We discuss a new search which builds upon the method used there. The new method aims to "stack" potential GW signals from multiple SGR for transient GW from these sources placed upper limits on a set of almost 200 individual SGR bursts. These limits were within the theoretically predicted range.
11:21AM B11.00004 Search for Compact Binary Signals Using Coherent WaveBurst1. CHRIS PANKOW, University of Florida — Compact binary coalescence (CBC) is one of the most promising sources of gravitational waves. These sources are usually searched for with matched filters which require accurate calculation of the GW waveforms and generation of large template banks. We present a complementary search technique based on burst algorithms. Initially designed for detection of un-modeled bursts, which can span a very large set of waveform morphologies, the search algorithm presented here is constrained for targeted detection of the smaller subset of CBC signals. The constraint is based on the assumption of elliptical polarization. We expect that the algorithm will be sensitive to CBC signals in a wide range of masses, mass ratios, and spin parameters. We also present preliminary studies of the algorithm on test data as well as the sensitivity of the search to different types of simulated waveforms. Also, we compare the performance of the constrained search and the coherent WaveBurst search used for the burst analysis of LIGO data.

11:33AM B11.00005 Low-latency search for gravitational-wave transients with electromagnetic follow-up: plans and progress. JOSHUA SMITH, Syracuse University. LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION — In the coming months the LIGO and Virgo laser interferometric gravitational wave detectors will recommence their coordinated search for gravitational waves with increased astrophysical reach. We present plans and progress towards implementing a low-latency search for gravitational-wave transients during the upcoming run. A goal of this search will be to identify candidate events and corresponding sky locations within tens of minutes. In the Advanced LIGO era (starting around 2014), when detections should be commonplace, prompt electromagnetic follow-up of burst signals will be extremely valuable for extracting the maximum astrophysical information from detections. To lay the foundations of this type of multi-messenger gravitational-wave astronomy, we are now arranging to carry out a pilot program of electromagnetic follow-ups, in collaboration with other astronomers.

11:45AM B11.00006 Prospects for Joint Searches between Gravitational-wave and High-Energy Neutrino Detectors. IMRE BARTOS, Columbia University, SHIN’ICHIRO ANDO, YOICHI ASO, BRUNY BARET, MATTEO BARSUGLIA, PATRICK BRADY, ERIC CHASSANDE-MOTTIN, SHOUROU KEITH CHATTERJI, IRENE DI PALMA, JOHN DWYER, VERONIQUE VAN ELEWYCK, CHAD FINLEY, KEI KOTAKE, SERGEI KLIENKO, ANTOINE KOUCHNER, SZABOLCS MÁRKA, ZSUZSA MÁRKA, CHRISTIAN D. OTT, THIERRY PRADIER, JAMESON ROLLINS, ANTONY SEARLE, PATRICK SUTTON, ERIC THRANE — Cataclysmic cosmic events, e.g. gamma ray bursts (GRBs), can be plausible sources of both gravitational waves (GWs) and high-energy neutrinos (HENs). Identifying correlations between GW and HEN detection channels shall enable new searches, as one has significant additional information about the common source. Beyond the benefit of a potential discovery, coincident detection of GW and HEN arriving from the same astronomical source might allow us to answer important scientific questions, which would be out of reach for a single channel detector. Analysis method options and Monte Carlo simulations will be discussed to demonstrate the expected performance of feasible searches. A survey of cosmic source candidates will be presented to describe the possible science reach of the data analysis initiative.

11:57AM B11.00007 Results from Prototype Advanced LIGO Seismic Isolation. JEFFREY KISSEL, Louisiana State University, for the LSC, LIGO VIRGO SCIENTIFIC COLLABORATION — In 2008, new seismic isolation systems were installed in the two LIGO 4km gravitational wave detectors. These systems are prototypes of the system planned for Advanced LIGO which will achieve improved interferometer sensitivity to astrophysical events. We present the measured performance of the new isolation systems. We compare this to the current advanced LIGO requirements and discuss potential improvements which may allow even better performance in the future.

12:09PM B11.00008 Update on Suspension Design for Advanced LIGO. NORMA ROBERTSON, LIGO - Caltech — The Advanced LIGO project aims at a tenfold improvement in sensitivity over the performance of the initial LIGO gravitational-wave detector while at the same time reducing the low-frequency cutoff from ~40 Hz to ~10 Hz. Achieving such an improvement is technically challenging, requiring a noise level at 10 Hz of ~10^{-19} m/√Hz at each test mass of the interferometer. Two fundamental noise sources which contribute at low frequencies are seismic noise and thermal noise associated with the suspension of the masses. In this talk we discuss our work on developing a quadruple pendulum suspension system incorporating a monolithic silica suspension for Advanced LIGO, and we present results from a prototype suspension and from associated experiments aimed at testing some of the aspects of the design.

Saturday, May 2, 2009 1:30PM - 3:18PM — Session C5 GGR DAP: Searches for Gravitational Waves with LIGO, GEO and Virgo Governor’s Square 15

1:30PM C5.00001 Overview of the LIGO-GEO S5 and Virgo VSR1 Science Runs, and Sources of Transient Gravitational Waves. MATTHEW EVANS, MIT — The five kilometer-scale gravitational-wave detectors in the United States and Europe collected data in 2005-2007 with better sensitivity and observing time than ever before. The data collected has been analyzed jointly, for maximum sensitivity, with a number of results released so far and more to come. I will summarize the instrument performance and data collection, and survey some of the transient gravitational-wave signals that we are searching for. Later talks in the same session will describe the specific searches carried out using the data.

2:06PM C5.00002 Status of the S5 search for compact object mergers with total mass between 25 and 100 solar masses. EVAN OCHSNER, University of Maryland, LIGO SCIENTIFIC COLLABORATION, VIRGO SCIENTIFIC COLLABORATION — We present the status of the search for gravitational waves from coalescing compact binary systems with total mass between 25 and 100 solar masses in the LIGO Fifth Science run (S5) data with the goal of constraining the merger rate. In this mass regime LIGO is sensitive to the inspiral, merger and ring down phases of the coalescence. We describe our ongoing effort to incorporate models based on recent advances in numerical relativity that probe the late inspiral, merger and ring down phases.

2:18PM C5.00003 GRB-triggered searches for gravitational waves from compact binary inspirals in LIGO and Virgo data during S5/VSR1. NICKOLAS FOTOPOLOUS, University of Wisconsin-Milwaukee, LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION — We describe a search for the gravitational-wave inspiral signatures of short gamma-ray bursts (GRBs) in LIGO and Virgo data taken during a two-year span that began in September 2005. The GRB community largely believes that most short GRBs are produced by the merger of two neutron stars or of a neutron star with a black hole. In their final orbits, such systems would produce strong gravitational waves. Through the efforts of electromagnetic astronomers, we know the time and sky location of these events, so we can search gravitational-wave data with a lower threshold than previous, untriggered searches.
2:30PM C5.00004 The Search for Low Mass Compact Binary Coalescences in LIGO’s S5 and Virgo’s VSR1 Data . DAVID McKECHAN, Cardiff University, ON BEHALF OF THE LIGO SCIENTIFIC COLLABORATION AND VIRGO COLLABORATION — We report on the search for gravitational waves from coalescing compact binary systems with total mass from 2-35 M⊙ in the LIGO Fifth Science run (S5) data and Virgo’s Science Run 1 (VSR1). We describe the pipeline employed by the LSC/Virgo to search for such waveforms in LIGO/Virgo data including how we suppress false signals originating from instrumental noise, how we evaluate the search efficiency for systems which may include spinning component objects, and how we establish confidence in likely detection candidates. Finally, we describe Bayesian coalescence rate upper limit calculations as a function of mass of the binary system and for several canonical mass systems including mass distributions representing binary neutron stars, binary black holes, and black hole neutron star binaries.

2:42PM C5.00005 Search for gravitational-wave burst counterparts to gamma-ray bursts using data from the fifth LIGO science run and the first Virgo science run . ISABEL LEONOR, University of Oregon, LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION — We present the status of an on-going search for short-duration gravitational-wave bursts (GWBs) associated with gamma-ray bursts (GRBs) detected by gamma-ray satellite experiments during the LIGO science run S5 / Virgo science run 1. This sample consists of more than 200 GRB triggers, most of which were observed by the Swift satellite. The search for GWBs associated with GRBs takes advantage of the known sky position and time of the GRB to construct linear combinations of the data that maximize or minimize the signal-to-noise ratio of a gravitational-wave signal with a given polarization. This allows for both high sensitivity to real gravitational waves and powerful consistency tests for suppressing background noise. We apply these techniques to search for gravitational radiation associated with individual GRBs, and also apply statistical tests to search for a gravitational-wave signature associated with the collective sample.

2:54PM C5.00006 All-sky search for gravitational wave bursts with LIGO, GEO and Virgo . MICHELE ZANOLIN, E. KATSAVOUNIDIS, MIT, LIGO SCIENTIFIC COLLABORATION1, VIRGO COLLABORATION2 — The network of gravitational-wave detectors LIGO, GEO and Virgo collected data of unprecedented sensitivity in their 2005-07 science runs. Using data from these runs, we describe the search for bursts: short-duration gravitational wave signals with unknown or poorly modeled waveforms. Such signals, may accompany astrophysical events like core-collapse supernovae, the merger phase of coalescing binary compact stars and gamma-ray bursts (GRBs). In this talk we focus on the all-sky search of such signals with frequency content in the 64-2000Hz range- this encompasses the most sensitive regime of the ground-based interferometers.

3:06PM C5.00007 All-Sky Burst Searches for Gravitational Waves at High Frequencies . BRENNAN HUGHEY, MIT, LIGO SCIENTIFIC COLLABORATION, VIRGO COLLABORATION — Previous burst searches with ground-based interferometers have generally been limited to frequencies below 2 kilohertz. However, various models predict gravitational wave emission in the few-kilohertz range from gravitational collapse, neutron star modes, the mergers of some compact binaries or other astrophysical phenomena. We present all-sky gravitational wave burst searches at frequencies up to 6 kilohertz, conducted on data taken during LIGO’s fifth science run and Virgo’s first science run.

Saturday, May 2, 2009 1:30PM - 3:06PM –
Session C11 GGR DCOMP: Numerical Analysis of Black Hole Binary Systems  Plaza Court 1

1:30PM C11.00001 Algebraic Classification of Numerical Spacetimes and Black-Hole-Binary Remnants1 , MANUELA CAMPANELLI, CARLOS LOUSTO, YOSEF ZLOCHOWER, Rochester Institute of Technology — In this paper we develop a technique for determining the algebraic classification of a numerical spacetime, possibly resulting from a generic black-hole-binary merger, using the Newman-Penrose Weyl scalars. We demonstrate these techniques for a test case involving a close binary with arbitrarily oriented spins and unequal masses. We find that, post merger, the spacetime quickly approaches Petrov type II, and only approaches type D on much longer timescales. These techniques allow us to begin to explore the validity of the “no-hair theorem” for generic merging-black-hole spacetimes.

1The authors acknowledge grant support from NSF and NASA.

1:42PM C11.00002 Binary Black Hole simulations using multi-block domains . ENRIQUE PAZOS, MANUEL TIGLIO, University of Maryland, LARRY KIDDER, Cornell University, OLEG KOROBKIN, Louisiana State University, MATT DUEZ, SAUL TEUKOLSKY, Cornell University — We present results from the simulation of equal mass binary black holes using a multiple block domain decomposition. Our scheme makes use of high-order finite difference operators, excision and the generalized harmonic formulation of Einstein’s equations. We are able to compute wave-forms and compare them with numerical solutions obtained by pseudo-spectral methods.

