remained unfinished, in the back of Jim's filing cabinet. But only until June 2, when Jim ended his talk by handing Kip the final draft!

To honor Kip Thorne's commitment to bringing exotic physics to non-scientists, five talks were presented on Saturday, June 3, by speakers with a gift for communicating the ideas of science. These talks, free to the public, were held in Caltech's Beckman auditorium, and attracted over a thousand listeners. Stephen Hawking and Igor Novikov discussed wormholes and time travel, and Kip Thorne made predictions for what lay ahead in our field in the coming decade or so. There were also two talks not directly dealing with specific scientific questions. The well known science writer Timothy Ferris talked about the problem of communicating science to the public, and Alan Lightman, who is both a scientist and a novelist, gave his insights about the different kinds of creativity involved in his two careers.

It is not really possible to describe the banquet on Friday evening. You had to be there. There were a few of the short speeches that one expects, most notably by John Wheeler. But there was a somewhat unexpected reminiscence by football/TV star Merlin Olsen, about the early scientific curiosity of his boyhood friend Kip. (It had to do with frogs, non-relativistic frogs.) Kip's sisters shared other memories of his early days, and Kip did a wonderful job of hiding his discomfiture. Tradition grew yet thinner as Linda Williams, the "Physics Chanteuse," celebrated physics and Kip with music. Undeterred by the high musical standards she had set, the physics singing group "Bernie and the Gravitones" went to the stage to make a rare appearance and to make fools of themselves, an endeavor in which they were judged to have been completely successful. The group was four of Kip's former graduate students (Sandor

Kovacs, Richard Price, Bernie Schutz and Cliff Will) singing, in "the average key of B and a quarter flat," about their "Wise Old Advisor from Pasadena" to a Jan and Dean song from 1964. The big finish of the evening was a presentation to Kip of his academic family tree showing how he had populated the field with 42 academic children (PhD's with Kip), how they in turn had produced 70 academic grandchildren, and how they had produced 48 academic great grandchildren.

May the numbers continue to grow.

Third Capra Meeting on Radiation Reaction

Eric Poisson, University of Guelph
poisson@physics.uoguelph.ca

The Capra series of meetings on radiation reaction in curved spacetime were initiated in 1998 by Patrick Brady. The first meeting was held at Frank Capra's ranch in southern California, and the name stayed, even though the location of the meeting has changed. (Frank Capra is the famous movie director who made such films as "It's a wonderful life" and "Mr. Deeds goes to town". Capra had studied at Caltech before going to Hollywood; he bequeathed his ranch to his alma mater, which passed to Caltech upon his death.) The second meeting was held in Dublin, Ireland, and was organized by Adrian Ottewill. This latest installment was held at Caltech June 5–9, 2000, and was organized by Lior Burko and Scott Hughes. Here I will present a rather broad overview of the main issues discussed during the meeting, and highlight just a few of the contributions. The complete proceedings — a copy of the slides presented by all the speakers — can be found at the meetings's web site: http://www.tapir.caltech.edu/~capra3/.

This series of meetings is concerned with the motion of a small mass in a strong gravitational field. It is known that in the limit of vanishing mass, the particle moves on a geodesic of the background spacetime. Away from this limit, however, the motion in the background is no longer geodesic, and can be described in terms of a self-force. (In some sense, the motion is geodesic in the perturbed spacetime, which consists of the background plus the perturbation created by the particle. For a point particle, however, the perturbation is singular at the particle's location, and careful thought must be given to the removal of the singular part of the field, which does not affect the motion. In flat spacetime, this subtraction gives rise to the well-known half-retarded minus half-advanced potential.) The main focus of the meeting was the practical computation of this force.

While this problem raises many interesting issues of principle (such as the removal of the singular part of the metric perturbation created by a point particle), there is also a practical necessity. The detailed modeling of gravitational waves produced by a solar-mass compact object orbiting a massive black hole requires an accurate representation of the orbital motion, which evolves as a result of radiation loss. In the generic case involving a rapidly rotating black hole, this evolution must be calculated on the basis of a radiation-reaction force. Such sources of gravitational waves will be relevant for the Laser Interferometer Space Antenna (LISA), a space-borne detector designed to measure low-frequency waves (it has a peak sensitivity at around 1 mHz).

