Summaries of the presentations given at the LIGO Scientific Symposium, held November 11, 1999 at the LIGO Livingston Observatory.

General Relativity and Gravitational Waves

Prof. Clifford M. Will
Department of Physics – Washington University, St. Louis

Dr. Cliff Will reviewed many of the tests that Einstein's theory of General Relativity has successfully passed. He discussed the various tests of the conceptual central piece of general relativity, the Einstein Equivalence Principle (EEP). EEP consists of three parts: the weak equivalence principle, WEP, (test bodies fall with same acceleration independent of composition—think of dropping a feather and a ball in a vacuum; they will fall at same rate), Local Lorentz Invariance (local velocity doesn't matter) and Local Position Invariance (it doesn't matter where you are). EEP is a statement of what can be called strong equivalence principle; a small region of space-time in a free-falling frame, all the laws of physics are the same as in special relativity. From the Einstein Equivalence Principle, one can argue that the theory of gravity should be a metric theory of gravity. Metric theories include general relativity, the Brans-Dicke and Rosen theories. Each of these theories can be expanded in parameters near the Newtonian case. Experiments give values for some of the parameters in this Parameterized Post Newtonian (PPN) approximation from which one can decide which theory best matches experiment. In each case, general relativity is the winner. For example, theories, like Brans-Dicke, that introduce a scalar gravity field will violate WEP and no experiment has seen this yet.

Will further showed that gravity wave experiments, such as LIGO, could in principle check the validity of general relativity. That is, LIGO would be investigating the quantitative nature of gravity itself. He listed several ways of doing this: determination of speed of gravity wave propagation, determination of polarization and studies of strong field gravity. One can, for instance, in principle, use the detection rates of inspiral signals from NS (neutron star)-NS binaries and NS-BH (black hole) binaries and the black hole masses to discriminate between the Brans-Dicke theory and general relativity.
(Summary prepared by Dr. Anthony Rizzi)

Cosmology and Gravitational Waves

Prof. Michael S. Turner
Department of Astronomy and Astrophysics – The University of Chicago

Dr. Michael Turner discussed the large amount of evidence for the big bang cosmology as well as recent attempts to tweak it with inflation and other ideas. The big bang model assumes, to some order, general relativity and a Robertson-Walker-Lemaitre-Friedmann metric. It makes correct predictions about the abundance of some elements and other features of the present epoch universe. Turner gave many interesting numbers relating to the big bang model; the numbers are particularly noteworthy, because of their decreasing error bars. For example, he gave the latest value for the Hubble constant, H_0 and for T_0 , the temperature of the cosmic background radiation; H_0=65 +/- 7 km/s/Mpc and T_0=2.728+/-.002K over 3 ½ decades of wavelength (very black body like). He pointed at newer measurements that indicate that Ω=1+/- .2. Ω is the fraction of energy density for the universe to be closed (spatially); thus, unity value for Ω means a flat (barely open) universe. The inflationary scenario predicts a very fast expansion period early in the universe. The inflation theory's predictions include Ω=1 and other large-scale quantitative features of the universe that agree well with experiment.

LIGO, according to Turner, can also contribute to cosmology by, for example, testing the inflationary scenario. Because of the phase transitions associated with the "freezing out" of the various forces, there will be gravity waves produced within the LIGO frequency band. The strain of such waves promises to be both very small and hard to determine with certainty. Turner says, in reference to deciding about the correctness of inflation and other new ideas about the early universe, "LIGO is the first step toward this ambitious goal." *(Summary prepared by Dr. Anthony Rizzi)*

Solar Neutrinos and LIGO: Any Parallels?

Prof. John N. Bahcall
School of Natural Sciences - Institute for Advanced Study

After briefly reviewing the history of neutrino detection research, Prof. Bahcall compared prediction and observation of the rate of solar neutrino events. The prediction was based on a combination of the standard solar model and the standard electro-weak theory. He reported that the prediction is always greater than the observation for any kind of neutrino. After pointing out that the standard solar model is correct, he mentioned that in order to explain the difference between the observation and prediction new physics must be taken into account.

In the latter half of the presentation, he made comparisons between solar neutrino detection and GW detection. Similarities include that both gravity waves and neutrinos are “new messengers” of information and both are examples of physicist-driven astronomy. Other parallels are that both fields struggle with noise, take decades to obtain results, stimulate the theory and may have unanticipated results.