1:54PM C11.00003 Binary Black Hole Evolutions of Approximate Puncture Initial Data . TANJA BODE, The Pennsylvania State University, FRANK HERRMANN, University of Maryland, IAN HINDER, Max-Planck Institute fuer Gravitationsphysik, PABLO LAGUNA, DEIKDRE SHOEMAKER, Georgia Institute of Technology, BIRJOO VAISHNAV, University of Texas at Brownsville — We present a study of numerical evolutions using an approximate, i.e. constraint-violating, non-spinning, equal-mass binary black hole initial data as proposed by Faye et al. (2004). Analysis of the waveforms from this approximate initial data and that of the constraint-satisfying initial data shows a match larger than 0.97 for an initial separation of 10M, well within the match required for signal detection. We also demonstrate the differences in the evolution are due to negative Hamiltonian constraint violations in the neighborhood of the punctures. We show these constraint violations behave as negative energy/matter clouds which lead to a decrease in the masses of the black holes, affecting the dynamics of the binary system.

2:06PM C11.00004 Evolving Black Holes with Wavy Initial Data . BERNARD KELLY, NASA Goddard Space Flight Center, WOLFGANG TICHY, Florida Atlantic University, YOSEF ZLOCHOWER, MANUELA CAMPANELLI, Rochester Institute of Technology, BERNARD WHITTING, University of Florida at Gainesville — In Kelly et al. [Phys. Rev. D v. 76, 024008 (2007)], we presented new binary black-hole initial data adapted to puncture evolutions in numerical relativity. This data satisfies the constraint equations to 2.5 post-Newtonian order, and contains a transverse-traceless “wavy” metric contribution, violating the standard assumption of conformal flatness. We report on progress in evolving this data with a modern moving-puncture implementation of the BSSN equations in several numerical codes. We will discuss the effect of the new metric terms on junk radiation and continuity of physical radiation extracted.
Using nano-Hz gravitational waves. This talk will give an overview of this detection technique as well as discuss the various astrophysical phenomenon we will be able to study in a way never before possible. It turns out that observations of a set of exotic stars known as radio pulsars will enable us to detect and characterize nano-Hz gravitational wave observatory.

FREDRICK A. JENET, The Center for Gravitational Wave Astronomy, University of Texas at Brownsville

2:30PM C11.00006 Blandford-Znajek in binary black holes systems

CARLOS PALENZUELA, Max Planck Institute, Albert Einstein Institute, MATTHEW ANDERSON, Department of Mathematics, Brigham Young University, ERIC W. HIRSCHMANN, Department of Physics and Astronomy, Brigham Young University, LUIS LEHNER, Department of Physics and Astronomy, Louisiana State University, STEVE LIEBLING, Department of Physics, Long Island University–C.W. Post Campus, DAVID NEILSEN, Department of Physics and Astronomy, Brigham Young University — We investigate the behavior of electromagnetic fields influenced by the dynamics of a binary black hole system. In particular, our studies are tied to understanding the interaction between magnetic fields produced at a circumbinary disk in the late stages of the supermassive black hole merger.

2:42PM C11.00007 Characteristic-Cauchy code patching for a binary-black hole evolution

MARIA BABIUC, Marshall University — The methodology called Cauchy-Characteristic Extraction (CCE) utilizes Cauchy evolution within some prescribed timelike world-tube, but replaces the need for an outer boundary condition by matching to a characteristic evolution in the exterior of this world-tube. The Cauchy and the characteristic approaches have complementary strengths and weaknesses. Unification of the two methods seems to be a promising way of combining the strengths of both formalisms. At the boundary, since the coordinates of the Cauchy system are arbitrary while the coordinates of the characteristic system are based on the light-cone structure of space-time, a non-trivial coordinate transformation takes place when matching the characteristic and Cauchy evolution equations. The waveform extraction is carried out at some inner worldtube in order to avoid the errors introduced by the outer boundary treatment. This methodology has not yet been extended to the binary black hole problem, due to the errors introduced by the finite size and other geometrical properties of the extraction worldtube. This work investigates the steps involved in developing the algorithms and implementing it into a computational module that will perform the important task of patching a Characteristic code to a Cauchy evolution code, in the astrophysical realistic case of a binary black hole evolution, which have strong requirements for numerical accuracy and place greater demands on computational resources.

2:54PM C11.00008 Investigating Variational Integrators for Numerical Relativity

WILL FARR, MIT — We report on numerical simulations of simple general relativistic systems using variational integrators. Our variational integrators apply the stationary action principle to discretized versions of the Plebanski action for gravity to derive discrete evolution equations. The discrete action has (discrete) diffeomorphism and local Lorentz transformation symmetries; these symmetries generate discrete constraints which are analogous to the constraints of the continuous system. Because they are derived from the discrete action, the discrete evolution equations are discrete-constraint-preserving. We demonstrate this remarkable property in our simple simulations and discuss the issues involved in using this technique in larger, astrophysically-interesting simulations.

Session D5 GGR: Spanning the Gravitational Wave Spectrum

Saturday, May 2, 2009 3:30PM - 5:18PM

3:30PM D5.00001 Gravitational Wave Astrophysics using LIGO

VUK MANDIC, University of Minnesota — The field of gravitational-wave searches has entered a very exciting time. The LIGO gravitational-wave detectors have achieved unprecedented sensitivities and have recently completed a two-year long observation run. The data acquired during this run are being analyzed and are beginning to yield astrophysical implications. This includes searches for transient sources of gravitational-waves such as GRBs, searches for periodic sources such as pulsars, and searches for stochastic background of gravitational-waves which could be of cosmological or astrophysical origin. Moreover, the next generation ground-based gravitational-wave detectors are already being built. In this talk, I will describe the present status of the LIGO detectors, some of the most recent results obtained using LIGO data, and prospects for the next-generation gravitational-wave detectors.

4:06PM D5.00002 The Science and Technology of LISA

GUIDO MUELLER, University of Florida — LISA has long been recognized as an extraordinarily bold mission with an unprecedented huge discovery potential that can not be unlocked from ground or by any other space mission. LISA’s observations of gravitational waves in the 0.1mHz to 1Hz frequency range will allow us to study the astrophysics and evolution of black holes, of compact galactic binaries, and of the universe itself. LISA will provide precise measurements of the masses, spins, and luminosity distances of merging massive black holes (MBH) out to the borders of the visible universe. The details in the gravitational waves generated by compact stars falling into a MBH allow us to trace out space time in the strong field limit; the ultimate test of general relativity in an otherwise difficult to study regime. These extreme mass ratio inspirals as well as the MBH mergers will help to understand the evolution of MBHs found for example in the center of most galaxies. The luminosity distances together with red shift measurements from parallel electro-magnetic observations of the host galaxies will produce precise absolute distance measurements on cosmological scales. This enables us to calibrate the Hubble diagram out to red shifts of z=15 shining light on the properties of “dark energy” throughout the universe. The astrophysics, evolution, and density of ultra-compact objects such as white dwarfs, neutron stars, and stellar size black holes is another science area covered by LISA. LISA will resolve and measure the properties of several 100 individual binaries. In addition, several ten thousand mostly WD binaries will form a gravitational-wave background which contains information about the density of WD binaries in our galaxy. We will review the science case for LISA and will give a brief overview of the technology, and the status of the LISA project.

The author acknowledges the support he receives from NASA through grant 07ATFP07-0116.

4:42PM D5.00003 Pulsar timing and Gravitational Wave Detection: Building a galactic scale gravitational wave observatory

FREDRICK A. JENET, The Center for Gravitational Wave Astronomy, University of Texas at Brownsville — We are entering a new stage in astrophysics, the era of gravitational waves. The detection and study of such waves will allow us to see the universe in a way never before possible. It turns out that observations of a set of exotic stars known as radio pulsars will enable us to detect and characterize nano-Hz gravitational waves. This talk will give an overview of this detection technique as well as discuss the various astrophysical phenomenon we will be able to study using nano-Hz gravitational waves.

Session D11 GGR: Theoretical and Quantum Gravity

Saturday, May 2, 2009 3:30PM - 5:18PM

Plaza Court 1
3:30PM D11.00001 Unitarity and Holography in Gravitational Physics, DONALD MAROLF, UCSB — Because the gravitational Hamiltonian is a pure boundary term on-shell, asymptotic gravitational fields store information in a manner not possible in local field theories. This fact has consequences for both perturbative and non-perturbative quantum gravity. In perturbation theory about an asymptotically flat collapsing black hole, the algebra generated by asymptotic fields on future null infinity within any neighborhood of spacelike infinity contains a complete set of observables. Assuming that the same algebra remains complete at the non-perturbative quantum level, we argue that either 1) the S-matrix is unitary or 2) the dynamics in the region near timelike, null, and spacelike infinity is not described by perturbative quantum gravity about flat space. We also consider perturbation theory about a collapsing asymptotically anti-de Sitter (AdS) black hole, where we show that the algebra of boundary observables within any neighborhood of any boundary Cauchy surface is similarly complete. Whether or not this algebra continues to be complete non-perturbatively, the assumption that the Hamiltonian remains a boundary term implies that information available at the AdS boundary at any one time $t_1$ remains present at this boundary at any other time $t_2$.

3:42PM D11.00002 Causal Dynamical Triangulations, RAJESH KOMMU, University of California, Davis — An overview of the Causal Dynamical Triangulations (CDT) approach to quantum gravity is presented. CDT is a non-perturbative approach defined as a state sum over causal geometries. Some important results that have been obtained are presented and discussed, including the phase structure of the model, dimensionality of spacetime, etc.

3:54PM D11.00003 Gauge invariant observables in de Sitter, IAN MORRISON, University of California at Santa Barbara (UCSB) — The construction of gauge-invariant observables is a longstanding problem in quantum gravity. Cosmologically relevant spacetimes are a particularly interesting context in which to study such observables. Using the technique of group averaging we construct gauge-invariant observables in the case where spacetime is perturbatively global de Sitter. In the appropriate limit these observables reduce to local observables of quantum field theory; additionally, they reproduce the local observable algebra. Bounds on the locality of these observables are briefly discussed.

4:06PM D11.00004 Effective Four-Dimensional Actions in Braneworld Scenarios, JOLYON BLOOMFIELD, EANNA FLANAGAN, Cornell University — We discuss a general method to efficiently derive four dimensional effective actions from higher dimensional models with branes in a long wavelength limit, and discuss some specific applications to models that yield a coupling between dark energy and dark matter.

4:18PM D11.00005 Particle emission from a static black-hole on a tense codimension-2 brane, USAMA AL-BINNI, GEORGE SIOPSIS, University of Tennessee — The introduction of finite brane tension to the study of mini black-hole evaporation in braneworld models has been recently shown to modify possible observables that might be seen at the LHC. We present an analytical study of grey-body factors for Hawking radiation emitted by Schwarzschild black-holes localized on a tensional 3-brane in a 6-dimensional bulk. The calculations are done for low frequencies and for large imaginary frequencies for various types of perturbation, and the results are then compared with exact numerical results.

4:30PM D11.00006 Quantum Corrections to the Mass of a Black Hole coupled to $N$ scalars, MARTIN SCHADEN, Rutgers University - Newark — Einstein gravity coupled minimally or conformally to $N$ scalar fields has well-known static and spherically symmetric classical black hole solutions of Schwarzschild and extremal Reissner-Nordström type, respectively. These classical solutions depend on a single integration constant corresponding to their Schwarzschild radius $\mathcal{N}$. Assuming that this system can be considered in isolation and/or other mass scales may be neglected, the mass $m$ of such a configuration is of the form $m(N \sim \infty) = \frac{2\mathcal{N}R}{\mathcal{N}R + \frac{\mathcal{N}}{\ell}} + O(G\mathcal{N}^2/\mathcal{N}R^3)$, where $\mathcal{N} = \sqrt{Gc^2}$is the Planck length and $R$corresponds to the Schwarzschild radius for a single scalar.Only the first two terms of the expansion are relevant in the formal asymptotic limit of an infinite number of only gravitationally interacting scalars forming a black hole whose mass essentially is proportional to the number of degrees of freedom. The correction to the classical mass that is inversely proportional to $R$ may be interpreted as due to the change in vacuum energy caused by forming a black hole of radius $\mathcal{N}$, i.e. as a Casimir effect. The dimensionless constant $\chi$ describing this correction is estimated semi-classically using periodic orbit theory. The value (and sign) of $\chi$ in this approximation is determined by the unstable classical periodic orbits on the photon sphere of the black hole.