The electromagnetic analogue to this problem was solved in 1960 by DeWitt and Brehme [1], who derived a curved-spacetime expression for the self-force acting on a point electric charge. The gravitational self-force was obtained much more recently, first by Mino, Tanaka, and Sasaki [2], and then by Quinn and Wald [3]. There is also a similar force in the case of scalar radiation, which was calculated by Quinn [4]. In all three cases the self-force is expressed as an integral over the past world-line of the particle, and the integral involves the nonsingular part of the retarded Green's function, which has support inside the past light cone of the particle's current position. The explicit evaluation of only this part of the Green's function is challenging, however, and a good portion of the meeting was devoted to this issue.

A plausible method for calculating the Green's function involves a separation-of-variable approach made possible by the symmetries of the black-hole spacetime. (Thus far, all calculations have been restricted to the case of a Schwarzschild black hole). It is a simple matter to derive and solve the ordinary differential equation that governs each mode of the Green's function. The problem lies with the fact that the sum over all modes doesn't converge. (This is essentially because the individual modes do not distinguish between the singular and nonsingular parts of the Green's function.) Amos Ori, Leor Barack, and Lio Burko [5] have devised a way of regulating the mode sum, so as to extract something meaningful. Their results for simple situations involving scalar radiation were presented at the meeting, and are extremely promising. A similar regularization method was used by Carlos Lousto [6], who calculated the gravitational self-force acting on a radially infalling particle in Schwarzschild spacetime. Regularization was also exploited by Hiroyuki Nakano and Yasushi Mino to calculate the gravitational self-force in the weak-field limit.

Insight into the self-force problem can be gained by adopting a more local point of view, and focusing on the immediate vicinity of the particle. Such an approach permits a clear identification of the singular part of the particle's field, which can then be decomposed into modes and subtracted from the full field. Such a strategy was adopted by Steve Detweiler (in the gravitational case) and by Patrick Brady (in the scalar case). A variation on this theme is to start with the Mino *et al.* expression for the gravitational self-force [2], and to evaluate the contribution to the world-line integral that comes from the particle's very recent past. Results along those lines were presented by Warren Anderson.

The third Capra meeting has shown that the radiation-reaction problem is progressing very nicely. There are still many issues left to sort out, but it is nice to see that concrete results have now been obtained. I expect that progress will be swift in the coming year, and that the fourth (perhaps last?) meeting will be just as exciting as the preceding ones.

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General Relativity and Quantum Gravity, at the XIIIth International Congress on Mathematical Physics

Abhay Ashtekar, Penn State
ashtekar@gravity.phys.psu.edu

The International Association of Mathematical Physics hosts a tri-annual congress to review the recent developments in the field. The 13th congress in this series took place at Imperial College, London, from 17th to 22nd July 2000. While quantum field theory and statistical mechanics have been the major components of these conferences, general relativity and quantum gravity have been well represented at least since the early eighties and, over the years, interest in sessions in our field has steadily increased.

At the London conference, Gerhard Huisken gave a plenary lecture on *Energy inequalities for isolated gravitating systems* in which he presented the recent proofs of the Penrose inequality (in the case of a maximal slice). Roughly, the inequality says that the total mass should be greater than the square-root of the area of the apparent horizon and thus strengthens the positive mass theorems proved in the late seventies. It was a lucid presentation of deep results, much appreciated also by participants outside general relativity. In addition, there were two invited sessions. The first talk in the classical gravity session was given by Lars Andersson in which he summarized recent results on approach to singularities in general relativity coupled to a scalar field. In a well-defined sense, the scenario put forward by Belinskii, Khalatnikov and Lifshitz (BKL) in the early sixties can now be rigorously justified in this case. In the second talk, Piotr Bizon first gave a succinct and exceptionally clear review of the "critical phenomena" first discovered by Choptuik and then summarized recent work which shows that many of the key features arise already in simpler dynamical systems and are thus not unique to Einstein's equations.

In the invited session on quantum gravity, John Barrett provided an overview of the state sum models, emphasizing the use of combinatorial methods and bringing out relation between diverse ideas that have come from mathematics and physics. John Baez summarized the recent results on black hole entropy based on the quantum geometry of isolated, non-rotating horizons. Although the subject involves rather technical ideas from diverse fields, he demonstrated his exceptional skill at zeroing-in on the essentials and making everything fit together naturally. In addition, there were two contributed sessions which were also well attended. The classical gravity session emphasized recent mathematical results on black holes. In the quantum gravity session, while the first two talks were on "standard" mathematical physics topics on the interface of general relativity and quantum physics, the last two were on the interface between quantum gravity, philosophy of science and quantum computing. Unfortunately, this attempt to broaden and reach out to neighboring field did not succeed; there was a marked difference in the level of precision and emphasis between the two sets of talks. Finally, there was a poster session which contained a number of exceptionally interesting presentations.