The difference is that the neutrino physics is non-relativistic while the GW physics is relativistic, GW research needs 100 times higher budget and 30 times more scientists, and GW research is more difficult because artificial laboratory events are impossible. They are also different in the sense that if there is no detectable event, this can be a discovery for solar neutrino research but only an uncertainty for GW research. *(Summary prepared by Dr. Sanichiro Yoshida)*

Gravitational Waves: Sources and Signals

Prof. Kip S. Thorne
California Institute of Technology

Dr. Kip Thorne addressed several interesting astrophysical questions having to do with gravitational wave generation. Two of the topics he discussed were based on very recent works. A particularly exciting one is the prediction by Simon F. P. Zwart and Stephen L. W. McMillian that changes, in the opinion of some, the most likely expected LIGO source from NS (neutron star)-NS inspiral to BH (black hole)-BH inspiral. Zwart and McMillian predict BH-BH merger rate of 1.6 x 10^{-7} /year/Mpc^3 (apparently assuming H_0 ~ 80 km/s/Mpc) which they say translates into ~.5 detection/ year for LIGO I and ~1 detection/day for LIGO II. Whereas, they say the detection rate for NS-NS mergers for LIGO-I is a few detections per millennium. To arrive at these higher BH-BH merger rates, they consider not the black holes that become close binaries through internal binary star evolution, but a BH-BH creation mechanism in dense stellar systems.

Thorne also mentioned that the gravity wave frequency, f_{td} , at the onset of NS tidal disruption is strongly dependent on the star radius, R. He mentions Michele Vallisneri who says that LIGO-II might be able to measure R to 15% precision at 140Mpc (~ 1 event/year rate). The radius then, in turn, gives useful information about the equation of state of NS's.

The third topic covered by Thorne has been around longer; it is the issue of Rosby waves or r-modes. These waves are one instance of a class of waves that are susceptible to the CFS instability. This instability results when gravitational radiation reaction creates positive feedback into the r-waves increasing without bound (until other effects come into play) the size of the r-waves and, in turn, the amount of gravitational radiation. According to Levin and Ushomirsky, thin rotating shells, and the r-modes in them, have been studied by geophysicists and meteorologists for a century. In rapidly rotating hot neutron stars, through the CFS mechanism, r-modes are a source of gravitational waves, which can potentially tell us interesting things about NS's. This topic and the whole of the topics considered by Thorne, illustrate well the broad spectrum of interesting problems that can be investigated via gravitational wave detection. ." *(Summary prepared by Dr. Anthony Rizzi)*

Suspended Mass Interferometry

Prof. Peter R. Saulson
Department of Physics – Syracuse University

The experimental goal of suspended mass interferometry is to measure the motions of free masses to one part in 10^{-21} in order to find gravity waves. The big leap in sensitivity comes from making the baseline long (4 km) and significantly improving the measurement capability of interferometry from Michelson's $\lambda/20$ to $\lambda/10^{12}$. This is achieved by using high laser power (10 W) built up in the optical cavities of the interferometer arms that have low losses and by recycling the output light of the interferometer. The other difficulties lie in removing the noise due to seismic motion and thermally excited motions of different parts of the interferometer and controlling the interferometer so that it stays locked at its operating point over long periods of time. This is partly remedied by understanding the frequency dependence of the noise. One of the big challenges remaining is the extraction of the anticipated small gravity wave signal from a large noise background. *(Summary prepared by Dr. Joe Kovalik)*

LIGO: Challenges Past, Present and Future

Dr. Stan Whitcomb
California Institute of Technology

The LIGO project has created the need for very advanced vacuum systems, optics and interferometric techniques in order for it to achieve its projected sensitivity. The vacuum envelope in which LIGO operates utilizes two 4 km long beam tubes as parts of a ultra high vacuum system that achieves a vacuum of less than 10^{-9} mbar with no leaks detected. The test masses, or mirrors, of the interferometer are polished and coated with a micro-roughness less than 1 nanometer RMS. The losses due to scattering are less than 50 parts per million and those due to absorption are less than 2 parts per million. The length control must be on the order of 10^{-11}-10^{-13} m and the angular pointing on the order of 10^{-8} radians. A great deal of analytical and numerical modeling was performed to understand how to control the interferometer to such a degree of accuracy. The 2 km arm tests should be done by 2/00, a power recycled short Michelson by 4/00 and the full recycled Fabry Perot Michelson should be operational by 9/00. *(Summary prepared by Dr. Joe Kovalik)*

VIRGO/GEO/TAMA

Prof. Adalberto Giazotto
Instituto Nazionale di Fisica Nucleare – Sezione di Pisa

Other interferometer projects around the world consist of TAMA - a 300 m interferometer near Tokyo, Japan, GEO - a 600 m British-German collaboration near Hanover, Germany and the VIRGO project- a 3 km French-Italian collaboration near Pisa, Italy. The TAMA project is now operational and has a strain sensitivity of 10^{-19} $\mathrm{Hz}^{-1/2}$ which is about an order of magnitude above its projected sensitivity. The GEO interferometer will be operational by 4/00 and is interesting because it does not use Fabry Perot arms and because it has a mirror to recycle the output dark fringe which allows narrow band improvement in sensitivity. It also uses fused silica fibres for suspending its test masses. The VIRGO Project has finished construction of its central building and its vacuum tanks. The arms will be installed over the next two years. Installation of a central interferometer using the near mirrors to form a recycled Michelson is underway. The VIRGO seismic isolation system is a cascade of 7 pendula which should allow a measurement band down to 10 Hz. *(Summary prepared by Dr. Joe Kovalik)*

Detection of Gravitational Waves with LIGO/VIRGO

Dr. Albert Lazzarini
California Institute of Technology

Albert Lazzarini, a senior staff scientist at LIGO / Caltech, gave an interesting talk that described the community's planned strategies and techniques to be used to reduce the data streams we expect from the LIGO, Virgo, and GEO detectors.