4:42PM D11.00007 Anisotropic Evolution of $D$-dimensional FRW Spacetime, CHAD MIDDLETON, Mesa State College — We examine the evolution of the $D$-dimensional Einstein field equations subject to a flat, anisotropic Friedmann-Robertson-Walker (FRW) metric. By choosing equations of state relating the 4- and d-dimensional pressures to the density, we obtain an expression relating the scale factors to an integration constant. For certain special cases, we obtain exact solutions to the field equations. When the integration constant is set to zero, we obtain the dynamical compactification scenario of Mohammadi et al. When the volume of the $D$-dimensional spacetime is held constant, we find a late-time accelerated expansion of the 4-dimensional Universe without a cosmological constant.

4:54PM D11.00008 Self Coupled Gravity: Another Approach to General Relativity, JAMES CRAWFORD, Penn State University — In 1960, Arnowitt, Deser, and Misner published a paper arguing (in the context of General Relativity) that if one includes the gravitational self-energy in the total energy of a point charge, the total energy is rendered finite. This paper is also discussed in Ashtekar’s book where he gives a more “simple-minded calculation.” Motivated by this work, I consider a “toy” field theoretic model of gravity where the static gravitational energy density is assumed to be in electrostatic form and where this (negative) energy density contributes as a gravitational source. In the case of a charged point particle, the additional gravitational energy density renders the total energy finite. In addition, the self coupling results in a non-Newtonian form for the gravitational field of a massive body, giving rise to perihelion precession. The amount of precession depends on the precise form of the relativistic force law, but for the theoretically reasonable choices it gives the same order of magnitude as the General Relativistic value. Finally, I comment on the form that a fully relativistic version (in particular, including time dependence) of this model should take, and rediscover, among other possibilities, the Einstein-Hilbert action. Work Supported in part by a grant from the Eberly Science Fund – Penn State Fayette.

5:06PM D11.00009 The Geometry of Time in General Relativity, ALEXANDER MAYER, Pritzker Fellowship — A conceptual model of special relativity that rests on relative temporal geometry motivated by H. Minkowski, rather than relative temporal rate motivated by H. Lorentz, provides a more robust intellectual foundation for the synthesis of special relativity with accelerated reference frames than Einstein’s perspective yielded in 1905-1915. Minkowski’s geometry implies local orthogonality of space and time dimensions for a freefalling reference frame; for an idealized region of “flat” spacetime devoid of gravitational influence, all local time coordinates associated with the neighborhood of all distinct points in space are parallel. Geometric deformation of spacetime due to the presence of mass implies that no two of these local time coordinates in the “curved” spacetime remain parallel. Relativistic effects between points in the gravitational field are most accurately described, both qualitatively and quantitatively, in terms of the relative angular displacement of local time coordinates associated with those points. In addition to relying general relativity, temporal geometry provides a means of calculating transverse gravitational redshift, a subtle relativistic gravitational effect implied by first principles that was previously overlooked in gravitational theory. Calculations (presented in Section E, Poster Session 1) accurately predict empirical observation of the effect.

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2 This work was supported by the NSF with Grant No. PHY0555580.
8:30AM G5.00001 Einstein Prize Talk: The Quantum Origin of Our Classical Universe. JAMES HARTLE, University of California, Santa Barbara — A striking feature of our indeterministic quantum universe is the wide range of time, place, and scale on which the deterministic laws of classical physics hold. This talk will describe the origin of this quasiclassical realm in a quantum cosmology based on Hawking's no-boundary quantum state of the universe. Classical spacetime is the key to the quasiclassical realm, and the no-boundary probabilities for different classical spacetimes lead to different predictions for cosmological observations today. In a simple model, these probabilities favor a minimum amount of matter, a long period of inflation, small fluctuations such as those seen in the CMB, but significant fluctuations away from homogeneity on very large scales. Probabilities will also be discussed of early properties such as whether the universe was singular or bounced at a small radius, and the direction of the arrow of time.

9:06AM G5.00002 Spin Foam models: models of quantum space time. LAURENT FREIDEL, Perimeter Institute — I will give an overview of spin foam models which describe the dynamics of quantum gravity in a background independent context. I will focus especially and the recent developments which concerns the construction of these models in 4 dimensional gravity and present some of the key results obtained in this context like the proof of the semi-classical limit and the relationship with loop quantum gravity and SU(2) spin network states.

9:42AM G5.00003 The Formulation of Quantum Field Theory in Curved Spacetime. ROBERT WALD, University of Chicago — The usual formulations of quantum field theory in Minkowski spacetime make crucial use of Poincare symmetry, positivity of total energy, and the existence of a unique, Poincare invariant vacuum state. These and other key features of quantum field theory do not generalize straightforwardly to curved spacetime. We discuss the conceptual obstacles to formulating quantum field theory in curved spacetime and how they can be overcome.

9:06AM G11.00004 Critical Gravitational Collapses in Neutron Star Like Systems. MEW-BING WAN, KE-JIAN JIN, WAI-MO SUEN, Department of Physics, Washington University in St Louis — We study the critical solution of neutron star like system previously found (Jin and Suen (2007)). In particular we show that the solution is a semi-attractor in the threshold plane separating the black hole phase and the neutron star phase. We find interesting space time and hydrodynamic properties of the solution.

9:18AM G11.00005 Spatially-Homogeneous Vlasov-Einstein Cosmology. JAMES FRIEDRICHSEN, Austin Community College, T. OKABE, P.J. MORRISON, L.C. SHEPLEY, UT Austin — The evolution of anisotropy in the Bianchi cosmological models, which are a set of spatially homogeneous solutions to the Einstein field equations classified by the three-dimensional Lie algebra which describes the symmetry group of the model, is studied due to the influence of matter as described by the Vlasov equation. The Einstein equations for the Bianchi models reduce to a set of coupled ordinary differential equations due to the spatial homogeneity of the models. The class A Bianchi models admit a Hamiltonian formulation in which the components of the metric tensor are the canonical coordinates. It is known that the evolution of anisotropy in the vacuum Bianchi models is determined by a potential due to the curvature of the model according to its symmetry. Matter potentials are obtained by first introducing a new matter action principle for the Vlasov equation in terms of a conjugate pair of functions and then enforcing the symmetry of the model in order to simplify the expression of the matter potential. The resulting expressions for the matter potential is given in terms of the phase space density, which is further simplified by the assumption of cold streaming matter. A qualitative difference is found in the dynamics of the non-trivial vacuum class A Bianchi models and the Bianchi Type I models with cold streaming Vlasov matter potentials that are analogous to the curvature potentials of the corresponding vacuum models.

9:30AM G11.00006 Quasilocal Energy of FRW Universe. MARCUS AFSHAR, University of California - Davis — The quasilocal energy of an arbitrary FRW model of the universe is calculated. The results have the correct behavior in the small-sphere limit. Higher order corrections are found when comparing these results to classical calculations of cosmological energy. This example is unique in that it involves a non-stationary spacetime. As previous definitions are inadequate, a more precise definition of quasilocal energy is provided to accommodate non-stationary spacetimes.
9:42AM G11.00007 Self-force in compact binaries using the effective field theory approach.
CHAD GALLEY, University of Maryland — We present our recent progress applying the effective field theory (EFT) approach to extreme mass ratio compact binaries (LISA sources) undergoing self-force from the backreaction of emitted gravitational waves. We focus our attention on the second order self-force on the small compact object and the corresponding emitted gravitational waves, which are both needed for doing precision gravitational wave astronomy with LISA. We also present recent work in applying the EFT approach to LIGO sources, time permitting.

9:54AM G11.00008 Gravitational Lorenz gauge self-force calculations in the time domain in 2+1D: progress report.
KRISTEN LACKEOS, University of Alabama in Huntsville, LEOR BARACK, University of Southampton, GAURAV KHANNA, University of Massachusetts Dartmouth, LIOR M. BURKO, University of Alabama in Huntsville — The goal of this project is to calculate the self force acting on a point particle in motion in the spacetime of a Kerr black hole. Already in vacuum the problem presents several challenges, e.g., gauge-condition violating unstable modes. We decompose the field into separable azimuthal \( m \)-modes, although for each \( m \)-mode all 10 fields are coupled. Individual \( m \)-modes of the metric perturbations diverge logarithmically (in the proper distance from the point particle), and practical regularization may be done using a “puncture function.” This approach has several advantages, e.g., the amenability to numerical solutions in the time domain, thus benefiting from experience gained by several groups in the numerical solution of linearized wave equations on a Kerr background, and the adaptability to more complex orbits, including generic ones. We first implement this program for the simpler context of circular orbits in Schwarzschild, without exploiting the spherical symmetry of the Schwarzschild background or the symmetry of the orbit. Instead, we construct the scheme so that generalizations to either more complex orbits or to Kerr spacetime are susceptible of implementation at later stages, and work in 2+1D. This talk is on work still ongoing.

10:06AM G11.00009 ABSTRACT WITHDRAWN

Sunday, May 3, 2009 10:45AM - 12:33PM
Session H11 GGR DAP: LISA Plaza Court 1

10:45AM H11.00001 The status, achievements, and prospects of the Mock LISA Data Challenges.
MICHELE VALLISNERI, Jet Propulsion Laboratory/Caltech, MOCK LISA DATA CHALLENGE TASKFORCE TEAM — For the last three years, many gravitational-wave analysts around the world have supported the Mock LISA Data Challenges (MLDCs), a program to demonstrate and encourage the development of LISA data-analysis capabilities, tools and techniques. In the MLDCs, a task force chartered by the LST periodically issues challenge data sets containing GW signals from sources of undisclosed parameters, embedded in synthetic LISA noise. Challenge participants have a few months to analyze the data and submit detection candidates, which are then compared with the sources originally injected in the data sets. In this talk, I review the milestones achieved in the first three MLDCs, and I describe Challenge 3 (for which, at the time of this meeting, we will have just received participant entries). I discuss how future challenge problems may broaden in scope from the technical analysis of LISA data to the investigation of LISA’s science objectives, and to a systematic characterization of the instrument effects that will affect data analysis.

10:57AM H11.00002 Massive Black Hole Mergers: Can we see what LISA will hear?1
JOAN CENTRELLA, NASA Goddard Space Flight Center, COLE MILLER, CHRIS REYNOLDS, University of Maryland, JAMES VAN METER, JOHN WISE, JOHN BAKER, NASA Goddard Space Flight Center, DARIAN BOGGS, University of Maryland, BERNARD KELLY, SEAN MCMILLIANS, NASA Goddard Space Flight Center — Coalescing massive black hole binaries are formed when galaxies merge. The final stages of this coalescence produce strong gravitational wave signals that can be detected by the space-borne LISA. When the black holes merge in the presence of gas and magnetic fields, various types of electromagnetic signals may also be produced. Modeling such electromagnetic counterparts requires evolving the behavior of both gas and fields in the strong-field regions around the black holes. We have taken a first step towards this problem by mapping the flow of pressureless matter in the dynamic, 3-D general relativistic spacetime around the merging black holes. We report on the results of these initial simulations and discuss their likely importance for future hydrodynamical simulations.