In addition to these sessions which Peter Aichelburg and I organized, there were other activities related to gravitational physics. In particular, there were two round-table discussions. The first was on *Quantum theory of space-time*, organized by Chris Isham and chaired by John Klauder, in which John Barrett, Fay Dowker, Renate Loll and Andre Lukas presented very interesting but strikingly different perspectives. In the second round table, entitled *Entropy and information: Classical & quantum*, chaired by Joel Lebowitz, John Baez spoke about entropy in the context of black hole thermodynamics. Finally, the congress had a Young Researchers Symposium, with a number of plenary lectures intended to introduce graduate students and post-docs to the exciting recent developments in various areas of mathematical physics ranging from biophysics to quantum chaos. I represented gravitational physics and spoke on the *Interface of general relativity, quantum mechanics and statistical physics.* All three sessions drew a large number of participants also from other sub-fields of mathematical physics.

3rd International LISA Symposium

Curt Cutler, Max-Planck-Institut fuer Gravitationsphysik, Golm
cutler@aei-potsdam.mpg.de

The 3rd International LISA Symposium was held July 11-14, 2000 at the Max-Planck-Institut fuer Gravitationsphysik in Golm, Germany. LISA Symposia are being held every two years, with venues alternating between Europe and the United States. The first LISA Symposium was held at RAL in July, 1996; the second was held in July, 1998 at Caltech. The main organizing bodies for the 3rd LISA Symposium were the Max-Planck-Institut fuer Gravitationsphysik and the Max-Planck-Institut fuer Quantenoptik. The were about 100 participants. The Symposium proceedings will be published as a special issue of Classical and Quantum Gravity in July, 2001. A detailed (320-page) description of the LISA Mission, the recent LISA STS Report, is available on-line at ftp://ftp.rzg.mpg.de/pub/grav/lisa/sts_1.02.pdf

A LISA conference naturally begins with an update on the politics. Within ESA, LISA is already approved as a Horizon 2000+ Cornerstone Mission, but that status has little practical worth, since "approval" leaves open the flight sequence, and without NASA cost-sharing the flight probably could not happen before 2017. Practically, LISA's proponents within both NASA and ESA see LISA as a joint NASA/ESA mission to be flown around 2010. There is now considerable enthusiasm for a shared LISA at NASA–so much enthusiasm that, as of this writing, Goddard is competing with JPL over leadership of the project. A cost-shared LISA would be a "moderate mission" from NASA's perspective, lying within the SEU Program (Structure and Evolution of the Universe). It was important that LISA did very well in the recent Taylor/McKee decadal review, "Astronomy and Astrophysics in the New Millennium"–being the secondest-highest ranked "moderate" mission. (GLAST was first.) The full report is at http://books.nap.edu/books/0309070317/html/.

However the general perception is that, for LISA to get funded, there first needs to be technology demonstration mission, to be launched (one hopes) around 2005-6. Several possible avenues for this are being pursued; as of this writing, the best bet seems to be a NASA ST3 mission, shared with ESA. The demonstrator mission would be a single satellite and would basically test the drag-free system (which cannot be tested on the ground), with the goal of demonstrating test mass isolation to within $3 \times 10^{-14}\mathrm{ms}^{-2}\mathrm{Hz}^{-1/2}$ between 1 and 5 mHz, i.e., within one order of magnitude of the LISA goal. (Noteworthy: two "graybeards" at the Symposium gave strong warnings about the technology demonstrator. Rai Weiss warned repeatedly that it should not be made too ambitious, since 1) you can't risk it failing and 2) you don't want it to absorb all your time/energy. Ben Lange, a pioneer of drag-free flight and a veteran of many, many of successful space missions, advised that he'd "avoid a demonstrator mission like the plague.")

The Symposium included about 50 talks, which is too many to summarize. I'll confine myself to listing what were, to me, a few highlights, and apologize in advance for the many excellent presentations I won't even mention here, but which you'll be able to read in the Proceedings.

Sterl Phinney gave a beautiful and very upbeat summary of LISA sources. New to me were the quite optimistic estimates for the merger rate for massive black hole binaries (MBH's), based on a hierarchical clustering picture of structure formation, where small galaxies form first and merge to form bigger galaxies. This picture leads to estimates of event rates of

$\sim 0.1 - 10/\mathrm{yr}$ for $10^6 M_\odot$ BH's out to $z = 2$. But, importantly, LISA can see far beyond $z = 2$; Phinney argued that the merger rate for $\sim 10^5 M_\odot$ BH's out to $z \sim 20$ might be $\sim 1/\mathrm{day}$.