As an introduction, he outlined several ground-breaking astronomical observations from history: Galileo's first use of a telescope to observe Jupiter's moons, Janske's discovery of extra-terrestrial radio waves, and Penzias and Wilson's first observation of the cosmic microwave background.

Each LIGO detector is a "MIMO" system, that is it has multiple inputs and outputs in its complex signal pathways. The signal that truly represents the gravitational-wave strain, "*h*", is to be extracted from a combination of the instrument's output signals. A detector will generate approximately 3 megabytes of data each second, only 1% of which is the GW signal.

To extract what we really want, several steps must be taken. In some cases, instrumental noise that pollutes the GW signal may be removable by studying the mechanism of the noise's getting into the GW output, and removing it by careful pre-processing. In order to study the signals and not the remaining instrumental noise, it is often helpful to use so-called "optimal filters" which produce a data stream for further analysis that contains mostly data with potential signal rather than known noise.

Some processing steps vary with the kind of GW the observer is looking for. For example, a search for coalescing binary compact objects (such as neutron stars or black holes) requires preparation of families of templates which represent (at least at first) theoretical predictions of GW waveforms from these source systems. These template families are then compared, in high-speed computers, with the data stream. In this way, we can use some prior knowledge of physics to dig a bit down into the noise to find true signals. Similar specialized techniques will apply to other source categories, such as transient (burst) sources and stochastic GW's.

An international committee has been formed to facilitate exchange and comparison of data among the various detectors around the world. *(Summary prepared by Prof. Joe Giaime)*

Resonant Bars

Prof. David G. Blair
Department of Physics – The University of Western Australia

David Blair, of the University of Western Australia, gave a fine overview of the current activities of the resonant-bar GW detector community. A collaboration called IGEC consists of 5 resonant bars around the word, located in Australia, Switzerland, Italy and the US. One detector, ALLEGRO, is located near this meeting, at LSU, and will be used in conjunction with the LIGO Livingston detector to study stochastic GW's near 900 Hz, where ALLEGRO and LIGO are expected to have comparable noise levels.

Resonant bar detectors employ a several-meter long metal bar, isolated from external vibration and held at cryogenic temperatures, to absorb energy from GW's. This energy is then coupled into a transducer, whose motion is monitored using a SQUID or other ultra-low-noise amplifier. These bars are currently able to see GW's at the h=10^-23 level near their resonance frequencies.

Many of the same techniques that are being planned for LIGO data are in use in the bar community: optimal filtering, multiple coincidence comparisons among the world's bars, and monitoring of multiple environmental monitors as vetos. Together the 5 IGEC instruments have conducted coincidence runs that place fairly strict limits on GW sources with energy in their bandpass. These will continue, and will be joined by the interferometric (and more broadband) signals from LIGO-like detectors in the years to come. *(Summary prepared by Prof. Joe Giaime)*

Gravitational Waves in Space

Prof. Karsten Danzmann
Institut fuer Atom und Molekuelphysik – Universitaet Hannover

LISA (Laser Interferometer Space Antenna) is a proposed space mission to detect GW's at frequencies from below a millihertz to about one hertz, considerably lower than the Earth-based antennas such as LIGO. Planned for about 10 years from now, LISA consists of three spacecraft in solar orbit separated by 5 million kilometers (compared with 4 km for LIGO). This long baseline, together with its immunity from the noise of the Earth's surface, will allow it to see sources not visible to LIGO.
LISA's three spacecraft are to fly in a triangular formation, 20 degrees behind the Earth's orbit. This formation slowly rotates as it revolves around the Sun, sweeping out the entire sky in its detection field. "Aiming" is done in processing the data.

Some of the sources that LISA is designed to detect are "sure things," signals from binary stars in our galaxy that have already been observed by other means and for which the GW strength can be calculated. Other sources may include interactions with massive and super-massive black holes, both sites of extremely interesting physics where space is strongly curved. Super-massive black holes might form as galaxies collide, for example. Another candidate for detection is radiation from cosmological phase transitions.

The technology needed to build LISA is fairly straightforward. The distances among the spacecraft are measured by timing the fringes formed between a spacecraft's local laser and its transponded return from each adjacent one. The long flight time of the light can also be used to subtract out much of the laser noise. (LISA's interferometers are not locked in a null servo as in LIGO)

Technical challenges arise from the need to construct a "drag-free" system. Micro-newton thrusters are used to servo each spacecraft's position relative to local inertial reference blocks. These blocks also function as the endpoints of the interferometers. The drag-free technique has been used before in satellites including the soon-to-be-launched Gravity Probe B, but never to the high precision, 10^{-16} g, that is needed for this experiment. *(Summary prepared by Prof. Joe Giaime)*