1 This work was supported in part by NASA grant 06-BEFS06-19, and the simulations were carried out at the NASA Center for Computational Sciences (Goddard Space Flight Center).

11:21AM H11.00004 Observing Merging Massive Black Hole Binaries with LISA.
JAMES THORPE, SEAN MCMILLIANS, JOHN BAKER, KEITH ARNAUD, NASA/GSFC — The Laser Interferometer Space Antenna (LISA) is expected to detect gravitational radiation from inspiraling and merging massive black hole binaries with large signal-to-noise ratios (SNRs). Observing these waveforms with large SNRs will allow physical parameters such as hole masses and spins, luminosity distance, and sky position to be measured. Two important questions are the ultimate precision of these measurements and the manner in which the precision increases with observation time. These qualities will affect LISA’s impact as an individual instrument as well as its potential for synergy with other instruments. We present estimates of LISA parameter errors for the special case of non-spinning black holes with an emphasis on the contribution of the late inspiral and merger portions of the waveform. This regime has only recently become accessible due to the success of numerical relativity in providing a precise description of the merger waveform.

11:33AM H11.00005 Applying numerical simulation results to LISA.
JOHN BAKER, BERNARD KELLY, SEAN MCMILLIANS, JAMES THORPE, NASA-Goddard Space Flight Center — Binary black hole systems are key observational targets of both ground- and space-based gravitational wave observatories. Interpretation of these observations depends on a detailed understanding of the gravitational radiation waveforms predicted by General Relativity. Advances in numerical relativity are leading to an increasingly rich understanding of the strong radiation generated in the final moments of these mergers. This knowledge can now be applied to answer questions of gravitational wave data analysis. Using the Effective-One-Body formalism together with ideas from an implicit rotating source characterization of numerical relativity waveforms, we construct a parameterized analytic waveform model representing the complete gravitational waveform. Then using standard data analysis techniques we apply this model toward an improved understanding of how well the Laser Interferometer Space Antenna (LISA) will be able to measure the astrophysical parameters of massive black hole mergers.

11:45AM H11.00006 Detection templates for extreme mass ratio inspirals: Is the radiative approximation sufficient?
EANNA FLANAGAN, Cornell University, TANJA HINDERER, Caltech — Gravitational waveform templates for generic extreme mass ratio inspirals, in the radiative approximation, are now nearly in hand. There has been some debate about whether such templates will suffice for signal detection. We describe computations of templates for general equatorial inspirals of a compact object into a Schwarzschild black hole, using as a toy model the geodesic equations supplemented with self-force terms taken from the Kidder-Will-Wiseman hybrid equations of motion. We compute the maximum phase error incurred by the omission of conservative self force terms during the last year of inspiral, as a function of initial eccentricity and of the binary masses, including optimizing over initial conditions, extending earlier work of Pound and Poisson. The phase errors are less than three cycles in all cases. Nevertheless, it is not clear that the radiative approximation will be sufficient for detection templates, for reasons which we describe.
12:09PM H11.00008 Black hole quasinormal mode spectroscopy with LISA. MANISH M. JADHAV, LIOR M. BURKO, University of Alabama in Huntsville — The signal–to–noise ratio (SNR) for black hole quasinormal mode sources of low–frequency gravitational waves is estimated using a Monte Carlo approach that replaces currently available methods that use all–sky averaging approximations and parameter fixing. We consider an eleven dimensional parameter space that includes both source and detector parameters. For the black–hole spin dependent radiation efficiency, η, we use recent numerical relativity results. We find that in the black–hole mass range \( M \approx 4\times10^6M_\odot \), the SNR is significantly higher than the SNR for the all–sky average case, as a result of the variation of the spin parameter of the sources. This increased SNR may translate to a higher event rate for the Laser Interferometer Space Antenna (LISA). We also study the directional dependence of the SNR, and show at which directions in the sky LISA will have greater response. We also identify the LISA “blind spots” for this type of sources.

12:21PM H11.00009 sdB binaries as gravitational-wave sources for LISA ¹, RAVI KUMAR KOPPARAPU, CGWP, Penn State, RICHARD WADE, Dept. of Astronomy, Penn State — We discuss binary systems containing hot subluminous dwarf B (sdB) stars as gravitational-wave (GW) sources for the proposed space-based detector LISA. “sdB” stars are core-helium burning systems with masses near 0.5 Msun, covered with thin hydrogen envelopes. They lie at the extreme blue end of the horizontal branch of the H–R diagram. They directly evolve to the white dwarf (WD) cooling sequence, avoiding the asymptotic giant branch. Observational evidence in some sdB binaries points to a WD or NS/BH companion, indicating that the short period systems could be potential low frequency (10^{-4} - 1 Hz) GW sources. Here, we first discuss different scenarios of forming sdB binaries, including the formation of a sdB+sdB system that can probably live long enough to be observable as a GW source. We also estimate the fraction of sdB+companion binaries that are detectable by LISA in our Galaxy, compared to a similar population of double-WD binaries.

¹This work was supported by the Center for Gravitational Wave Physics, which is supported by the National Science Foundation under cooperative agreement PHY 01-14375.

Sunday, May 3, 2009 1:30PM - 3:18PM –
Session J4 DAP GGR: Merging Galaxies  Plaza F

1:30PM J4.00001 Gas inflows in galaxy mergers as a key to the pairing, growth and formation of supermassive black holes. LUCIO MAYER, Institute for Theoretical Physics, University of Zurich — Galaxy mergers are known to deliver a large fraction of the interstellar gas of galaxies towards the inner few hundred parsecs. The large resulting gas concentrations are of paramount importance to understand the fueling of central supermassive black holes, and may determine the conditions under which a pair of such black holes can sink and coalesce at the center of the merger remnant following a burst of gravitational waves. However, for a long time direct calculations that model the gravitational, hydrodynamical and radiative processes involved had only been able to hint qualitatively at the phenomenon of gas inflows, mostly due to their limited resolution in the nuclear region. Here I review the results of recent state-of-the-art simulations performed with some of the largest parallel supercomputers available which have allowed to resolve scales of parsecs and below while the mergers of two galaxies takes place. I will show how the gas brought towards the central hundred parsecs produces a massive, star forming nuclear disk which compares well with recent observations of merger remnants in the nearby Universe. The numerical simulations demonstrate that a pair of supermassive black holes embedded in such nuclear disk can bind into binary on very short timescales, less than a million year. Whether the binary of supermassive black holes will easily be able to shrink down to the separation at which loss of energy via gravitational waves becomes the dominant process eroding its orbit is still under investigation. Moreover, in another calculation probing sub-parsec scales in the nuclear disk it is shown that more than a hundred million solar masses of gas can be transported to the inner parsec via torques driven by spiral instabilities. This strongly suggests not only that such disk torques are responsible for the fueling of supermassive black holes in galaxy mergers, but also that a massive black hole may form directly and rapidly from the collapse of a central gas cloud produced by the inflow. Direct, fast massive black hole formation may explain why bright quasars are seen to be in place already less than a billion year after the Big Bang.

2:06PM J4.00002 Black hole mergers along the cosmic history. MARTA VOLONTERI, University of Michigan — Galaxy mergers are an integral part of the structure evolution scenario. Massive black holes have inhabited the centers of galaxies since early cosmic times, when we detect them as the engines of luminous quasars. Mergers are therefore expected from the evolving population of massive black holes along the hierarchy of galaxy formation. I will discuss the expected properties of massive black hole mergers from early times to the present, and describe observational diagnostics that can shed light on the history of massive black holes.

2:42PM J4.00003 Probing Black Hole Mergers with LISA. ALBERTO VECCHIO, University of Birmingham — The Laser Interferometer Space Antenna (LISA) is a gravitational wave observatory in the frequency window 0.1 mHz - 0.1 Hz, capable of observing black hole mergers throughout the Universe. I will discuss the potential of LISA high-redshift surveys for novel studies of black hole demographics, formation of cosmic structures, cosmology and detailed investigations of the behaviour of gravity in the strong non-linear regime.
To determine the renormalized spin of a static field. We use a numerical matching procedure to remove the singular field to one additional order. Remarkably, only one term in a lengthy expression for the singular field contributes at this order, and that term coincides up to an overall factor (associated with a boost) with the perturbed Weyl scalar of a static field. We use a numerical matching procedure to remove the singular field to one additional order. Finally, following the procedure outlined in KFW (Phys Rev D, 75, 2007) we calculate the renormalized Hertz potential (from the renormalized Weyl scalar), and observe the effects of orbital motion in general SAV spacetimes. The results of a method to systematically check for higher order Killing tensors which may describe orbital motion in general SAV spacetimes are presented.

1 I gratefully acknowledge support from the Sherman Fairchild Foundation

2:30PM J11.00006 Characterizing particle orbits in general stationary axis-symmetric vacuum spacetimes1. JEANDREW BRINK, Caltech — Determining the nature of a central compact object in a highly curved spacetime, requires detailed knowledge of the orbital trajectories of probe particles within this spacetime. The Carter Constant fully characterizes the geodesic structure of the Kerr spacetimes making the computation of observational waveforms for extreme mass ratio inspirals (EMRI's) possible. In more general stationary axis-symmetric vacuum (SAV) spacetimes not much is known. The first results of a method to systematically check for higher order Killing tensors which may describe orbital motion in general SAV spacetimes are presented.

2 T. S. Keidl, J. L. Friedman, A. G. Wiseman, Phys. Rev. D, in press; gr-qc0611072

2:42PM J11.00007 Finding Fields and Self-Force in a Gauge Appropriate to Separable Wave Equations. TOBIAS KEIDL, University of Wisconsin–Washington County, JOHN FRIEDMAN, University of Wisconsin–Milwaukee, DONG-HOON KIM, Caltech, LARRY PRICE, ABHAY SHAH, University of Wisconsin–Milwaukee — Gravitational waves from the inspiral of a stellar-size black hole to a supermassive black hole can be accurately approximated by a point particle moving in a Kerr background. A procedure for finding the renormalized self-force from the Tukolosky equation has been outlined in the separate paper. This talk focuses on analytic work developed in this formalism and incorporating the l = 0 and l = 1 parts of the self-force. The self-force is calculated from either the renormalized spin +2 or the spin −2 Weyl scalar (ψļ or ψļ). The self-force can then be calculated algebraically from either renormalized Weyl scalar.

2:54PM J11.00008 Self-force for a particle in circular orbit around Schwarzschild black hole. ABHAY SHAH, JOHN FRIEDMAN, LARRY PRICE, University of Wisconsin, Milwaukee, TOBIAS KEIDL, University of Wisconsin, DONG-HOON KIM — This talk reports the successful computation of the self-force in the radiation gauge for a particle orbiting a Schwarzschild black hole. We find the renormalized spin-2 Weyl scalar for a particle in circular orbit in Schwarzschild geometry, subtracting from the retarded field an expression for the singular field to subleading order. Remarkably, only one term in a lengthy expression for the singular field contributes at this order, and that term coincides up to an overall factor (associated with a boost) with the perturbed Weyl scalar of a static field. We use a numerical matching procedure to remove the singular field to one additional order. Finally, following the procedure outlined in KFW (Phys Rev D, 75, 2007) we calculate the renormalized Hertz potential (from the renormalized Weyl scalar), from which one finds the renormalized perturbed metric and hence the conservative part of the self-force.