John Armstrong and Massimo Tinto discussed their very important work (done with Frank Estabrook), showing how one can (with some changes in hardware) linearly combine the LISA data streams, with time delays, to form three linearly independent combinations for which the laser phase noise exactly cancels. Two combinations contain information on the two gw polarizations, and the third describes a "breathing mode" that doesn't couple to GR. This third mode can be used to help calibrate and eliminate noise sources, and to discriminate between non-Gaussian noise bursts and real gw bursts.

There were several very interesting talks on solar-mass compact objects spiraling into MBH's. Scott Hughes showed that, when the MBH is near-extreme Kerr, the inspiral is strongly affected by superradiant scattering of gw's from the BH horizon. Gw's that scatter off the horizon tend to "hold up" the test-body and increase the inspiral time by $\sim 3\%$ (which is a lot of cycles). Wolfgang Tichy discussed work-in-progress with E. Flanagan, claiming that, because the background Kerr metric is stationary, it actually *is* possible to determine how the Carter constant evolves from fluxes at infinity (and at the horizon). And Bernard Schutz discussed his worry (aroused, I assume, by recent work by Janna Levin) that because the orbits of spinning bodies in Kerr are chaotic, the number of matched filters will grow exponentially with the integration time, and may be vastly greater than previously anticipated–effectively obliterating the usual gains from matched filtering. This was a warning, not result, and somebody needs to look more carefully at this issue.

Large extra dimensions (perhaps as large as 0.3 mm) are now much-discussed in string theory, and Craig Hogan showed how these might lead to a gw background observable by LISA. He argued that the early universe should produce copious gw's with wavelength comparable to the size of the large extra dimension, which would be redshifted into the LISA band today. Since the gw spectrum so-produced would be highly peaked rather than flat, it is not constrained by bounds at much lower frequencies coming from millisecond pulsar timing and COBE.

Ben Lange, who attended the whole meeting and then gave us his outsider's perspective, made several recommendations, especially emphasizing advantages of spherical test masses, instead of cubes as in the current plan. And he gave a delightful, short summary of how in practice one can use a felt pen and the classical mechanics of precession to find the principal axes of an almost-perfect sphere.

Something new for a LISA Symposium: there were several talks describing laboratory prototypes for LISA systems. (Oliver Jennrich: "LISA is now more than just ink on paper.") Harry Ward discussed his work on developing an interferometric read-out system. He also reported on tests of how well hydrogen catalysis bonding of optical elements would survive the rigors of launch and space–and found the bonding held quite well under shaking and thermal cycling. Oliver Jennrich described his experiment showing the feasibility of the LISA phase measurement scheme, using the same amount of light as will be available for LISA. Manuel Rodrigues described a laboratory prototype for the inertial sensor, and Stefano Vitale described a torsion pendulum test bench he is building to testing the performance of the inertial sensor on the ground to some $5 \times 10^{-13}\mathrm{Newton}/\sqrt{\mathrm{Hz}}$. And Michael Petersheim discussed a a prototype for the highly stable laser required by LISA ($\Delta P/P < 4 \times 10^{-4}/\sqrt{\mathrm{Hz}}$).

Lastly, there was very interesting discussion both of possible variations in the LISA mission and possible follow-on missions (the latter to be flown around 2020-2025, so fancy was free). Bernard Schutz pointed out the possible advantages of LISA starting out as short-arm interferometer, before moving the satellites to the current baseline separation of 5×10^6 km. He also suggested the addition of a 4th spacecraft, to fly at the midpoint of one of the three arms. NASA has strongly encouraged LISA scientists to think about possible follow-on missions to LISA, and is especially interested in missions that might detect a primordial background of gw's. There is little chance that LISA itself can detect a primordial background, since in the LISA band it will be swamped by the background from galactic and extra-galactic binaries. The binary background falls off at high frequencies, which leads to a next-generation LISA concept featuring 3 constellations of mini-LISA's, with the constellations forming a equilateral triangle around the Sun at 1 AU, and each mini-LISA having short ($\sim 20,000$-km) arms to push the sensitivity band up to $1 - 10$ Hz. All of this seems technologically feasible even in the near term–it's "just" a matter of money.