MATTERS OF GRAVITY

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Editorial

Well, this newsletter is growing into its third year and third number with a lot of strength. In fact, maybe too much strength. Twelve articles and 37 (!) pages. In this number, apart from the "traditional" research briefs and conference reports we also bring some news for the community, therefore starting to fulfill the original promise of bringing the gravity/relativity community closer together.

As usual I am open to suggestions, criticisms and proposals for articles for the next issue, due September 1st. Many thanks to the authors and the correspondents who made this issue possible.

If everything goes well this newsletter should be available in the gr-qc Los Alamos bulletin board under number gr-qc/9402002. To retrieve it send email to gr-qc@xxx.lanl.gov (or gr-qc@sissa.infn.it in Europe) with Subject: get gr-qc/9402002 (issue 2 is available as gr-qc/9309003). Or email me. Have fun.

Jorge Pullin

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Open letter to gravitational physicists

Beverly Berger, Oakland University

I believe the time has come to create a Topical Group (TG) in Gravitation within the American Physical Society (APS).

Substructures of the APS include Divisions (e.g. Particles and Fields, Nuclear Physics, Astrophysics), TG's (e.g. Metrology, Laser Science), and Fora (e.g. Physics and Society). The APS constitution states "If at least two hundred members wish to advance and diffuse the knowledge of a specific subject or subfield of physics, they may petition the Council [of the APS] to establish a Topical Group." If the membership of the TG becomes sufficiently large, the TG can then become a Division.

Although the existing divisions of Particles and Fields and Astrophysics have interests which include various aspects of gravitational physics, their primary concerns lie elsewhere. There are many reasons to develop a TG at this time. Such a group would allow us to define and promote our interests and enhance our visibility within the larger community of physicists. The construction of LIGO and the Grand Challenge Supercomputing Project on the two black hole problem are only two examples of the significant developments in our field that render such advocacy essential.

There are several other advantages to the formation of the TG. As a subgroup of APS, we would have access to APS public relations activities (e.g. press releases, lobbying) that might be marshaled for our benefit. Some of our local meetings and workshops (e.g. the Pacific Coast or Midwest Meetings) could become TG meetings with access to APS publicity and possibly support. Members of the TG could organize sessions at APS general meetings. The TG would be a distinct entity through which to support the positions and activities of the International GRG Society. (Many countries already have separate national general relativity societies.) Finally, members of the TG can nominate candidates to become APS Fellows.

The procedures to form the TG are the following: As quoted above, a petition signed by 200 APS members requesting formation of the TG must be received by the Executive Council of the APS. (The signed petitions must be actual hard-copy rather than electronic mail.) The council, in consultation with existing APS divisions and TG's may either accept or reject the petition. If the signatures are obtained and the petition is accepted, an organizational structure including TG officers and bylaws must be put into place. At that point, the TG comes into existence. Any APS member may join the TG for an additional $5 per year.

The APS is open to physicists of any nationality for an annual dues of approximately $80 per year (less for students, postdocs, and retirees). One benefit of APS membership is the opportunity to subscribe to some journals at a reduced rate. The list includes *Physical Review*, *Physical Review Letters*, *Journal of Mathematical Physics*, and *Classical and Quantum Gravity* among others.

If you agree with the need to form a TG in gravitation and are an APS member please print out the attached petition, sign it, urge your colleagues who are APS members to sign it, and mail the completed petition to me. I also invite 10-20 public spirited theoretical and experimental relativists who are APS members to act as an *ad hoc* organizing committee. The function of this committee would be to generate the bylaws of the organizational structure required for the TG and to serve as an initial nominating committee for TG officers.

I welcome your comments and questions.

Sincerely,

Beverly K. Berger

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PETITION TO THE COUNCIL OF THE AMERICAN PHYSICAL SOCIETY

We, the undersigned members of the American Physical Society, petition the Council of the American Physical Society to establish a Topical Group in Gravitation. Areas of interest to the proposed Topical Group include, but are not limited to, experiments and observations related to the detection and interpretation of gravitational waves, experimental tests of gravitational theories, computational general relativity, relativistic astrophysics, solutions to Einstein's equations and their properties, alternative theories of gravity, classical and quantum cosmology, and quantum gravity. The purpose of the Topical Group is to provide a unified forum for these areas of current research which now span several Divisions of the Society.

Signature	Name (Printed)	Affiliation

Return to:

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A Missouri Relativist in King Gustav's Court

Clifford Will, Washington University, St. Louis

The award of the 1993 Nobel Prize in Physics to Joseph Taylor and Russell Hulse of Princeton University for their discovery of the binary pulsar PSR 1913+16 puts a welcome seal of approval on general relativity. It was a long time coming.

Einstein's general theory has revolutionized our view of space and time and the universe. Yet the Nobel prize has never, until now, been awarded for work so directly related to general relativity. Even Einstein's Nobel in 1921 was for his work on the photoelectric effect, not for relativity. Part of the problem is that theory is difficult to test, and the Nobel committees historically prefer to reward work that has had experimental confirmation.

Until 1974, the solar system provided the principal testing ground for GR. However, the discovery of the binary pulsar in the summer 1974 [1] showed that certain kinds of distant astronomical systems may also provide precision laboratories for testing general relativity. The system consists of a 59 ms period pulsar in an eight-hour orbit with a companion that has not been seen directly, but that is generally believed to be a "dead" neutron star. The unexpected stability of the pulsar "clock" and the cleanliness of the orbit allowed Hulse and Taylor and later co-workers to determine the parameters of the system to extraordinary accuracy. Furthermore, the system is highly relativistic ($v_{\rm orbit}/c \approx 10^{-3}$). Observation of the relativistic periastron advance ($4^{\rm o}.22663 \pm 0^{\rm o}.00002\,{\rm yr}^{-1}$), and of equivalence-principle effects on pulse arrival times (gravitational redshift, time dilation – 0.07% accuracy) can be used, assuming that general relativity is correct, to determine the pulsar and companion masses, with the result $m_p = 1.4411 \pm 0.0007 M_\odot$ and $m_c = 1.3873 \pm 0.0007 M_\odot$. The measurement of the rate of decrease of the orbital period in 1979 [2] gave the first evidence for the effects of gravitational radiation damping. With the measured orbital elements and the two masses, the general relativistic quadrupole formula predicts the damping rate $dP/dt = -2.40243 \pm 0.00005 \times 10^{-12}$. The observations are now better than 0.5 percent in accuracy, with $dP/dt_{\rm observed} = -(2.408 \pm 0.011) \times 10^{-12}$, agreeing completely with the prediction [3]. This verifies the existence of gravitational waves, its quadrupole character, and the validity of the quadrupole formula of GR.

Forty binary radio pulsars are now known. Two of these, PSR 1534+12 in our galaxy, and PSR 2127+11C in the globular cluster M15, are particularly promising as relativity laboratories. Because of its high timing accuracy and its proximity to the Earth, 1534+12 is expected to yield an even more accurate determination of dP/dt than did 1913+16 [3].

In addition to verifying the existence of gravitational radiation, binary pulsars provide "strong-field" tests of general relativity, in contrast to the solar-system "weak-field" tests, in the following sense. Since such systems contain at least one, and probably two neutron stars, the bodies contain strongly relativistic internal gravitational fields. In most alternative theories of gravity (but **not** GR), the motion of compact objects is affected by their internal structure (violation of the Strong Equivalence Principle); in addition, most theories predict "dipole" gravitational radiation in addition to the quadrupole part, whose source is the difference in internal gravitational binding energies of the two stars. Because of these two phenomena, many alternative theories of gravity, which otherwise might agree with solar-system observations, can be strongly tested by binary pulsar systems (for review and references see [4]).

Binary pulsars are also important as a foundation for gravitational-wave observatories such as LIGO and VIRGO. Because their lifetimes against coalescence induced by gravitational radiation reaction are short compared to the age of the galaxy, one can expect that coalescing binary neutron stars are happening today. Based on this fact, several estimates have been made of the coalescence rate, leading to numbers of the order of 3 per year with a detectable signal strain of 10^{-21} in a volume of the universe 200 Mpc on a side.

The actual award ceremony took place in Stockholm during the week of December 7-11. I and my wife had the honor and privilege of attending the festivities as guests of the Nobel Committee in recognition of my role as a "special referee" in helping them make the decision, formulate the citation, and so on (Alvaro de Rújula of CERN was the other physicist so honored). The experience was fantastic, and I highly recommend it to everyone (the only assured way of being invited, however, is to win the prize)! The Laureates, families and guests stayed at the Grand Hotel of Stockholm, the kind of place that, if you have to ask the price, you probably don't belong there.