3:06PM J11.00009 Relativistic Images as Probe of Alternative Gravity. AMITAI BIN-NUN, University of Pennsylvania — In this presentation I consider the effects of RS-braneworld geometry on gravitational lensing observables. Findings show that the resolution needed to distinguish RS lensing from Schwarzschild lensing is expected to be obtainable in the next generation of VLBI arrays, but the expected magnitudes of these images present great challenges. Several approaches to finding observables are explored: 1) A straightforward calculation of relativistic image properties in several proposed RS gravity metrics. 2) Femtolensing of gamma-ray bursts from tiny braneworld primordial black holes, including effects from microlensing of relativistic images. Results are obtained using numerical solutions of the Virbhadra- Ellis lens equation and are compared with results obtained from approximations of the lens equation frequently used in the literature, confirming the validity of the approximations.

Sunday, May 3, 2009 3:30PM - 5:06PM —
Session L11 GGR: Binary Inspiral and Gravitational Wave Kicks Plaza Court 1
the computation of pieces of the forcing terms in the equations of motion which are currently unknown. It is powerful for developing physical intuition about the nonlinear dynamics of curved spacetime. Although our formalism is gauge-dependent, it is possible to explore momentum flow in such binaries, we explain the bobbing as due to an exchange of linear momentum between the holes and the surrounding, near-field curved spacetime. Using the Landau-Lifshitz pseudotensor in Maxwell-like form, we demonstrate that, when the holes are moving synchronously upward due to frame dragging and spin-curvature-coupling, the nearby curved spacetime contains an equal and opposite downward momentum, and conversely. Although our formalism is gauge-dependent, it is powerful for developing physical intuition about the nonlinear dynamics of curved spacetime.

Recent numerical-relativity simulations of binary-black-hole mergers have revealed large gravitational recoils. These results motivate us to explore the distribution and flow of linear momentum inside compact binaries. A powerful tool in our explorations is a formulation of the first post-Newtonian approximation to general relativity in a “gravitoelectromagnetic” Maxwell-like form that facilitates physical intuition. Relying heavily on work of Damour, Sofue and Xu, we have fleshed out this formulation, including all nonlinearities. We focus especially on density and flux of gravitational momentum, as expressed in terms of the Landau-Lifshitz pseudotensor, which we bring into forms that are almost identical to those for the electromagnetic field.

1 This work has been supported in part by NSF grants PHY-0601459 and PHY-0653653.

Momentum flow in numerical simulations of binary black hole mergers $^1$. GEOFFREY LOVELACE, Cornell University, MARK SCHEEL, ULRICH SPERHAKEN, YANBEI CHEN, DREW KEEPEL, DAVID NICHOLS, KIP THORNE, California Institute of Technology — Most research on extracting science from binary-black-hole simulations has adopted a “scattering matrix” perspective: given the binary’s initial parameters, what are the final hole’s parameters and the emitted gravitational waveform? In contrast, we are using binary-black-hole simulations to explore the nonlinear dynamics of curved spacetime. We use the Landau-Lifshitz pseudotensor to describe the density and flux of a binary’s linear momentum. Focusing on the head-on plunge, merger, and ringdown of a binary black hole with antiparallel spins, we explore numerically the momentum flow between the holes and the surrounding spacetime. To investigate the gauge dependence of our results, we compare simulations in different gauge, and we also compare our simulations with the Maxwell-like post-Newtonian approximation.

1 For support we would like to thank the Sherman Fairchild Foundation, the Brinson Foundation, and NSF grants PHY-0652952, PHY-0653677, PHY-0652929, PHY-0601459, PHY-0652905, DMS-055302 and NASA grants NNG05GG51G and NNG05GG52G.

Recoil velocities from black hole mergers using perturbation theory $^1$. A. SUNDARARAJAN, Massachusetts Institute of Technology, GAURAV KHANNA, University of Massachusetts, Dartmouth, SCOTT A. HUGHES, Massachusetts Institute of Technology — We measure the gravitational recoil for unequal-mass-black-hole-binary mergers with the smaller BH having a dimensionless spin $a^2 = 0.8$, and the smaller BH non-spinning. We choose our configurations such that, initially, the spins lie on the orbital plane. The spin and orbital plane precess significantly, and we find that the out-of-plane recoil (i.e., the recoil perpendicular to the orbital plane around merger) varies as $a^2/(1 + q)$, in agreement with our previous prediction, based on the post-Newtonian scaling.

We measure the recoil from black hole mergers using perturbation theory $^1$. We measure the gravitational recoil for unequal-mass-black-hole-binary mergers with the smaller BH having a dimensionless spin $a^2 = 0.8$, and the smaller BH non-spinning. We choose our configurations such that, initially, the spins lie on the orbital plane. The spin and orbital plane precess significantly, and we find that the out-of-plane recoil (i.e., the recoil perpendicular to the orbital plane around merger) varies as $a^2/(1 + q)$, in agreement with our previous prediction, based on the post-Newtonian scaling.

Progress in modeling of black hole binaries $^1$. JAMES VAN METER, JOHN BAKER, WILLIAM BOGGS, JOAN CENTRELLA, BERNARD KELLY, SEAN MCMILLANS, NASA/GSFC, NASA/GSFC TEAM — Frontiers of numerical studies of black hole binaries include large mass ratios, analysis of gravitational waveform-dependence on spin and comparison with analytic models, qualitatively new effects of large precession, precise calculation of spin, general analytic fitting of radiative recoil, and modeling of accreting matter. Results of simulations pertinent to these areas are presented, as well as some discussion of relevant numerical methods.

Transient resonances in the inspirals $^1$. TANJA HINDERER, California Institute of Technology, EANNA FLANAGAN, Cornell University — We show that the two body problem in general relativity in the highly relativistic regime has a qualitatively new feature: the occurrence of transient resonances. The resonances occur when the ratio of polar and radial orbital frequencies, which is slowly evolving under the influence of gravitational radiation reaction, passes through a low order rational number. The resonances make the orbit more sensitive to changes in the initial data (though not quite chaotic), and are genuine non-perturbative effects that are not seen at any order in the standard post-Newtonian expansion used for two body systems at large separation. Our results directly apply to an important potential source of gravitational waves, namely the gradual inspiral of compact objects into much more massive black holes. Exploring observations of these gravitational waves to map the spacetime geometry of black holes, we find that the orbit is contingent upon accurate theoretical models (templates) of the binary dynamics. At present, only the leading order in the mass ratio gravitational waveforms can be computed. Corrections to the waveform’s phase due to resonance effects scale as the square root of the inverse of the mass ratio and are characterized by sudden jumps in the time derivatives of the phase. We numerically estimate the net size of these corrections and find indications that the phase error is of order a few cycles for mass ratios $q \sim 10^{-4}$ but will be significant (of order tens of cycles) for mass ratios $q \sim 10^{-6}$. Computations of these corrections would improve the computational accuracy of the forcing terms in equations of motion which are currently unknown.

1 The authors acknowledge grant support from NSF and NASA.

3:30PM L11.00001 Modeling gravitational recoil from precessing highly-spinning unequal-mass black-hole binaries $^1$. CARLOS LOUSTO, MANUELA CAMPANELLI, YOSEF ZLOCHOWER, Rochester Institute of Technology — We measure the gravitational recoil for unequal-mass-black-hole-binary mergers with the smaller hole having a dimensionless spin $a^2 = 0.8$, and the smaller hole non-spinning. We choose our configurations such that, initially, the spins lie on the orbital plane. The spin and orbital plane precess significantly, and we find that the out-of-plane recoil (i.e., the recoil perpendicular to the orbital plane around merger) varies as $a^2/(1 + q)$, in agreement with our previous prediction, based on the post-Newtonian scaling.

1 The authors acknowledge grant support from NSF and NASA.
4:54PM L11.00008 A self-force primer for numerical relativists, STEVEN DETWEILER, JAN VEGA, University of Florida — A small mass $\mu$ moving about a much more massive black hole $M$ travels along a world line that is most easily described as being a geodesic of the perturbed metric $g_{\alpha\beta} + h_{\alpha\beta}$, where $h_{\alpha\beta} \sim O(\mu)$ is the metric perturbation suitably regularized at the location of the small mass. This motion is said to result from the gravitational self-force acting on $\mu$. A novel technique uses currently available methods of numerical relativity to calculate the regularized $h_{\alpha\beta}$, the self-force acting back on $\mu$, and the effects of the self-force on the gravitational waves being emitted in the context of extreme mass ratio inspiral.

Monday, May 4, 2009 10:45AM - 12:33PM – Session Q11 GGR GPMFC: Experimental Tests of Gravitation Plaza Court 1

10:45AM Q11.00001 Next Generation of Lunar Laser Ranging Instruments, STEPHEN MERKOWITZ, NASA Goddard Space Flight Center, David ARNOLD, PHILIP DABNEY, JEFFREY LIVAS, JAN MCGARRY, GREGORY NEUMANN, THOMAS ZAGWODZKI — Laser ranging over the past 40 years to retoreflector arrays placed on the lunar surface by the Apollo astronauts and the Soviet Luna missions have dramatically increased our understanding of gravitational physics along with Earth and Moon geophysics, geodesy, and dynamics. The precision of the range measurements has historically been limited by the ground station capabilities. With the A-PAROL instrument at the Apache Point facility in New Mexico achieving sub-centimeter level precision, future measurements are likely to be limited by errors associated with the Apollo retoreflectors. In addition, the clustering of the lunar arrays and similar latitudes of the available lunar ranging stations weakens our ability to precisely measure the lunar librations. Advanced retoreflectors placed at locations far from the Apollo sites would enable the study of additional effects, particularly those that rely on the measurement of the lunar librations. Active laser transponders are also under development that can provide a strong enough signal to enable the use of most of the more than 40 existing satellite laser ranging stations to make frequent range measurements, even during the daytime. We report here on a recent study of possible next generation lunar laser ranging instruments that will be ready for NASA's return to the Moon.

10:57AM Q11.00002 A WEP Test on a Sounding Rocket¹, ROBERT REASENBERG, BIJUNATH PATLA, JAMES PHILLIPS, Eugeniu POPSECU, SAO — We are developing a payloads for detecting a possible violation of the weak equivalence principle (WEP) while on a sounding rocket’s free-fall trajectory. We estimate an uncertainty of $10^{-16}$ from a single flight. The experiment consists of 8 drops, each lasting 40 s, of the two test mass assemblies (TMA). The instrument orientation will be reversed between successive drops, which reverses the signal but leaves most systematic errors unchanged. Each TMA consists of a pair of cubes connected by a short rod. The four cubes are in a square lying in a plane perpendicular to the symmetry axis (x axis) of the payload and close to its CM. At a distance of 0.3 m along the z axis, there is a highly stable plate that holds four of our tracking frequency laser gauges, which measure the distances to the cubes. The TMA are surrounded by capacitance plates, which allow both measurement and control of position and orientation. During the short night-time flight, the payload outside temperature drops slowly from around 300 K. Temperature stability of the instrument is essential and we can achieved it passively. This work was Supported in part by NASA grant NNX08AO04G.

¹Supported in part by NASA grant NNX08AO04G.

11:09AM Q11.00003 Testing Theories of Gravity Using Galactic Center Stars, DAVID MERRITT, Rochester Institute of Technology, SEppo MIKKOLA, Toru Observatory, Turku, CLIFFORD WILL, Washington University, St. Louis, TAL ALEXANDER, Weizmann Institute, Israel, STEPHEN FLANDRINE, University of Arizona — Stars orbiting very close to the supermassive black hole at the center of the Milky Way will experience precession of their orbital planes induced by relativistic frame dragging and by the quadrupolar gravity of the hole, at levels that are potentially observable using adaptive optics on the next generation of large ground-based telescopes. Astrometric observations of the orbits of at least two such stars can in principle lead to a determination of the angular momentum vector of the black hole and its quadrupole moment, allowing a test of the general relativistic no-hair theorem. We present the first relativistic N-body simulations of stellar motions around the Milky Way black hole and evaluate the degree to which orbital precession would be influenced by Newtonian perturbations from other stars and from compact stellar remnants.