The activities kicked off on Tuesday the 7th with a press conference and reception for the Physics, Chemistry and Economics winners at the Swedish Academy of Sciences. Not surprisingly, most of the press questions were for the Economists and for the Chemists (who worked on aspects of DNA replication immortalized in *Jurassic Park*); GR still seems to be a mystery to most of the press. Wednesday morning, Hulse and Taylor gave the Nobel lectures. Hulse, who was Taylor's University of Massachusetts graduate student during that fateful summer, described the actual steps involved in the discovery of the binary pulsar. Ironically, following his Ph.D. and a post-doctoral stint, Hulse left radio astronomy and now does plasma physics at the fusion laboratory at Princeton. Taylor, now the James S. McDonnell Professor of Physics at Princeton, related the techniques by which the system is used for tests of relativistic gravity and of the existence of gravitational waves. Other events included a special Nobel concert by the Stockholm Philharmonic, and a big reception hosted by the Nobel Foundation at the ornate Great Hall of the Royal Swedish Academy.

By far the highlight of the week, however, was the award ceremony at the Concert Hall and the banquet at the Stockholm City Hall. Required dress was white tie and tails for the men and ball gowns for the women. For the Physics Prize, the citation read by Professor Carl Nordling of the Nobel Committee emphasized the uniqueness of PSR 1913+16 as the first radio binary pulsar, and its importance as a new laboratory for testing general relativity and revealing the existence of gravitational waves. Then Hulse and Taylor stepped forward to receive their prizes from the King. Following the awards, the participants were limousined or bused to the City Hall for the banquet, held in the "Blue Hall". (Some readers will recall that this was the site of the buffet dinner at GR 11 in 1986. Joe Taylor was an invited speaker at GR 11, and participated in that buffet dinner – kind of a rehearsal for the real thing). Counting the Laureates in Physiology/Medicine and Literature (the author Toni Morrison – *Beloved*, *Jazz*), their families and guests, the members of the various Nordic Academies and their guests, the list came to an intimate 1300 people. A 60-page book, complete with fold-out map, gave the seating plan (Hulse sat next to the Queen). One nice tradition is the inclusion of about 250 university students in the festivities, each wearing a cap distinctive of his or her institution. The four-course meal, served on special gold-trimmed Nobel table settings created for the 1991 Jubilee of the Prize, was served with military precision by some 130 waiters. The wine was served by choral groups who sang Swedish songs as they poured. Although you might think such an affair would be formal and stuffy, it was far from it. The thing was a total blast. The dance following was lively, although the orchestra must have experienced severe time dilation some time in the past, for it had not yet reached the 1960's. Some of the post-dance parties went on until 5:00 in the morning. The final event for the Physics people was a panel discussion at the Royal Institute of Technology, with Taylor, Hulse, de Rújula, Thibault Damour and me as panelists.

Taylor graciously invited to the festivities as one of his personal guests Jocelyn Bell-Burnell, the co-discoverer of pulsars in 1967, who most astrophysicists feel was wrongly overlooked for the 1974 Nobel Prize, shared by her Ph.D. adviser and co-discoverer Anthony Hewish and radio astronomer Sir Martin Ryle. This year's situation was quite similar: Hulse was Taylor's graduate student, doing the day-to-day work at the Arecibo radio telescope in Puerto Rico, while Taylor was on campus in Amherst. Hulse actually made and confirmed the discovery, and then he and Taylor together made the initial accurate orbit determinations and measured the periastron advance (for a detailed account of the discovery, see [5]). Subsequent work by Taylor and other co-workers enabled a determination of the orbital damping. This time, however, the Nobel Committee properly gave the prize to both men.

This newsletter seems an appropriate place, on behalf of the U.S. general relativity community, to salute Russell Hulse and Joseph Taylor on the award of the 1993 Nobel Prize in Physics.

[1] R. A. Hulse and J. H. Taylor, *Astrophys. J. Lett.* **195**, L51 (1975)

[2] J. H. Taylor, L. A. Fowler and P. M. McCulloch, *Nature* **277**, 437 (1979)

[3] J. H. Taylor, A. Wolszczan, T. Damour and J. M. Weisberg *Nature* **355**, 132 (1992)

[4] C. M. Will, *Theory and Experiment in Gravitational Physics* Revised Edition, (Cambridge University Press, Cambridge, 1993)

[5] C. M. Will, *Was Einstein Right?*, 2nd Edition (Basic Books, New York, 1993), Chapter 10

Gary Horowitz wins the Xanthopoulos Award

Abhay Ashtekar, Penn State University

The second international Basilis Xanthopoulos award in Relativity and Cosmology was awarded to *Professor Gary T. Horowitz* of the University of California at Santa Barbara for his wide ranging contributions to the mathematical aspects of gravitational physics. The citation singled out, in particular, Horowitz's work on positive energy theorems, his influential ideas on global problems in general relativity and his numerous papers which have illuminated the global properties of space-time geometry in string theory. The award honors the memory of the well-known relativist Basilis Xanthopoulos who was shot to death while he was giving a seminar in Crete on November 27th, 1990. This unspeakable act of violence ended without forewarning a life of joy and energy, rich in accomplishment and promise.

The award ceremony took place during the reception at the Lanczos Centennial conference at Raleigh, North Carolina on Sunday, December 12th. Professor James York of the University of North Carolina chaired the session. He introduced Professor Sotirios Persides of the University of Thessaloniki who had flown from Greece specially for the occasion. Persides was in the audience during the seminar on that fateful day in November 1990 and thanks to his extraordinary personal courage and self-sacrifice, many lives were saved. He himself was badly wounded and it is only now that he is close to a full recovery. Persides recalled the origin of the award. Since the readers of this newsletter may not all be aware of this, we will reproduce his remarks in full:

I am here today on behalf of the Foundation for Research and Technology Hellas (FORTH) to say a few words about the Basilis Xanthopoulos award and about our beloved colleague.

The seminar on algebraic computing has started that evening of November 27, 1990, at the University of Crete, the Greek inland. Basilis Xanthopoulos was lecturing on the blackboard and about 25 professors and graduate students were listening. Suddenly, a deranged gunman burst into the room and opened fire. Basilis Xanthopoulos, at his 39th year of life, and Stefanos Pnevmatikos, at his 33rd, two young professors, internationally known scientists, and dear friends of ours were brutally murdered. Another professor and a female student were injured. Personally, in a desperate act of defense, I was severely wounded. A distraught mind and the availability of guns have brought death, distraction and unbearable pain. Basilis and Stefanos, two teachers of scientific truth, were lost at a moment when their studies and academic work had started to blossom.

Basilis Xanthopoulos was born in Drama, Greece, in 1951. He was the best student I had at the University of Thessaloniki where he received his B.S. in Mathematics in 1973. After his military service, he followed graduate studies at the Physics Department of the

University of Chicago, where he became a teaching assistant and later a research assistant. He received his M.S. in 1976 and his Ph.D. in 1978 with Robert Geroch as his advisor. He continued as a visiting assistant professor at the Physics Department of Montana State University and Research Associate at Syracuse University. In December 1979, he returned as chief assistant at the Astronomy Department of the University of Thessaloniki. Finally, in 1982, he was appointed as an assistant professor at the Physics Department, University of Crete, where he became associate professor the next year and professor in 1987. During his career, he held many positions in various universities and research centers. From September 1987, he was Chairman of the Physics Department of the University of Crete.

Basilis Xanthopoulos had a passionate love for science. His main field of research was theoretical general relativity. He published about 60 original research papers in scientific journals trying to unravel the complexities of mathematical gravity. He worked on the asymptotic structure, exact solutions, perturbations of black holes, gravitational waves, Yang-Mills fields, formation of singularities and many other topics of intense mathematical nature in the framework of the Einstein and Einstein-Maxwell geometry of space-time. These articles appeared in distinguished international journals. He collaborated with many well known scientists as R. Geroch, A. Asthekar, S. Chandrasekhar, C. Hoenselaers, W. Kinnersley, V. Ferrari and others. He gave lectures on his research work in many universities, research institutes and scientific conferences.

As a teacher Basilis was also exceptional. He transmitted knowledge to his audience in an informal and friendly way, clearly stating the known, the assumptions, the reasoning and the conclusions, captivating specially the young. He organized seminars, undergraduate and graduate courses, summer schools, conferences. He worked hard for many years for science, for the students, for the University of Crete. He was always willing to help his colleagues and his students. He was always cheerful and philosophical in front of the difficulties of life. But, alas! As Professor Chandrasekhar, his teacher, collaborator and friend has noted, the violent termination of Basilis' life, on the verge of a most promising career, was an immense tragedy for science and for the University of Crete. I believe it is a severe loss for Greece, too, specially since Basilis worked in general relativity, a field where it is very difficult to find and train talented people.