11:21AM Q11.00004 Constraining Modified Gravity with SN 1987A, PHILLIP ZUKIN, EDMUND BERTSCHINGER, MIT — In the 1950's, Papapetrou found that extended bodies with spin, in general relativity, do not move along geodesics because of a spin-curvature coupling. Using an Eikonal approximation, we reproduce these results for Dirac and Majorana particles. We generalize these results to modified theories of gravity with a non-minimally coupled matter lagrangian and place constraints on the coupling field based on the arrival times of SN 1987A neutrinos.

11:33AM Q11.00005 Modification to the Luminosity Distance Redshift Relation in Modified Gravity Theories, ERAN ROSENTHAL, EANNA FLANAGAN, IRA WASSERMAN, Cornell — We derive an expression for the luminosity distance as a function of redshift for a flat Robertson-Walker spacetime perturbed by arbitrary scalar perturbations possibly produced by a modified gravity theory with two different scalar perturbation potentials. Measurements of the luminosity distance as function of redshift provide a constraint on a combination of the scalar potentials and so they can complement weak lensing and other measurements in trying to distinguish among the various alternative theories of gravity.

11:45AM Q11.00006 Relativistic Orbits in a Keplerian Limit, ANTONIO MONDRAGON, Colorado College — An approximate closed-form solution to the relativistic central-mass problem in a Keplerian limit is presented. This solution is limited to describing approximately elliptical (Keplerian) orbits, and provides orbital characteristics as relativistic corrections to the Keplerian orbits of classical mechanics. It is emphasized that (Schwarzschild) geometry alone predicts deviations from classical orbits, including precession, reduced radial coordinate, and increased eccentricity. The predicted rate of precession is in agreement with the established result, correctly describing precession of perihelia of the inner planets. Relativistic corrections to the radial coordinate and eccentricity are of the same order of magnitude as the rate of precession and may provide further verifications of general relativity. The results may also be applied to isolated binary systems.

11:57AM Q11.00007 ABSTRACT WITHDRAWN —
12:09PM Q11.00008 Bounds upon Graviton mass, and making use of the difference between Graviton propagation speed and HFGW transit speed to observe postNewtonian corrections to Gravitational potential fields, ANDREW BECKWITH — The author presents a post Newtonian approximation based upon an earlier argument / paper by Clifford Will as to why the revisions of gravitational potentials in part initiated by gravitons with explicit mass dependence in their Compton wave length. The Li-Baker detector, with its ultra refined capacity to observe HFGW signals is able to experimentally determine for HFGW empirical data sets which could determine upper bounds as to the existence of a graviton mass. Prior work with Clifford Will’s idea was stymied by the application to binary stars and other such astrophysical objects with non useful frequencies topping off as up to 100 Hertz, thereby rendering Yukawa modifications of Gravity due to gravitons effectively an experimental curiosity which was not testable with any known physics equipment. The appearance of HFGW data sets as could be measured by the Li Baker detector gives a real chance as to experimentally obtain a measurable upper bound to the Compton wave length of Gravitons, which leads to other tests as to Gravitons existence as a measurable quantity, contradicting Tony Rothman’s (2006) assertion that a detector the size of Jupiter would be needed to obtain measurements of a single graviton.

12:21PM Q11.00009 Search for Large Extra Dimensions via Observations of Neutron Stars with Fermi–LAT1, BLIAN BERENJI, ELLIOTT BLOOM, KIPAC-SLAC, Stanford University, REPRESENTING THE FERMI-LAT COLLABORATION — Large extra dimensions (LED) have been proposed to account for the apparent weakness of gravitation. These theories also indicate that the postulated massive Kaluza-Klein (KK) gravitons may be produced by nucleon-nucleon bremsstrahlung in the course of core collapse of supernovae. Hannestad and Raffelt have predicted energy spectra of gamma ray emission from the decay of KK gravitons trapped by the gravity of the remnant neutron stars (NS). These and other authors have used EGRET data on NS to obtain stringent limits on LED. Fermi-LAT is observing radio pulsar positions obtained from radio and x-ray catalogs. NS with certain characteristics are unlikely emitter of gamma rays, and emit in radio and perhaps x-rays. This talk will focus on the blind analysis we plan to perform, which has been developed using the first 2 months of all sky data and Monte Carlo simulations, to obtain limits on LED based on about 1 year of Fermi-LAT data. Preliminary limits from this analysis using these first 2 months of data will be also be discussed.

Monday, May 4, 2009 1:30PM - 3:18PM —
Session R5 GGR DAP COM CSWP: Women and Minorities in Multi-Messenger Astronomy of Gamma-Ray Bursts

1:30PM R5.00001 Gamma Ray Burst Observations with LIGO, LAURA CADONATI, University of Massachusetts, Amherst — A new era in gravitational wave astronomy is about to begin, as the LIGO and Virgo laser interferometers are preparing for the operation of enhanced detectors at unprecedented sensitivity. Right at the beginning of the observational era, most interesting science will come from multi-messenger observations, where the gravitational wave signal has an electromagnetic counterpart; in particular, Gamma Ray Burst searches have been the focus of LIGO searches since the early days of its data acquisition. Short Gamma Ray Bursts (GRBs) are believed to be produced in the merger of a neutron star binary or a neutron star-black hole binary, thus producing a gravitational wave signature that can be targeted with templated searches for compact binary coalescences. At the same time, sensitive, unmodeled burst searches are also implemented to cover other possible models for both short and long GRBs. Information on the progenitor (time, source location) is used to increase the sensitivity of the search and, in the event of a detection, confidence in the result. For close events, as in the case of GRB070201, even the absence of a detection yields useful insights in the physics of GRBs. In this talk I will review LIGO’s effort for the observation of Gamma Ray Bursts, with methods, interpretations and prospects, in the upcoming era of Enhanced and Advanced LIGO.

2:06PM R5.00002 The Progenitors of Short Gamma-Ray Bursts, ENRICO RAMIREZ, University of California Observatories — Recent years have witnessed dramatic progress in our understanding of short gamma-ray burst (SGRB) sources. There is now general agreement that SGRBs — or at least a substantial subset of them — are capable of producing directed outflows of relativistic matter with a kinetic luminosity exceeding by many millions that of active galactic nuclei. Given the twin requirements of energy and compactness, it is widely believed that SGRB activity is ultimately ascribable to a modest fraction of a solar mass of gas accreting onto a stellar mass black hole or to a precursor stage whose inevitable end point is a stellar mass black hole. Astrophysical scenarios involving the violent birth of a rapidly rotating neutron star, or an accreting black hole in a merging compact binary driven by gravitational wave emission are reviewed, along with other possible alternatives.

2:42PM R5.00003 Neutrino Messages from Gamma Ray Bursts, IGNACIO TABOADA, Georgia Institute of Technology — The mystery of where and how Nature accelerates the highest energy cosmic rays (up to 10^{20} eV) is still unresolved a century after their discovery. Energetics considerations predict a modest fraction of a solar mass of gas accreting onto a stellar mass black hole or to a precursor stage whose inevitable end point is a stellar mass black hole. Astrophysical scenarios involving the violent birth of a rapidly rotating neutron star, or an accreting black hole in a merging compact binary driven by gravitational wave emission are reviewed, along with other possible alternatives.

Monday, May 4, 2009 1:30PM - 3:18PM —
Session R11 GGR DAP: Gravitational Wave Astrophysics

1:30PM R11.00001 Gravitational Waves from Convection, the Standing-Accretion-Shock Instability and the Onset of Explosion in Core-Collapse Supernovae, CHRISTIAN D. OTT, TAPIR, Caltech, JEREMIAH W. MURPHY, Astronomy Dept., University of Washington, ADAM BURROWS, Dept. of Astrophysical Sciences, Princeton University — We present new results on the gravitational wave (GW) emission in the postbounce phase of nonrotating or slowly rotating core-collapse supernovae obtained from an extensive set of simulations with the 2D code BETHE/Hydro. Our calculations include the most recent presupernova stellar models, a finite-temperature nuclear equation of state and a prescription for neutrino cooling and heating. Investigating the postbounce evolution of progenitors of 12, 15, 20, and 40 solar masses with multiple parametrized neutrino luminosities, we for the first time establish the systematics with progenitor star mass and neutrino luminosity of the GW signal emitted by neutrino-driven convection and the standing-accretion-shock instability. In addition, we identify the GW signal associated with the onset of a neutrino-driven core-collapse supernova explosion.

1Support for this work was provided through a NSF Astronomy and Astrophysics Postdoctoral Fellowship (J.W.M.) and a Caltech Sherman Fairchild Prize Fellowship (C.D.O.)
1:42PM R11.00002 Gravitational Waves from Core Collapse Supernova: Simulations with CHIMERA, KONSTANTIN YAKUNIN, STEPHEN BRUENN, PEDRO MARRONETTI, Florida Atlantic University — We perform numerical simulations of Core Collapse Supernova using the multi-dimensional hydrodynamics code CHIMERA that includes a realistic nuclear networks, spectral neutrino transport, approximate GR, and a realistic EOS. Gravitational wave signals from different progenitor stars (12, 15, 20 and 25 solar masses) generated by both matter and neutrinos will be presented. We compare our results with other groups and analyze some features of the core-collapse supernova mechanism. These GW templates can be used to enhance the search for supernovae signals in current and future laser-interferometric gravitational wave detectors.

1:54PM R11.00003 Extracting equation of state parameters from inspiral waveforms1, JOHN L. FRIEDMAN, University of Wisconsin-Milwaukee, JOCELYN READ, Albert Einstein Institute, HARRIS MARKAKIS, University of Wisconsin-Milwaukee, MASARU SHIBATA, University of Tokyo, KOJI URYU, University of the Ryukyus, JOLIEN CREIGHTON, KEISUKE TANIGUCHI, University of Wisconsin-Milwaukee — In this and a companion talk by Markakis, we report the results of first studies that use numerical simulations of binary inspiral to estimate the accuracy with which gravitational wave observations of binary inspiral can determine parameters of the neutron-star equation of state. We use a parameterized equation of state (previously obtained in work with B.D. Lackey and B.J. Owen) based on piecewise polytropes. The EOS is chosen to make the number of parameters smaller than the number of neutron-star properties that have been measured or will have been measured in the next several years and large enough to accurately approximate the large set of candidate EOSs. Knowing the mass of the neutron star(s) in a neutron-star-neutron-star or neutron-star-black-hole binary allows one to use the inspiral waveform to reduce the equation-of-state parameter space by one dimension; the EOS is restricted to a surface associated with the measured departure from point-particle waveform. We estimate the accuracy with which one can extract a parameter transverse to that surface and the accuracy with which one can estimate neutron star radius.

1This work was supported in part by NSF grants PHY-0503366, PHY-0701817 and PHY-0200852, and by NASA grant ATP03-0001-0027.

2:06PM R11.00004 The Neutron Star Equation of State and Gravitational Wave Observations1, CHARALAMPOS MARKAKIS, JOCELYN S. READ, University of Wisconsin Milwaukee, MASARU SHIBATA, University of Tokyo, KOJI URYU, University of the Ryukyus, Okinawa, Japan, JOLIEN D. E. CREIGHTON, JOHN L. FRIEDMAN, University of Wisconsin Milwaukee — Properties of the neutron star equation of state can potentially be measured via gravitational wave observations, by measuring departures from the point-particle limit of the waveform produced in the late inspiral of a neutron star binary. Numerical waveforms from simulations of inspiraling neutron star binaries, computed for equations of state with varying stiffness, are compared. As the stars approach their final plunge and merger, the gravitational wave phase accumulates more rapidly for smaller values of the neutron star compactness. This suggests that gravitational wave observations at frequencies around ~1 kHz will be able to measure a compactness parameter and constrain the possible neutron star equations of state.