To honor his memory, the Foundation for Research and Technology-Hellas has established an International Award for Relativity (carrying a financial value of $9,000) to be given every two years to a young scientist (below 40) who has published outstanding work in gravitational physics (preferably theoretical). An international committee of distinguished scientists with S. Chandrasekhar as Chairman has awarded the first award in 1991 to Demetrios Christodoulou of the Courant Institute. Today, we are here for the presentation of the second Basilis Xanthopoulos Award.

The committee which selected the 1993 winner of the award consisted of Professors Subrahmanyan Chandrasekhar (Chair), George Contopoulos, Roger Penrose, Kip Thorne and myself. Since Professor Chandrasekhar was out of the country at the time, I —

being the committee member who was most closely associated with Xanthopoulos— had the pleasure of presenting the award. In his acceptance speech, Horowitz recounted the story of a delightful collaboration he had with Xanthopoulos. As graduate students, one Christmas the two of them wrote a paper on how Santa Claus draws on a multitude of relativistic effects –including the extraction of rotational energy from a Kerr black hole at the North Pole– to carry out his many wonderful tasks. The story was picked up by many newspapers and, according to Horowitz, is the most widely known work of his!

Gamma-ray Bursts and their Possible Cosmological Implications

Peter Meszaros, Penn State University

Gamma-ray bursts (GRBs) are brief gamma-ray flashes detected with space-based detectors in the range 0.1-100 MeV, with typical photon fluxes of $10^{-2} - 10^{2}\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and durations of $10^{-1} - 10^{3}$ s. Their origin is clearly outside the solar system, and more than a thousand events have been recorded so far. Before there was any firm evidence on the isotropy of classical gamma-ray bursts, the most plausible interpretations involved magnetospheric events on neutron stars (NS) within our Galaxy. However, the remarkable isotropy of these events discovered within the last two years by the BATSE experiment on the NASA Compton Gamma Ray Observatory (together with the 'flatter than Newtonian' counts) clearly shifts the odds substantially in favor of a cosmological interpretation.

In principle, the isotropy could be interpreted in terms of either (1) a cosmological distribution similar to that of the distant galaxies and clusters, i.e. hundreds of Mpc, (b) a distribution in an 'extended halo' of our galaxy, which is so large that the small dipole moment associated with our off-center location is not noticeable (i.e. greater than 50 Kpc), or (c) a 'galactic disk' distribution, where objects are sufficiently faint that they are detectable only out to distances smaller than the width of the disk (less than a few Kpc). Of these, the 'galactic disk' model does have a semi-plausible energy source: the fluences required are of the order of $10^{39} - 10^{40}$ ergs, and these could be associated with brief, mildly super-Eddington outflows from neutron stars undergoing a star-quake, comet impact or brief accretion episode. However, it is difficult to explain a large number of events (a few per day) occurring within a few Kpc. The 'extended halo' option is even more difficult, since it is hard to see how such an extended halo would have formed or survived tidal stripping by neighboring galaxies, the frequency of occurrence is not much easier to explain, and the required fluences ($10^{41} - 10^{43}$ ergs) are much larger than for typical brief events on neutron stars. On the other hand, the 'cosmological' interpretation does have at least two rather plausible energy sources: either NS-NS (or NS-black hole) binary mergers (e.g. binary pulsars merging under the effect of gravitational wave energy losses), or else 'failed supernova' events (where a star undergoes core collapse to a NS but with much reduced optical display). Either of these should occur with a frequency of 10^{-5} per galaxy per year, and produces $10^{50} - 10^{51}$ ergs, visible out to redshifts z of order unity, so that the typical frequency and fluence is easily explained.

Irrespective of the typical distance (but particularly in cosmological models), the energy density in a GRB event is so large that an optically thick photon/$e^{\pm}$ fireball is expected to form, which will expand carrying with itself some fraction of baryons. A question of major interest is how such an event can lead to an optically thin, non-thermal (generally broken power-law type) gamma-ray spectrum. The radiation burst escaping when the fireball becomes optically thin is much too brief, has a quasi-thermal spectrum, and carries only a very small fraction of the total energy (most of which ends up as kinetic energy of the expanding baryons). However, all of this energy will be reconverted into radiation when the baryons are decelerated by the external medium. This results in a blast wave moving into the external gas, and a reverse shock moving into the baryonic ejecta, both of which are optically thin by the time deceleration occurs. If the baryon loading is small, the expansion is relativistic, and both the blast and reverse shocks will be strong, leading to acceleration of particles with a power-law distribution of relativistic energies. These can radiate efficiently even if the magnetic fields in the shocked regions (which may be amplified by turbulence) are well below equipartition. The resulting burst of gamma-rays has a total energy and time-delayed duration of the order of that observed. The synchrotron-inverse Compton spectrum produced in the shocks is also in rough agreement with observations. One can also predict the optical, X-ray and TeV spectrum expected from such bursts, which in principle could also arise in galactic models. The calculations indicate that cosmological models generally produce much lower optical and X-ray fluxes, in agreement with current non-detection upper limits, whereas galactic models (except for short ones of less than about 1 s) would predict X-ray fluences comparable to gamma-ray ones, and conspicuous optical fluences, in disagreement with observations. Even if an adequate number of galactic sources were available, the predicted spectra would be acceptable only if the duration is determined by an intrinsic time scale, rather than by the more straightforward relativistic time-delay arguments.

A straightforward prediction of cosmological models is that, if GRB are "standard candles", one would expect the weaker fluence bursts (which presumably are farther) to have longer durations due to cosmological time-dilation. Such an effect has been recently reported, both in preprint and New York Times form. However, the duration of the burst can depend on intrinsic properties of the event, such as the total energy, so that this cosmological signature may be masked by details of the source physics, which are model-dependent. If gamma-ray bursts are indeed cosmological, one very interesting consequence would be that gravitational wave bursts of energy comparable to a solar rest mass should occur at the same time as the GRB events. These would be detectable at the rate of several per year with coincidence measurements from two advanced versions of the proposed LIGO or VIRGO detectors, at frequencies of $10^2 - 10^3$ Hz. Such measurements might also be able to distinguish between failed supernova events, NS-NS or NS-black hole mergers, through their wave profile. It will probably be hard to obtain any reliable information concerning cosmological parameters, such as the closure parameter or the Hubble constant, due to the smearing effects introduced by the luminosity or density evolution of the bursts over cosmological time scales. Similarly, potential information about large-scale structures (such as voids or superclusters of galaxies) will probably be diluted beyond recognition by evolutionary effects. However, one may obtain valuable information concerning early star formation, through limits on the typical redshift derived from the counts of events as a function of the fluence, and it may be possible to derive limits on the GRB luminosity distribution.

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Current activity and results in laboratory gravity experiments

Riley Newman, University of California, Irvine

G. At least five groups are actively measuring G (still by far the least well-known fundamental constant): Luther at Los Alamos, Karagioz in Russia, Schurr at the University of Wuppertal, Germany, Michaelis at the PTB (German NIST equivalent), and Luo Jun in China, with their respective collaborators. The Wuppertal group uses a novel technique: two suspended masses forming the walls of a microwave Fabry-Perot resonator act as a gradiometer in response to a source mass. Schurr reports that they have determined G to 220 ppm, with a result in good agreement with the "CODATA" value (whose assigned uncertainty is 128 ppm); an improved experiment is in the works. The PTB group uses a mercury-supported balance, developed by de Boer and collaborators; their experiment is recently completed and they will soon publish in Metrologia a surprising result: $G = 6.71540 \pm 0.00056 \cdot 10^{-11} Nm^2 kg^{-2}$ (83 ppm uncertainty); about 1.006 times the currently accepted (CODATA) value! The group reports it could find no error in their work in spite of a long period of searching. Karagioz's results are published [1], but not yet available in English translation and I have lost e-mail contact with Russia. New methods for measurement of G in the laboratory (with homogeneous fields) and with satellites are under development in Russia, V.N. Melnikov reports. (Melnikov expressed an interest in collaboration and joint projects with groups in the USA.)

Funny gravity/new forces/weak equivalence principle. These topics are intertwined – operationally, one man's feeble "fifth force" could equally well be another's "anomalous gravity." An excellent review of this area as of 1991 is given by Adelberger, Heckel, Stubbs and Rogers [2]; a comprehensive index of relevant publications as of 1992 has been compiled by Fischbach, Gillies, Krause, Schwan, and Talmadge [3]. Here I will informally give the flavor of recent results and current activity. I believe no one currently claims evidence for anomalies.

Inverse square law tests. Anomalous forces with a range between 1 meter and a few kilometers remain the most poorly constrained. Assuming an effective potential $-GM(1+\alpha e^{-r/\lambda})/r$, α is constrained to be less than about .002 for these ranges by the value of G $(6.677 \pm 0.013 \cdot 10^{-11})$ determined from submarine measurements through a 5-km-thick slab of sea water [4]. Zumberge reports that his group is developing a deeply towed unmanned gravity meter with which a much larger volume of sea can be sampled over a longer time; he hopes in a couple of years to repeat the G experiment with much higher precision. Meanwhile, lab experiments chip away at (α, λ) parameter space for increasing ranges. Goodkind et al. [5] report an experiment in which an attracting mass is placed at various heights below a gravimeter based on a levitated superconducting ball; their result for mass separations from 0.4 to 1.4 m is consistent with earlier constraints.

Direct tests of the inverse square law are extremely sensitive to uncertainties in source mass distribution. Two ingenious approaches are being developed which largely circumvent this problem: 1. Measure the Laplacian of the gravitational potential, $\nabla^2\Phi$, or: 2. Measure the gradient of this quantity. A non-vanishing value for either of these (in vacuum) is a signal of inverse square law violation, independent of source mass distribution. The first approach is used by Paik at Maryland, who continues to refine his three-axis superconducting gradiometer to measure $\vec{\nabla} \cdot \vec{g}$ as a test of Gauss's law; his experiment using a swinging 1.5 ton lead ball source mass, reported last spring [6], places a 2σ limit: $\alpha = (0.9 \pm 4.6) \times 10^{-4}$, at $\lambda = 1.5$ m, improving by an order of magnitude on existing limits at this range. Paik is developing [6] a null source – a shaped hollow cylinder to surround his gradiometer – with which he hopes to achieve sensitivity to α at a level of 10^{-6} at 0.2 m. Using geological-scale sources Paik sees a potential sensitivity to $\alpha = 10^{-5}$ at 100 m. The second approach to an inverse square test insensitive to source mass detail – measurement of the gradient of the Laplacian – is being pursued by Boynton at the University of Washington [7]. Boynton's student Moore has shown how to build a torsion balance whose (design) conventional multipole moments vanish to high order, with correspondingly zero coupling to fields whose Laplacian vanishes, but which has non- zero moments of $r^3 Y_{\ell m}$ for $\ell = 1$ and $m = \pm\, 1$ – moments which couple to the gradient of the Laplacian to produce torques on the balance. Boynton and collaborators plan two experiments with this instrument – one with a local source mass designed to produce minimal gravity gradients (for a second level of defense against spurious Newtonian signals), and one to use a mountainside as source. They expect near term results from the two experiments at a level $\alpha = 10^{-4}$, for ranges of order 10 cm and 10 meters respectively, with a potential for much greater sensitivity later with tighter fabrication tolerances.

The Wuppertal group is also pursuing $1/r^2$ tests using the instrument described under G above. No tower or borehole tests are currently in the works, as far as I know. In Japan, Hideo Hanada concludes [8] that sensitivity to α on order 10^{-6} for $\lambda < 10^5$ should be possible from gravity surveys of the earth with a gravity gradiometer.

Composition dependence/weak equivalence principle. The big news here is dramatically improved limits on couplings to N - Z (or B-2L), from controlled local source experiments. Put in terms of an inequality of the accelerations of a neutron and a proton toward a neutron at a distance greater than one meter (and assuming electrons behave normally), the best limit in 1991 was about 185 ppm. This has been reduced by the TIFR group in India [9] to 120 ppm, in an experiment achieving an unprecedented acceleration sensitivity of $10^{-13} cm/s^2$. But the n-p acceleration difference limit has now shrunk to 8 ppm, based on preliminary results announced last summer [10] by the "Eöt-Wash" group. This group uses a stationary torsion balance to search for differential acceleration of copper and lead toward a rotating 3 ton uranium attracting mass. As the uranium extends to within 10 cm of the test masses, this experiment not only dramatically improves constraints on anomalous forces with range above 1 meter but also yields significant constraints for smaller ranges than heretofore probed (down to 1 cm).

The rotating torsion balance of the Eöt-Wash group has yielded improved equivalence principle test preliminary results, using the earth's field as acceleration source [11]:

$$\eta(Be, Cu) = (-4.0 \ \pm \ 2.8) \times 10^{-12}$$

$$\eta(Be, Al) = (-2.7 \ \pm \ 3.4) \times 10^{-12}$$

Following a suggestion of Stubbs', the Eöt-Wash group has used their instrument for an ingenious test of the 'gravitational' properties of dark matter, demonstrating that the accelerations of the tested materials – Be, Al, and Cu – toward dark matter [11] must be equal to about 3 parts/thousand (2σ limits).

Improved WEP/anomalous force experiments are currently being developed by a number of groups. The Eöt-Wash group is building a completely new rotating torsion balance, with longer fiber. Boynton's group at UW is beginning operation of a new torsion balance at their cliff-side "Index" site in Washington, and plans to develop a new mountainside site at DOE's Hanford reservation – overlooking one of LIGO's sites. At Irvine, we are testing a new rotatable torsion balance, and are beginning a systematic test of the Q's of various torsion fiber materials at 4.2K with an eye toward the low thermal noise promised by cryogenic torsion balances. At U. Mass Amherst, Krotkov (of Roll, Krotkov, Dicke WEP test fame) has been working on a torsion balance experiment testing for differential acceleration of copper and polyethylene toward a modulated water source (pumped storage reservoir). The University of Bremen in Germany is setting up an experiment using the drop tower of Bremen, with 110 m free fall – their goal is a test of WEP with 10^{-12} accuracy.

Do antiprotons fall up? Adelberger argues persuasively that in the usual scaler/vector picture of how a new force could work, present limits on anomalous forces make it clear that an antiproton should fall down. But whether it **does** can't be known until one is actually dropped and watched. Michael Nieto reports that the Los Alamos-CERN collaboration hopes to measure the acceleration of antiprotons in the earth's gravitational field with a precision of better than 1% by 1997. Toward this end, the collaboration has already successfully trapped a million antiprotons from a single accelerator pulse, holding them for several minutes while cooling them to an energy of a few eV.

Spin-dependent new-forces/gravity? I will report on this area in a future issue of "Matters of Gravity".

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Update on Representations for Quantum Gravity

Donald Marolf, Penn State University

I would like to report on some recent progress toward building representations for canonical quantum gravity. Two new perspectives have been found on spaces that can be used as domain spaces of wavefunctions in a quantum theory and I will describe each of these in turn. The first concerns the so-called "connection representation" and the second is a new "extended loop representation." Both provide excellent prospects for further advancement.

It will be good to begin with a reminder of what connection representations are and what they have to do with quantum gravity. Recall that one way to canonically quantize a system uses the "configuration space representation" in which quantum states are represented by functions on the configuration space of the system, or on some closely related space. Familiar examples are position representations in one particle quantum mechanics and the Schrödinger representation of free scalar quantum field theory (QFT). In the QFT case, the states are not just functions on the classical configuration space of smooth fields but depend in an essential way on *distributional* fields. The situation can be summarized as follows: The Fock representation of free scalar QFT is unitarily equivalent to a representation in terms of functions on the space $\mathcal{S}'$ of tempered distributions (distributional field configurations) in $\mathbf{R}^3$ with an inner product given by integration with respect to a Gaussian measure μ_G. Thus, the Fock space is unitarily equivalent to the space $L^2(\mathcal{S}', \mu_G)$. While the space $\mathcal{S}$ of smooth rapidly decreasing fields is dense in $\mathcal{S}'$ and $\mathcal{S}'$ may be considered as a completion of the classical configuration space, the smooth fields actually belong to a set of measure zero with respect to the Gaussian measure μ_G. Surprising as it seems, this means that the value of the wave function on the classical configuration space has no effect on the quantum state of the system.

Something similar is expected to be the case for quantum gravity and a structure along these lines has been developed. This takes place in the context of the connection representation associated with the so-called "new variables" or "Ashtekar variables." This formalism describes gravity in terms of a complexified $SO(3)$ connection and a complex triad which are canonically conjugate. Taking the connection to be the configuration variable, the configuration space is just space $\mathcal{A}$ of smooth connections.

From the canonical perspective, such a description of gravity involves three kinds of gauge symmetries: complex $SO(3)$ rotations, spatial diffeomorphisms, and Hamiltonian gauge transformations. In principle, we might like to work with a "reduced configuration space," which is the quotient of $\mathcal{A}$ by the action of these gauge groups. However, this is not possible for gravity because the Hamiltonian constraint does not map the configuration space into itself but instead mixes coordinates and momenta. Thus, the approach taken is to deal with each class of gauge transformations separately.

The first step in this process is to consider the (partially) reduced configuration space $\mathcal{A}/\mathcal{G}$ where $\mathcal{G}$ is the space of complexified $SO(3)$ gauge transformations. Suitable structures should be found on this space or an appropriate completion that have nice properties under the action of spatial diffeomorphisms. This will allow a space of "diffeomorphism invariant wavefunctions" to be defined, on which the Hamiltonian constraint is to be enforced. Note that while a Gaussian measure could be defined on the space $\mathcal{A}$ and this space could be completed in direct analogy with the scalar QFT case, this is based on the structure of $\mathcal{A}$ as a linear space – a structure that is not preserved by the action of $\mathcal{G}$.