1Supported by Grant No. PHY0503366, NASA Grant No. NNG05GB99G.

2:18PM R11.00005 The Breaking Strain of Neutron Star Crust and Continuous Gravitational Wave Radiation, C.J. HOROWITZ, Indiana University, K. KADAU, LANL, J. HUGHTO, D.K. BERRY, Indiana University — Mountains on rapidly rotating neutron stars efficiently radiate gravitational waves. The maximum possible size of these mountains depends on the breaking strain of neutron star crust. We use large scale molecular dynamics simulations of Coulomb solids to determine the breaking strain. We find that the breaking strain of small single crystals is very large and that this strength is only modestly reduced by impurities, defects, and grain boundaries. Therefore, neutron star crust is likely very strong and can support mountains large enough so that their gravitational wave radiation could limit the spin periods of some stars and might be detectable in large scale interferometers.

2:30PM R11.00006 Astrophysics with gravitational-wave measurements of binary compact object mass distributions1, RICHARD O’SHAUGHNESSY, Pennsylvania State University, CHRIS VAN DEN BROECK, Cardif, CHRIS BELCZYNSKI, New Mexico State University; Los Alamos National Lab — Future gravitational wave detectors (advanced LIGO; Virgo) will detect tens of peak star formation (z ∼ 4). “Gravitational-wave tomography” will be possible, providing data products including a map of the low-redshift universe as seen in binaries and a redshift-dependent mass distribution. We describe how future detectors could use this information to provide astrophysically precise constraints on our understanding of CBC formation.

1ROS supported by NSF PHY 06-53462 and the Center for Gravitational Wave Physics.

2:42PM R11.00007 Estimating the parameters of non-spinning binary black holes using ground-based gravitational-wave (GW) detectors: Statistical errors1, SUKANTA BOSE, Washington State University, P. AJITH, California Institute of Technology — We assess the statistical errors in estimating the parameters of non-spinning black-hole binaries using ground-based GW detectors and discuss their cosmological implications. While past assessments were based on partial information provided by only the inspiral and / or ring-down pieces of the coalescence signal, our projections use “complete” inspiral-merger-ringdown waveforms, and employ the Fisher-matrix formalism, vetted by Monte-Carlo simulations. Parameter accuracies of the complete waveform are found to be significantly better than those of just the inspiral waveform. In the Advanced LIGO detector, parameter estimation is the most accurate in the total-mass range M ≈ 100 – 200M⊙. For M ≈ 100M⊙ systems, the errors in measuring M and the mass-ratio are reduced by an order of magnitude or more compared to waveforms of the inspiral phase alone. Moreover, for M ≈ 100M⊙ systems at distances of 1 Gpc, we estimate that an Advanced LIGO-Virgo type network is capable of determining the sky-position with an accuracy of from about 0.01 square-degree to a square-degree, with a mean of nearly 0.1 square-degree. The sky-averaged fractional error in its distance is about 20%.

1Supported in part by the NSF grants PHY-0239735 and PHY-0758172.
2:54PM R11.00008 Distinguishing GRB progenitors: An application of Maximum Entropy Gravitational-wave Data Analysis

RUXANDRA BONDARESCU, RAVI KUMAR KOPPARAPU, LEE SAMUEL FINN, Pennsylvania State University, TIFFANY SUMMERSCALES, Andrews University — What are the progenitors of short duration Gamma Ray Bursts (GRBs)? Theory predicts a variety of short GRB models with Neutron Star - Neutron Star binary mergers and the tidal disruption of a neutron star by a black hole being the most favored scenarios. Will the emitted gravitational radiation help in distinguishing between different types of progenitors? Can the gravitational radiation emitted by a long duration GRB source be confused with that from a short GRB source? How do we differentiate between the different sources in noisy detector data? To answer some of these questions, we use maximum entropy analysis for a network of gravitational-wave detectors, such as LIGO or VIRGO, and recover simulated burst waveforms from noisy data. The efficiency with which we recover the waveforms is computed by cross-correlating with simulated core-collapse and mergers waveforms. We also estimate how strong a gravitational-wave signal needs to be, before we can distinguish between different types of progenitors.

This work is supported by NSF grants PHY 03-26281, PHY 06-00953 and PHY 06-53462 and by the Center for Gravitational-Wave Physics (NSF grant PHY 01-14375).

3:06PM R11.00009 Using Gravitational Wave Pulsar Observations to measure electron column density

SHANE LARSON, Utah State University, SETH TIMPANO, CGWP, Penn State — For binaries whose sky position, orientation, and chirp mass $\mathcal{M}_c$ are known, the observed gravitational wave amplitude of the binary system is a direct measure of the distance to the binary. In a similar spirit, the distance to radio pulsars can be inferred from pulsar observations from the dispersion measure, the integrated column density of electrons along the line of sight to a pulsar that causes an observational broadening of a radio pulse. This talk considers a multi-messenger observation of galactic binary systems that contain a pulsar component detectable in the electromagnetic spectrum, and a detectable gravitational wave signal, and demonstrates how the two independent distance measures can be used to measure the electron column density along the line of sight to the pulsar.

Monday, May 4, 2009 3:30PM - 5:18PM
Session T5 GGR: Precision Measurements in Gravity Governor’s Square 15

3:30PM T5.00001 Beyond the quantum limit in gravitational wave detectors

NERGIS MAVALVALA, Massachusetts Institute of Technology — The sensitivity of current and next generation interferometric gravitational wave detectors is limited by the quantum properties of the laser light. The quantum noise can be manipulated to improve the sensitivity of gravitational wave detectors in a variety of ways, one of the most promising being injection of squeezed states of the electromagnetic vacuum field into the output port of the interferometer. I will describe recent progress toward and future prospects for sub-quantum noise limited operation of gravitational wave detectors.

4:06PM T5.00002 LISA Pathfinder: testing the limits of pure geodesic motion for gravitational wave observation in space

WILLIAM WEBER, University of Trento and INFN — Placing a gravitational reference test mass in nearly perfect geodesic motion, without any perturbing forces, is a critical problem for space-based gravitational wave detection and for a wide class of precision gravitational measurements. For the Laser Interferometer Space Antenna (LISA), high resolution observation of gravitational radiation from distant coalescing massive black holes will require that the geodesic reference test masses that serve as interferometry end mirrors be in free-fall to within a residual acceleration noise of order femto-m / s^2 / \sqrt{\text{Hz}} at frequencies near 0.1 mHz. The LISA Pathfinder mission, scheduled for launch by ESA and NASA in 2010, aims to demonstrate geometric purity for a LISA-like test mass inside a co-orbiting spacecraft at a level approaching this LISA free-fall goal. In this talk, I will discuss the LISA Pathfinder flight experiment and what we have learned, in ground-based preparations for the mission, about the limits of free-fall that are relevant to gravitational wave detection and to other precise small force measurements.

4:42PM T5.00003 The Gravity Recovery and Climate Experiment (GRACE) — Measuring Climate Change via Gravity

MICHAEL WATKINS, California Institute of Technology, Jet Propulsion Laboratory — The joint NASA/DLR GRACE mission is a pioneering project launched in 2002 to measure large-scale mass redistribution on the Earth through precise satellite-satellite microwave tracking. Using dual frequency K and Ka band microwave carrier phase tracking between the two spacecraft to obtain 5 second Doppler normal points with \~100 nanometer/second precision, and coupled with precision accelerometers on board each spacecraft, mass changes equivalent to 1 cm of water over regions a few hundred km in spatial extent can be mapped each month over the entire Earth. These monthly GRACE mass maps have provided an astonishing amount of previously poorly known (or unknown) aspects of large scale climate related phenomena, including mass loss rates in Greenland, Antarctica, Alaska, Arctic ocean circulation, water storage in major river basins, pan-Arctic river discharge, and much more. In this talk, we will discuss the design challenges and engineering approaches for GRACE, the current state-of-the-art science results, and look at approaches for improved follow-on missions, including the use of laser interferometry closely related to that envisioned for LISA.

In collaboration with Srinivas Bettadpur, University of Texas Center for Space Research and William Folkner, California Institute of Technology, Jet Propulsion Laboratory.

Monday, May 4, 2009 3:30PM - 5:18PM
Session T11 GGR: Neutron Star and Black Hole Binary Simulations Plaza Court 1

3:30PM T11.00001 Black Hole - Neutron Star Binary Simulations at Georgia Tech

ROLAND HAAS, Georgia Institute of Technology — Mixed compact object binaries consisting of a black hole and a neutron star are expected to be not only one of the primary sources of gravitational radiation to be observed by interferometric detectors but also the central engine of short gamma-ray bursts. We report on the status of our effort at Georgia Tech to model these mixed binary systems using the moving puncture method. The results are obtained with an enhanced version of our vacuum MayaKranc code coupled to the hydrodynamics Whisky code. We present preliminary results of gravitational waveforms and the disruption of the neutron star for simple polytropic equations of state.
3:42PM T11.00002 A new numerical method for the construction of binary neutron star initial data\textsuperscript{1} , WOLFGANG TICHY — We present a new numerical method for the generation of binary neutron star initial data using the Wilson-Mathews or conformal thin sandwich approach. Our method uses six different computational domains, which include spatial infinity. Each domain has its own coordinates which are chosen such that the star surfaces always coincide with domain boundaries. We use an efficient pseudospectral method to solve the elliptic equations associated with the conformal thin sandwich approach. The main purpose is to introduce our new method and to present code tests for several different configurations.

\textsuperscript{1}This work was supported by NSF grant PHY-0652874.

3:54PM T11.00003 Simulations of Black Hole-Neutron Star Binaries , FRANCOIS FOUCART, MATTHEW DUEZ, LAWRENCE KIDDER, Cornell University, HARALD PFEIFFER, MARK SCHEEL, California Institute of Technology, SAUL TEUKOLSKY, Cornell University — We present our latest simulations of the inspiral and merger of black hole-neutron star binaries. Our evolutions use the two-grid approach: the Einstein equations are solved in generalized harmonic coordinates using pseudospectral methods, while the relativistic fluid equations are evolved on a separate grid using shock-capturing finite difference techniques. We explore the effects of different mass ratios, black hole spins, and neutron star equations of state on the behavior of the binaries. We extract gravitational waveforms from the simulations and observe for some binary parameters the formation of a long-lived accretion disk.

4:06PM T11.00004 Neutrino Transport in General Relativistic Neutron Star Evolutions , PEDRO MARRONETTI, STEPHEN BRUENN, Florida Atlantic University — Binary neutron star and neutron star / black hole mergers will only be accurately modeled when all the key microphysics is included: magnetic fields, photon and neutrino radiation and nuclear networks, all of which should be implemented in a full GR algorithmic infrastructure. Great progress has been made recently with the addition of MHD to current numerical full-GR codes. On the other hand, the addition of neutrino transport to the simulations has yet to be explored. Neutrino radiation is an essential part of state-of-the-art core collapse supernova simulations, where it has shown to have a preponderant role in the production of the corresponding explosions. While this seems to indicate that neutrino interactions might play an important role in compact object mergers too, this still remains poorly understood. I will report on progress made on the implementation of neutrino transport to our code GRHyd and the different approaches to the task.