Ashtekar and Isham [1] provided a completion of $\mathcal{A}/\mathcal{G}$ by considering a commutative C*-algebra of traces of holonomy functions (Wilson loop functions). Their completion is what is technically called the "spectrum" of this algebra, which is the completion of $\mathcal{A}/\mathcal{G}$ in a particular topology due to Gel'fand. However, the holonomies of a connection will form such a C*-algebra only if they are bounded functions; that is, only if the gauge group is compact. Since complexified $SO(3)$ is not compact, the procedure cannot be directly applied to gravity, but some recent work provides considerable hope that the final results can be extended to the gravitational case. The case of compact gauge groups also be relevant to the study of QCD or other Yang-Mills theories.

Ashtekar and Lewandowski [2] have studied the Ashtekar-Isham completion $\overline{\mathcal{A}/\mathcal{G}}$ for the case of compact gauge groups and have introduced both a diffeomorphism invariant measure μ_{AL} and a differential structure on $\overline{\mathcal{A}/\mathcal{G}}$. Other diffeomorphism invariant measures on $\overline{\mathcal{A}/\mathcal{G}}$ were introduced by Baez [3]. The manner in which these structures are built led to the realization [4] that $\overline{\mathcal{A}/\mathcal{G}}$ can be characterized as a mathematical structure known as a "projective limit" constructed from products of the gauge group. In fact, the measure and differential structures introduced by Ashtekar and Lewandowski are just the projective limits of such structures on products of the gauge group. This realization provides an important tool for studying $\overline{\mathcal{A}/\mathcal{G}}$ and has the advantage that the projective limit exists even when the group is not compact, suggesting an extension of the Ashtekar-Isham compactification to the gravitational situation.

Returning to the case of compact gauge group, the characterization of $\overline{\mathcal{A}/\mathcal{G}}$ as a projective limit allows a simple proof [4] that $\mathcal{A}/\mathcal{G}$ is a measure zero subset of $\overline{\mathcal{A}/\mathcal{G}}$. Thus, if quantum states are taken to belong to the L^2 space defined by $\overline{\mathcal{A}/\mathcal{G}}$ and the Ashtekar-Lewandowski measure, the actual value of a wavefunction on the classical configuration space plays no part in determining the state – just as in the case of scalar quantum field theory. In addition, it turns out that the Ashtekar-Lewandowski construction also defines a measure on the original space $\mathcal{A}/\mathcal{G}$, though this measure lacks the nice property of "σ-additivity" so that the resulting L^2 space on $\mathcal{A}/\mathcal{G}$ is not complete. The completion of this space is just $L^2(\overline{\mathcal{A}/\mathcal{G}}, \mu_{AL})$ [4], leading back to $\overline{\mathcal{A}/\mathcal{G}}$. This, too, is similar to the case of scalar QFT.

Progress in studying such measures should also contribute to an understanding of the "loop representation," which is to be related to the connection representation by a functional integration over $\overline{\mathcal{A}/\mathcal{G}}$. Indeed, a loop representation can now be rigorously defined as those functions of loops that lie in the image of the "loop transform:"

$$\Psi(\gamma) = \int_{\overline{\mathcal{A}/\mathcal{G}}} \Psi_c(A) Tr\ H(\gamma, A) d\mu_{AL}$$

where $\Psi_c(A)$ is the connection representation of the quantum state, γ is a loop, and $H(\gamma, A)$ is the holonomy of the distributional connection $A \in \overline{\mathcal{A}/\mathcal{G}}$ around γ. The space $\overline{\mathcal{A}/\mathcal{G}}$ has the property that such holonomies are always well defined.

Another promising idea for improving the loop representation is the introduction of so-called "extended loops" by Gambini et. al. [5]. Each extended loop defines a gauge invariant function of connections that can, in a certain sense, be thought of as a "smoothened" version of the holonomy of connections around a loop. That is, extended holonomies depend on the value of the connection at all points in space, or at least on some set of nonzero measure, as opposed to loop holonomies which sample the connection only along a loop. Such an extended loop is given by a set of distributional multitensor densities that satisfy certain conditions. However, these multitensor fields can be expressed as linear combinations of arbitrary smooth fields with distributional coefficients of a well-defined form [5].

The extended holonomies suggest the definition of an "extended loop representation" from the connection representation through an "extended loop transform" in analogy with loop transform above. The idea [7] is that quantum states are represented as functions of extended loops and that this is to be related to the connection representation through the formula:

$$\Psi(M) = \int_{connections} \Psi_c(A) Tr\ W_A(M) d\mu_?$$

where $\Psi_c(A)$ is the connection representation of the state, M is a set of multitensor densities that define an extended loop, $W_A(M)$ is the extended holonomy for M evaluated at the connection A, and $\mu_?$ is some measure that is yet to be rigorously defined. For many calculations in this representation, the distributional coefficients separate from the smooth fields that parameterize extended loops, yielding well defined solutions and eliminating or regularizing a number of divergences that arise in the loop representation. In particular, this feature of the extended loop representation provides additional evidence that the Jones polynomial represents a state of quantum gravity. An additional simplification of this representation is that only *linear* functions of the multitensor densities need be considered. This can be seen from the extended loop transform above once it is recognized that the extended holonomy $W_A(M)$ is linear in the multitensor fields.

As with the connection representation, important questions for the extended loop representation still remain. Some of these are questions of convergence, as the extended holonomies are given as infinite sums over multitensor fields. Another is whether the extended holonomies can be defined on the space $\overline{\mathcal{A}/\mathcal{G}}$ and integrated against the measures referred to above to put the extended loop representation on a rigorous footing. Finally, to implement the next step in the discussion of extended loops, we must find some way to characterize equivalence classes of extended loops under spatial diffeomorphisms.

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LIGO Project Report: December 1993

Rochus E. Vogt, Director, LIGO Project, Caltech

The Nobel award to Hulse and Taylor has been a welcome development for LIGO. The Swedish Academy has now officially certified the existence of gravitational waves, thus supporting LIGO's goal to use gravitational waves in exploring the universe and for fundamental physics.

LIGO's design parameters continue to be the frequency band from a few Hz to several kHz, with a start-up strain sensitivity of $h \sim 10^{-21}$, and an ultimate sensitivity goal of $h \sim 10^{-23}$.

Funding for LIGO R&D and construction was \$19.1M in FY92, and \$24M in FY93. Congress continues to be very supportive of LIGO, and we expect a considerable jump in funding for FY94.

Land transfer for the LIGO facility at Hanford, Washington from DOE to NSF is complete, the geotechnical site characterization is done, the environmental FONSI (finding of no significant impact) has been approved, and the contract for rough grading of the site is expected to be awarded in December. The bulldozers will start moving, weather permitting, as soon as we have completed the obligatory ground-breaking ceremony.

Land acquisition for the Louisiana facility has been delayed by difficult negotiations with private landowners and oil companies whose pipelines we need to cross. As soon as these negotiations reach a satisfactory resolution, the (forested) land will be cleared along the two arms of the LIGO layout, geotechnical and hydrological characterization will be completed, and the (not at all trivial!) civil engineering preparation of the site will commence.

The engineering design contract for the 16 km of vacuum beam tubes has been awarded to Chicago Bridge and Iron, Inc. (CBI). The design will be completed in March '94, to be followed by an 8-month full scale mock-up of a partial beam tube section for verification of the manufacturing and degassing techniques.

Industrial contracts for the remainder of the vacuum system and the building design will be placed in the first half of 1994.

R&D activities at Caltech and MIT are progressing significantly in a variety of areas: good progress in strain sensitivity on prototypes, the development of the design for LIGO's first interferometers including the choice of the initial optical topology (broadband recycled), the development of alignment systems, optical modeling, new antivibration systems, and new mode cleaners (spatial and frequency filters for the laser light).

The 12-year old 40-m interferometer system at Caltech is being replaced by a totally new system, called "Mark II," which includes a much enlarged vacuum system (2-ft diameter beam tubes and 4-ft diameter vacuum chambers), and vastly improved ($\sim$ 3 orders of magnitude better) vibration isolation stacks. The interferometer is now operating in this new system, and over the coming months its various components will be replaced, one by one, as part of the detector R&D. This Mark II system, which is expected to serve us for the next decade, will be primarily focused upon displacement noise studies, while a new 5-m system at MIT (to be activated during 1994) will be optimized for phase noise studies. These two systems will be the key facilities for testing and development of components for the first LIGO interferometers.

Recruitment of staff for the LIGO project has been successful, and all key positions have been filled. The LIGO team consists now of about 50 souls!

During the past year, LIGO has also been the subject of unjustified negative publicity. (There also has been much positive and enthusiastic support of LIGO — but this tends to be less noticed!)

In particular, the LIGO team was involved in a difficult personnel matter at Caltech that was widely publicized. Only one side of the story was promulgated because the team, for ethical reasons, chose not to publicize its own side. Much of the stuff that was rumored and some that was printed was patently untrue; we urge you not to believe everything you heard or read.

There were also mistaken assertions that LIGO funding came at the expense of other physics support at NSF. This is not correct. LIGO is an identified item in the NSF budget and funded as such by Congress. We, in fact, fought very hard in support of the "other physics" budget at NSF. There is no way that the LIGO Project would support the funding of LIGO at the expense of individual investigator grants.

LIGO will always be subject to extensive scrutiny (which is appropriate!) and will never be safe from mistaken fears, or politics in general. LIGO **is** the biggest project at NSF and is thus highly visible, and is sometimes viewed with apprehension. The LIGO team understands that taking the heat is a price that must be paid if one wants to be a pioneer in something very new!

We appreciate the strong support that we have received from the gravity community, and we will endeavor to keep you in touch with future progress in LIGO.

Dark Matter or New Gravity?

Richard Hammond, North Dakota State University

There is no longer any doubt that the motion of the outer stars in galaxies is not compatible with the gravitational theoretical predictions based on the observed matter distribution. Toward the outer limit of the galaxy, once nearly all of the mass is enclosed, Newton's law predicts that the velocity is proportional to $\frac{1}{\sqrt{r}}$. However, for virtually all of the galaxies where rotation curves (velocity *vs.* distance) have been made, this does not occur. For large r the velocity tends toward a constant value, and the rotation curves become flat.

One of the original conjectures to explain this mystery was the speculation of dark matter. Using Newtonian dynamics, it is evident that if there is additional matter in the galaxy that is not observed *but behaves gravitationally exactly like ordinary matter* then the rotation curve must be modified. In fact, if the dark matter has a density given by $\rho_{dark} \sim 1/r^2$ then it follows that, for large r, the gravitational force is proportional to $\frac{1}{r}$, and therefore that the velocity is constant with distance. Thus, the postulate of the existence of dark matter with the $\frac{1}{r^2}$ density 'solves' the problem of the flat rotation curves.

However, problems with this solution soon arose. First of all, it is unknown why the density of dark matter should be what it is, and further, the density profile must change for small and large r. Of more immediate concern, though, is its invisibility. Typical galactic time constants are of the order of $10^8 yrs.$ Consider hydrogen gas. If it is in thermal equilibrium and supported by its pressure, one may balance the gravitational attraction against the radiation pressure. Using the ideal gas law and the presumed density for ρ_{dark}, one easily shows that the temperature of this gas is of the order of $10^6 K$, which would be observed, but is not [1]. This result is used to rule out the possibility that the dark matter consists of ordinary Hydrogen. Other arguments [2] have excluded the possibilities that ice, dust, red and brown dwarfs could be the origin of dark matter. Fortunately, as fast as astrophysicists could rule out conventional forms of matter as candidates for the dark matter, high energy physicists have been able to elect other forms of matter to the post. These include hot dark matter such as massive neutrinos, cold dark matter such as WIMPS, and particle that result from specific theories, such as axions, photinos, and so on. In addition to new particles, larger objects have entered the game. Recent evidence points to the existence of Jupiter type objects surrounding our galaxy, dubbed MACHOS for massive compact halo objects [3].

The postulate of dark matter is not the only explanation of flat rotation curves. Another school of thought takes aim at the use of Newtonian dynamics. Although general relativity (and therefore Newtonian dynamics in the proper limit, with the proper relativistic corrections) is experimentally verified on the scale of the solar system, it has not undergone any test in regions larger than that. (Cosmological solutions should not be considered as large scale verifications due to the number of other assumptions that are invoked.) In fact, one may argue, forsaking dark matter, that in the only tests of gravitational theory at length scales larger then the solar system, *it fails!* Well, ever since the birth of general relativity there have been more generalizations, modifications, and alterations that you could shake a stick at anyway, and perhaps some such an alternate theory is in fact responsible for the flattened rotation curves.

The first (modern) attack on gravitational theory was launched by Milgrom [4] who explained flat rotation curves by modifying Newton's law of motion. In recent years, a flash of interest, ignited by the Fischbach conjecture, in finite range gravitational forces has been felt. Such a force has been derived theoretically from both quantum gravity and classical gravity, and also appears when the dilaton field is coupled to gravity. Sanders [5] claimed that this force accounts for the flat rotation curves of six different galaxies, but later other problems with this solution were uncovered [6]. Very recently, however, this concept has been restoked by Eckhardt [7] who obtains flat rotation curves using a two (Yukawa) potential formulation, yet quenches the problems Sanders fired with a single potential. From another view, however, alternate theories may account for such curves. In conformally invariant fourth order theory, Mannheim derives an additional long range force, akin to that caused by the gluon field [8] and claims to account for flat rotation curves. The color singlet problem, or the very long range effects, of such a force are unsettled.

The controversy between dark matter and modified gravity is not new. It raged long ago in trying to understand the motion of Uranus. Alternate laws of gravitation were weighed against conjectures of unseen matter, which included not only the prediction of a new planet (Neptune), but 'cosmic fluid'— the original dark matter [9].

This brings us to the title of this article. Is the solution to flat rotation curves the existence of dark matter or a generalized theory of gravity? The overall consensus in this area lies in the Dark Matter solution. By conjuring up the appropriate distribution, it seems all motions, not only the outer stars but galactic motions themselves, can be satisfactorily explained. This also gives high energy physicists a lot of business. The character and amount of dark matter may be decisive in the choice of the correct fundamental unified theory, if there is one. However, if the solution lies in dark matter, and if dark matter comes from a new or current unified or supersymmetric theory, then this may lead to a new formulation of gravity after all. If the dark matter consists of a supersymmetric particle (probably the lightest supersymmetric particle), then the rotation curves, and the inferred dark matter density, could be the best evidence for pointing to the correct supersymmetric, or unified, theory.

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Gravitational Waves from coalescing compact binaries

Curt Cutler, Cornell

A 3-day workshop on "Gravitational Waves from Coalescing Compact Binaries" was held at Caltech in early January. Coalescing binaries are currently viewed as the most promising source for detection by LIGO/VIRGO. The workshop was attended by twenty-five theorists and by several members of the LIGO experimental team. The workshop was organized in order to allow those theorists who are currently working actively on this subject to compare notes and make plans for their future research. The central goal was to make sure that, by the time LIGO/VIRGO goes on line (ca. 1998), all theoretical foundations have been laid for fully utilizing the coalescing-binary observational data that LIGO/VIRGO can bring us.

There are plans to hold, within the next year, a larger, publicly advertised, several-day workshop on this same subject, so as to bring other researchers up to date on it and encourage them to contribute to the theoretical effort that will underlie LIGO/VIRGO.

Most discussions were concerned (in one way or another) with gravitational wave templates, theoretically generated waveforms that are used as filters to extract signals from the noisy LIGO data stream and which are also the basis for "reading off" from the measured waveform the binary's physical parameters, such as the masses of the two bodies, their distance from Earth and angular location on the sky, etc. To establish a notation, we can write

$$h_{GR}(t) = h_{NQ}(t) \;+\; \mathrm{post-Newtonian\ corrections}$$

where $h_{GR}(t)$ is the full waveform predicted by general relativity and $h_{NQ}(t)$ is the approximate version obtained using the Newtonian, quadrupole formula. To date, the post-Newtonian corrections to $h_{NQ}(t)$ have been calculated explicitly through $O(v/c)^3$.

The workshop focused on the research that people are currently doing and that they intend to do, rather than on already-published results. Accordingly, this summary will concentrate on the open questions. Two (related) questions which received a good deal of attention, and which should surely yield to a little effort, are:

1)Are the approximate waveforms $h_{NQ}(t)$ adequate as search templates for digging signals out of the noise (even though they are clearly not sufficiently accurate for determining the binary's parameters)?

S. Finn and D. Nicholson reported some preliminary calculations which indicated that

$h_{NQ}(t)$ is a better search template than many of us had expected, but precisely how good it is remains to be settled.

2)In practice, one will search for signals using some discrete set of templates–how many are necessary?

The answer to question 2) is one determinant of how much computing power will be necessary for conducting the search. Now, there is a natural metric on the space of waveforms, so one might naively expect the necessary number of search templates to be basically the total volume of measurable waveforms (times some number of order one which is set by the distance between discrete search templates). However B. Schutz suggested that this integral probably overcounts the total number of required templates, due to correlations between different templates. He further suggested that there may be some generalization of the sampling theorem which would be applicable to this question.

Another important class of open questions relates to the accuracy with which the binary's physical parameters (especially the masses and spins) can be extracted from the data:

3)What are the limitations on parameter extraction accuracy due to random detector noise?

4)What are the limitations on parameter extraction accuracy due to imperfect theoretical templates?

Though much work has already been done on 3) using successively more realistic models of the waveforms, the results have not yet "converged." The next step will be to incorporate waveform modulation due to orbital precession caused by the bodies' spins. Regarding 4), E. Flanagan presented preliminary results suggesting that one will need to include post-Netownian corrections through $O(v/c)^6$ to reach the point where systematic errors due to inaccurate templates are smaller than random errors due to detector noise. This was discouraging; L. Blanchet, who is spear-heading the PN expansion effort, expressed the opinion that carrying the expansion through $O(v/c)^6$ would be very difficult.

All the work on 4) relies on a specific testbed for determining the rate of convergence of the PN expansion: the problem of gravitational radiation emitted by a point particle spiraling into a Schwarzschild black hole. The use of this problem as a testbed was introduced by the Caltech group, and has been substantially advanced by recent numerical and analytical calculations by H. Tagoshi, T. Nakamura, and M. Sasaki. These calculations were presented at the workshop by Tagoshi, and Flanagan's $O(v/c)^6$ estimate is based on them.

The workshop also had a section on waveforms from the final merger of neutron-star binaries, and on the possible LIGO/VIRGO use of those waveforms to measure neutron-star radii. J. Centrella, M. Davies, and T. Nakamura all presented their recent numerical simulations of such mergers, and D. Laurence displayed and compared spectra (dE/df) of the gravitational waves from the various simulations. The most interesting results were (i) that the mergers were qualitatively different depending on whether or not the neutron stars were assumed to be rapidly rotating just prior to collision, with much more post-collision "ringing" in the non-rotating case, and (ii) in all cases there is a rather sharp cliff in the spectrum which is quite sensitive to the neutron-star radii. A. Wiseman warned, however, that PN effects, not-yet included in the simulations, may reduce substantially the sharpness of the cliff and its viability as a measure of neutron-star radii.

Many other topics were discussed, but the above should give a flavor of what went on at the workshop. Most participants seemed to find the experience very stimulating. Roughly 40% of the participants expressed strong interest in attending a much longer workshop–one that would last for several months.

Finally, since any interest group these days must have an electronic bulletin board, a merging-binaries bulletin board was established for us by S. Finn. Those wishing information about the bulletin board, or wishing to be placed on the associated mailing list, should send the request to

gwave-theory-request@holmes.astro.nwu.edu.

Mach's Principle: From Newton's Bucket to Quantum Gravity

Dieter Brill, University of Maryland

An international workshop on Mach's Principle was held July 26 - 30, 1993 at Tübingen, Germany . It was the first meeting ever devoted exclusively to this elusive principle, and was attended by about 50 physicists, a diverse group that fairly represented the various views on the Principle extant today. The organizers were J. Barbour (Oxford) and H. Pfister (Tübingen), with an advisory committee of B. Bertotti, D. Brill, J. Ehlers and J. Stachel.

It was the aim of the conference to give a reasonably complete overview of the activities derived from Mach's original questions, ranging from history of physics to general relativity theory and to observational astronomy. Recognizing the variety of views, J. Barbour suggested polling the conferees at the beginning and the end on the proposition that "Einstein's general relativity is a perfectly Machian theory". (The votes gave no decisive indication of any strong change of minds by the end of the conference; the majority opined that GR, even with "appropriate boundary conditions of closure of some kind" is not perfectly Machian, but agreed — overwhelmingly at the end — that GR is "very Machian.")

A number of papers were devoted to ways of giving a precise formulation of Mach's principle. A random sampling from this group follows. J. Narlikar and F. Hoyle spoke about direct particle formulations based on action at a distance similar to Wheeler-Feynman electrodynamics. There is no solution describing an empty universe, and the smallest possible number of particles appears, amusingly, to be three. In the limit of a large number of particles the theory resembles general relativity, but also allows interpretation in terms of creation of matter. D. Raine and K. Nordvedt presented contributions on the Green's function formulation. An integral representation formulates perhaps most directly the idea that the universe's matter content should determine the local inertial frames. The Discussion included questions about the epoch at which the integral representation is to be applied, and whether "true" matter should be distinguished from other sources of gravity, such as black holes. J. Isenberg reported on the "Wheeler-Einstein-Mach" formulation in terms of initial values. Here the emphasis is to characterize which features of gravity are freely disposable, and which are thereby determined. But some of the freely disposable features needed to determine inertia would seem unphysical, because hidden behind horizons. The question whether alternative schemes are needed or whether general relativity itself is perfectly Machian was discussed by J. Barbour, D. Lyndon-Bell, and others.

The best-understood Machian effect in general relativity and related theories is the dragging of inertial frames by rotating bodies. In addition to the rather general but perturbative calculations, reviewed by H. Pfister, there are now exact solutions for a rigidly rotating disk of dust, as presented by R. Meinl. Experimental tests of such Machian effects were discussed by C. Will, I. Ciufolini, and others.

In addition to the expository talks there were contributions reviewing critically various fundamental issues, by J. Ehlers, W. Rindler, H. Bondi and others. The meeting was rounded out by numerous spirited discussions, for which there was fortunately enough time. Only the discussion of Mach's principle in quantum gravity, at the very end of the sessions, failed to do justice to this interesting topic.

A number of the Tübingen meeting's pleasant and interesting arrangements deserve mention. It was held at the Max Planck House of the local Max Planck Institute, a nearly ideal location for a small conference that fosters lively interaction between the participants. On the evening that had the week's most pleasant weather there was a party at the home of Prof. Pfister that will remain memorable for its delicacies, both intellectual and gustatory. Equally memorable was a visit to a jewish cemetery at Bad Buchau that contains many graves of Einstein's forefathers.

In his closing remarks, Sir Hermann Bondi said: "This conference was a splendid idea, and I am only surprised that nobody thought of having such a conference before."

Many of the contributions to the Tübingen conference will appear in the *Einstein Studies* series published by Birkhäuser.

Cornelius Lanczos International Centenary Conference

David Brown, North Carolina State University

The Cornelius Lanczos International Centenary Conference was sponsored by the College of Physical and Mathematical Sciences of North Carolina State University, and took place in Raleigh on December 12–17, 1993. The conference was held in honor of Cornelius Lanczos, who contributed important and fertile ideas in an astonishingly broad range of disciplines. Lanczos pioneered the study of higher–derivative gravity theories and the use of Euclidean methods in relativity. His early work was instrumental in revealing the nonsingular nature of event horizons and in uncovering their physical properties. In a 1926 paper, Lanczos proposed a field formulation of quantum mechanics using integral equations, in anticipation of Schrödinger's equation. Lanczos also made important contributions to electromagnetic theory, and his book entitled *Variational Principles of Mechanics* is a testimony to his mastery of that subject. Lanczos's contributions to applied mathematics are likewise impressive. He laid the foundation for the Fast Fourier Transform, and developed a number of other computational algorithms that are currently of vital importance in the field of applied mathematics.

The topics covered at the Lanczos Conference included theoretical physics and computational mathematics, reflecting the scientific interests of Cornelius Lanczos. As a modern bridge between these disciplines, the conference also covered various aspects of astrophysics. A number of joint sessions brought together scientists from each of these fields. The joint plenary speakers included Roger Penrose, who spoke on "Relativity, Quantum Theory, and Computation". Penrose discussed the distinction between deterministic systems and computable systems, and suggested that our Universe might not be computable even if it is deterministic. John Stachel gave an interesting and informative talk on "Lanczos's Contributions to General Relativity". Kip Thorne's presentation, "Gravitational Waves: Challenges, Plans and Prospects", provided a summary of the astrophysical information carried by gravitational waves, the prospects for detecting and extracting information from gravitational waves, and the challenges that lie ahead. In his talk entitled "The Quasiclassical Domain in a Quantum Universe", James Hartle discussed the idea that the quasiclassical domain originates from the fundamental interactions along with the specific initial conditions of our universe. Hartle went on to review his work with Murray Gell–Mann on the derivation of deterministic physics through the decoherent histories generalization of quantum mechanics.

The joint sessions also featured several speakers from the computational mathematics community. Gene Golub discussed various uses for the 'Lanczos algorithm', which Lanczos originally developed as a method for computing the eigenvalues and eigenvectors of matrices. Beresford Parlett's talk addressed some subtle difficulties with the Lanczos algorithm and their resolution. James Cooley lectured on the work of Lanczos that contains the essential ideas of the Fast Fourier Transform, and covered the relationship between Lanczos's work and the currently familiar formulations of the FFT. Anne Greenbaum discussed the finite precision implementation of the Lanczos algorithm and stressed the benefits of this approach.

The remainder of the conference featured concurrent programs in computational mathematics and in theoretical physics and astrophysics. A highlight of the theoretical physics and astrophysics program was the lecture "Towards 'It from Bit'" by John Wheeler, which contained a wealth of insights and observations. Abhay Ashtekar reported on recent progress in developing a theory of integration on the space of connections modulo gauge transformations. This and other related work was discussed in the minisymposium "New Variables and Loop Quantization" organized by Lee Smolin. Karel Kuchař organized a minisymposium that addressed "The Problem of Time in Quantum Gravity", while Jonathan Halliwell's minisymposium on "Decoherence and the Foundations of Quantum Mechanics" provided further discussion of the issues raised in Hartle's talk.

Tsvi Piran presented evidence in his plenary talk that the observed γ–ray bursts originate in the merger of neutron star binaries. Michael Turner discussed the problem of explaining in detail how the small, primordial fluctuations in matter density lead to the presently observed structure in our universe. This and other related topics were discussed in the minisymposium "Galaxy Formation and Large–Scale Structure of the Universe" organized by Alex Kashlinsky. Clifford Will's minisymposium "Detection of Gravitational Radiation from Astrophysical Sources" served as a complement to Thorne's plenary lecture. The minisymposium organized by Manfred Scholer and Dan Winske covered "Numerical Simulations of Collisionless Space Plasmas", while the minisymposium organized by John Blondin and James Stone focused on "Computational Magnetohydrodynamics in Astrophysics".

Several of the plenary speakers chose black holes as the topic of their lectures. Claudio Teitelboim discussed the fundamental role played by the Gauss–Bonnet theorem in determining the entropy of a black hole through Euclidean path integral methods. Robert Wald presented a technique, based on variational principles, that yields a generalized first law of black hole mechanics for essentially any diffeomorphism invariant Lagrangian field theory. The lecture by Gary Horowitz concerned pair creation of magnetically charged black holes by magnetic fields. His results suggest that the rate of creation of extremal black holes is suppressed relative to the rate of creation of spatial wormholes by the exponential of the Bekenstein–Hawking entropy. These talks were complemented by the minisymposium "Black Hole Evaporation and Thermodynamics" organized by Paul Anderson.

Several minisymposia were devoted to important problems in classical general relativity. These included a session on "Cosmic Censorship" organized by David Garfinkle, and a session on the "Lanczos H–tensor" organized by Patrick Dolan and Abraham Taub. In the early 1920's, Lanczos addressed the Cauchy problem of general relativity and showed that it is well posed. The ongoing efforts to understand this problem were discussed in the minisymposium "The Cauchy Problem of General Relativity" organized by Jim Isenberg.

The theoretical physics and astrophysics program also included a plenary talk by Jerrold Marsden, who described a general method for generating a constrained variational principle governing the Euler–Poincare equations on any Lie algebra. Complementary minisymposia included "Geometric Mechanics" organized by Tony Bloch and Tudor Ratiu, and "Symplectic Methods in Physics" organized by Mark Gotay and Peter Olver.

Theoretical high energy particle physics was represented at the Lanczos Conference in the minisymposia "Supercollider Physics" organized by Paul Frampton, Tom Kephart, and Marc Sher, and "Open Questions in Particle Theory" organized by Carl Carlson and Adam Szczepaniak. Unfortunately, Yasushi Takahashi was unable to attend and deliver his plenary lecture "Four Dimensional Vector and the Gauge Transformation" due to a cancelled airline flight.

In addition to the plenary talks and minisymposium sessions, the Lanczos Conference featured a large number of contributed lectures and poster presentations covering a wide spectrum of topics in theoretical physics, astrophysics, and computational mathematics. A special public lecture by Michael Turner entitled "The Earliest History of the Universe" was a great success, attracting approximately 700 people from the Raleigh community. The week–long conference was fun and informative for the nearly 600 participants. Proceedings of the Lanczos Conference will be published in the summer or fall of 1994.

Third Midwest Relativity Conference

David Garfinkle, Oakland University

The third annual midwest relativity conference was held at Oakland University in Rochester Michigan on Nov. 5-6. There were about 50 participants, most of whom gave talks. Each talk was 15 minutes long. For the most part the topics covered fell into the following categories: 1) Black Holes, 2) Numerical relativity 3) Mathematical relativity 4) Observational topics 5) Quantum gravity.

Black Holes. Many of the talks on black holes concentrated on the notion of black hole entropy, both in general relativity and in other theories of gravity. Bob Wald presented a general method for finding the entropy of a stationary black hole in any diffeomorphism invariant theory. Vivek Iyer and Ted Jacobson presented some of the results of this method and addressed the issue of extending the method to the case where the black hole is not stationary. Robert Meyers considered the case of R^2 gravity and found conditions under which this theory obeys the second law of thermodynamics. David Garfinkle showed that there is a relation between black hole entropy and the rate of production of black holes by quantum tunneling. Gungwon Kang presented a conformally invariant generalization of the surface gravity of black hole. Jonathan Simon considered the issue of boundary terms in a Euclidean formulation of higher derivative gravity. Robert Mann presented some exact solutions for two dimensional Liouville black holes. Mike Morris showed why the Kerr-Newman metric is not a good model for an elementary particle.

Numerical Relativity. Numerical results for problems in 1, 2 and 3 spatial dimensions were presented; some in vacuum and some using matter. Ed Seidel and Wai-Mo Suen presented results for 2 and 3 dimensional codes describing the evolution of a distorted black hole. They also discussed their method of "horizon locking" which allows the numerical grid to end on the apparent horizon. Beverly Berger and Vijaya Swamy presented a numerical evolution of Gowdy spacetime. They investigated the interactions of gravity waves both with each other and with test matter. Comer Duncan presented a numerical algorithm for solving Poisson's equation in 3 dimensions and accurately finding the gradient of the solution. Malcolm Tobias presented a numerical evolution of plane gravitational waves as a code test of the 3 dimensional numerical code discussed by Seidel and Suen. Jayashree Balakrishna presented a numerical evolution of boson stars. Daniel Holz numerically searched for closed trapped surfaces in the initial data for Brill waves.

Mathematical Relativity. The mathematical talks were mostly about global issues such as singularities, topology and the concept of mass in general relativity. John Friedman presented a proof that in an asymptotically flat spacetime exotic topology is hidden behind an event horizon and cannot be seen by an observer at infinity. Ed Glass and Mark Naber presented results on Taub Numbers. These are quantities associated with perturbations of a background spacetime that has a Killing vector. John Beem showed that if a spacetime is singular then, under certain conditions, all "nearby" spacetimes are singular. Steve Harris showed that in a static, globally hyperbolic, nonsingular spacetime the curvature must satisfy certain fall off conditions. Jim Wheeler classified all the types of singularities possible in a spherically symmetric spacetime. Shyan-Ming Perng used spinorial techniques to define an analogue of mass for any initial data set (whether or not it is asymptotically flat). Jolien Creighton analyzed some of the properties of the Brown-York quasilocal mass. Matt Visser showed that the techniques of Lorentz geometry can be applied to the problem of perturbations of a fluid. Brien Nolan applied Israel's thin shell formalism to model a shell of matter in a Robertson-Walker spacetime. Jim Chan presented exact solutions of a generalization of 2 dimensional dilaton gravity.

Observational Topics. The observational talks were mostly related to LIGO, its uses and possible sources. Sam Finn talked about using LIGO to measure the Hubble parameter. Robert Caldwell discussed a stochastic background of gravity waves from inflation and the possibility of observing these gravity waves using the cosmic microwave anisotropy. Alan Wiseman and Lawrence Kidder used the post Newtonian approximation to treat the case of coalescing binaries. Liliana Simone treated head on collisions between black holes in the post Newtonian approximation.

Quantum Gravity. There are many approaches to quantum gravity; some (though not all) were presented at this meeting. Dieter Brill talked about using instanton methods to calculate the rates for topology changing quantum tunneling processes. Ian Redmount used the minisuperspace approach to treat the quantum dynamics of spherical wormholes. Jorma Louko presented some results on the quantization of 2+1 dimensional gravity on the manifold $R \times T^2$. Miguel Ortiz talked about the issue of physical states in $N = 1$ supergravity. Gilad Lifschytz did quantum field theory on the curved space of a 2+1 dimensional string theory black hole. Greg Daues did quantum field theory on the curved space of a Brans-Dicke type cosmology. Charles Torre discussed the problem of observables in canonical quantum gravity. Michael Reisenberger studied the loop representation of abelian gauge theories.

There was a wide range of research in general relativity presented at this meeting, as at the two previous midwest relativity conferences. I hope to see all of you at the next midwest conference in St. Louis.