4:18PM T11.00005 Evolutions of Magnetized Neutron Stars , STEVEN LIEBLING, Long Island University, MATTHEW ANDERSON, ERIC HIRSCHMANN, Brigham Young University, LUIS LEHNER, Louisiana State University, PATRICK MOTL, Indiana University Kokomo, DAVID NEILSEN, Brigham Young University, CARLOS PALENZUELA, AEI, JOEL TOHLINE, Louisiana State University — Magnetized neutron stars, whether considered individually or within compact binary systems, demonstrate a number of interesting dynamical effects and may represent an important source of observable gravitational waves. In addition, isolated, rotating, magnetized stars serve as a good testbed for a necessarily complex, distributed adaptive mesh refinement (AMR) code. As initial data, we use fully consistent, magnetized, rotating stellar configurations generated with the Lorene toolkit. Here results are presented which (i) demonstrate convergence and stability of the code, (ii) show the evolution of stable and unstable magnetized stars, and (iii) study the effects of a scheme to track the leakage of neutrinos.

4:30PM T11.00006 Magnetic field effects on non-vacuum binaries , MATTHEW ANDERSON, ERIC HIRSCHMANN, Brigham Young University, LUIS LEHNER, Louisiana State University, STEVEN LIEBLING, Long Island University, PATRICK MOTL, Indiana University Kokomo, DAVID NEILSEN, Brigham Young University, CARLOS PALENZUELA, Albert Einstein Institut, JOEL TOHLINE, Louisiana State University — Observational evidence suggests that sizeable magnetic fields are present in a fair number of neutron star binaries and neutron star-black hole binaries. These magnetic fields can have a strong influence on the fluid’s dynamics, the energetics of the system and even the production of gravitational radiation. We present results of non-vacuum binary neutron star and black hole–neutron star collisions and examine the influence of magnetic fields on the gravitational waves, fluid structure and dynamical behavior of the system.

4:42PM T11.00007 General Relativistic Simulations of Black Hole-Neutron Star Mergers: Effects of Black-Hole Spin , ZACHARIAH ETIENNE, YUK TUNG LIU, STUART SHAPIRO, University of Illinois at Urbana-Champaign, THOMAS BAUMGARTE\textsuperscript{1}, Bowdoin College — Binary black hole-neutron star (BHNS) binary mergers are candidate engines for both short-hard gamma-ray bursts and detectable gravitational radiation. Using our most recent conformal thin-sandwich BHNS initial data and our fully GR hydrodynamics code, which is now AMR-capable, we are able to simulate these binaries accurately through inspiral, merger, and ringdown. We explore the effects of BH spin (aligned and anti-aligned with the orbital angular momentum) by evolving binaries with BH-NS mass ratio $q = 3$ that are nearly identical, except the BH spin is varied between $a/M_{BH} = -0.5$ (anti-aligned) to 0.75. The number of orbits before merger increases with $a/M_{BH}$. We also study the nonspinning BH case in depth, varying $q$ between 1, 3, and 5. Gravitational waveforms are calculated and compared to binary BH waveforms. Only a small disk ($\lesssim 0.01 M_{\odot}$) forms for the anti-aligned spin case ($a/M_{BH} = -0.5$) and for the largest mass ratio case ($q = 5$). By contrast, a massive ($M_{a=0.75} \approx 0.2 M_{\odot}$), hot disk forms in the rapidly spinning $a/M_{BH} = 0.75$ aligned BH case. Such a disk could drive a SGRB, possibly by, e.g., producing a copious flux of $\nu - \bar{\nu}$ pairs.

\textsuperscript{1}Also at University of Illinois at Urbana-Champaign.

4:54PM T11.00008 Multipolar analysis of a binary black hole merger , ROBERT OWEN, Cornell University — A definition of source multipoles, applicable on dynamical horizons, is given and applied to studying the ringdown of the remnant of a binary black hole merger. With this method, it is shown in detail that the angular structure of the accreting black hole is the same as that of a Kerr horizon of the same mass and spin.

5:06PM T11.00009 Null Geodesics as a Tool to Analyze Properties of Spacetimes in Numerical Relativity , RANDY WOLFMeyer, University of Wisconsin-Milwaukee, JIAN TAO, Louisiana State University-Baton Rouge, HUI-MIN ZHANG, WAIMO SUEN, Washington University in St Louis — We analyze the properties of a spacetime in terms of measurable physical quantities through the construction of null geodesics. The technique enables the comparison of spacetimes independent of the choices of time slicings and spatial coordinates used in the numerical construction. We apply the technique to study the accuracy of the quasi-equilibrium approximation of neutron star binaries. The phase of the inspiraling binary as observed at infinity and the distance between the two stars are constructed with null geodesics. We determine the minimum separation required for the quasi-equilibrium conformally flat assumptions to yield astrophysically realistic initial data for irrotational binary neutron star systems.

Tuesday, May 5, 2009 10:45AM - 12:33PM —
Session W6 DCOMP GGR: Numerical Simulations of Coalescing Compact Objects: Black Holes and Neutron Stars Governor’s Square 16
10:45AM W6.00001 Numerical Relativity: A critical new tool for astrophysics
Yosef Zlochower, Rochester Institute of Technology — The past few years have seen a renaissance in Numerical Relativity that has transformed the field into a critical tool for studying astrophysical systems. Researchers around the world have made many important new discoveries in the evolution of black-hole systems. In this talk I will describe many of the results that a few years ago seemed impossible to obtain, including unexpectedly large recoil kicks, modeling of the remnant masses and spins, post-Newtonian / NR comparisons, highly-accurate long-term evolutions, explorations of mathematical structure of remnant spacetimes, and N-black-hole merger scenarios.

Yuk TunG Liu, University of Illinois at Urbana-Champaign — Black hole-neutron star (BHNS) mergers are expected to be among the leading sources of gravitational waves observable by ground-based detectors, and may be progenitors of short-hard gamma-ray bursts (SGRBs). BHNS merger simulations in full general relativity represent the ultimate challenge of compact binary evolution: they involve all of the complications of relativistic hydrodynamics, including shocks, in a strong dynamical field, together with all of the hurdles of evolving moving black holes without encountering their spacetime singularities. In this talk, I will review the numerical techniques used by various groups to simulate BHNS binaries through inspiral, merger and ringdown. I will discuss the effects of binary mass ratio, black-hole spin, and neutron star compaction on the final outcomes of the mergers, and the implications on the gravitational wave and SGRB physics. Finally, I will discuss the possibility of simultaneous detections of gravitational waves and SGRBs, and what we could learn from these detections.

11:57AM W6.00003 Modelling the Inspiral and Merger of Binary Neutron Stars
Luciano Rezzolla, Albert Einstein Institute, Max-Planck Inst. for Gravitational Physics — Investigating the final evolution of neutron stars binaries promises to be particularly rewarding. These systems are in fact excellent sources of gravitational waves, they are thought to behind the powerful engines powering short gamma-ray bursts, and they can unveil the behaviour of matter at extreme densities and temperatures. I will review the present understanding in the modelling the inspiral and merger of binary neutron stars in full general relativity, underlining the considerable recent progress, but also highlighting the potential pitfalls that can be encountered when studying these systems.

Tuesday, May 5, 2009 10:45AM - 12:21PM —
Session W11 GGR DAP: Data Analysis Techniques for Ground-Based Gravitational Wave Interferometers Plaza Court 1

10:45AM W11.00001 Exploring Use of NR Waveforms in Burst Analyses of BBH Mergers
Deirdre Shoemaker, Georgia Tech, Laura Cadonati, UMass Amherst, Shourov Chatterji, Caltech, Sebastain Fischetti, Satyanarayan Mohapatra, UMass Amherst — Gravitational wave ground-based detectors and numerical-source codes are individually performing at a top-notch level. We explore the added benefit to the detection and understanding of gravitational wave sources made possible by joining the expertise of numerical relativists and data analysts in addressing the question of what is the most effective role for numerical relativity (NR) waveforms in the detection and characterization of binary black hole (BBH) coalescence. We present a study of detection systematics using waveforms produced by the MayaKranc code that are added to simulated, colored, Gaussian noise and analyzed with the unmodeled burst search algorithm Omega (also used in LIGO-Virgo burst searches). Detection efficiency and parameter accuracy are systematically weighted against parameters such as spin and mass ratio as well as numerical details such as waveform accuracy, the number of included modes and extraction radius. These detection systematics are mapped to numerical and physical choices in NR to determine the effectiveness of numerical waveforms in burst analysis.

1Authors acknowledge NSF grants PHY-0653550 and PHY-0653443.

10:57AM W11.00002 TwoSpect: an all-sky search for continuous gravitational waves from neutron stars in binary systems
Evan Goetz, Keith Riles, University of Michigan — An all-sky search for continuous gravitational waves from binary pulsars is notorious for its computational challenge. We present a new hierarchical method called TwoSpect, which we propose for such a search. The search exploits the periodic orbital modulations of the source waves by searching for patterns in doubly-Fourier-transformed data. The algorithm will be described and sensitivity estimates presented.

11:09AM W11.00003 delayRatio: A Gravitational Wave Event Physical Likelihood Estimator Based on Detection Delays and SNR Ratios
Amber Stuver, California Institute of Technology/LIGO Livingston — delayRatio is an efficient physical likelihood estimator which is designed to be used as part of a candidate coincident burst/inspiral gravitational wave event follow-up investigation. Given the event parameter estimation of detection delays and the SNR ratio between a pair of detectors, delayRatio returns a Boolean indicating if the parameters fall within physical ranges determined by using polarization averaged antenna patterns. Since polarization effects can cause physical signals to lay outside the polarization averaged bounds, probabilities based on Monte Carlo simulations of physical signals are also calculated to estimate the likelihood of a polarized signal that falls outside of the polarization averaged bounds. This work has also been generalized for 3+ detectors. For these combinations, the primary likelihood condition is the physicality of detection delays while SNR ratios give secondary validation measurements. Therefore, this work has easily been extended to function as a simplistic source location tool based solely on the detection delays.

1Research supported by the National Science Foundation.

11:21AM W11.00004 ABSTRACT WITHDRAWN —

Larry Price, Patrick Brady, University of Wisconsin – Milwaukee — An important feature of low-latency searches for gravitational waves is the ability to quickly identify the sky location of possible sources. This then allows for rapid searches for possible electromagnetic signatures by pointing more conventional telescopes. Here we will discuss a method of localizing inspiral sources using time of arrival data from both LIGO detectors and Virgo and how well we can expect this method to perform based on the analysis of simulated signals. Particular focus will be placed on how many pointings will be required for each signal and its dependence on the signal to noise ratio.
of the fine-structure constant and provides a physical explanation of relativistic effects.

The physical relationship between dark energy and dark matter, is in agreement with the accelerating expansion rate of the universe, contributes to the understanding of unification of gravitation with quantum theory. SM has been tested against current observation and is in agreement with the age of the universe, suggests a valid conceptualizations of the relationship between space and time.

Why entertain SM? Scale Metrics gravity is quantized and may suggest a path for the full unification of gravitation with quantum theory. X

We have defined this effect as the object’s “orientation” (X). The SM orientation (X) is equivalent to the orientation of the 4-velocity vector positioned tangent to its worldline, where \( X^{-1} = \sin \theta + 1 \) and \( \theta \) is the angle of the 4-vector relative to the axis-of-motion. Both 4-vectors and SM appear to represent.

The current network of earth-based detectors are looking for the first traces of gravitational waves. Coalescence of binary neutron stars, binary black holes and neutron star black hole binaries are potential sources of gravitational waves. The three LIGO detectors, 4km and 2km detectors in Hanford, WA and a 4km detector in Livingston, LA, have been collecting data and searching for traces of gravitational waves. The two Hanford detectors are collocated and share the same vacuum system, hence the noise in the detectors are correlated. Interpretation of the data from the Hanford detectors requires accurate knowledge of the background due to detector noise. Some searches ignore data when only H1 and H2 are operating, due to our inability to measure the impact of correlated noise on our background rates. A study has been done to better estimate the background in H1 and H2 searches for compact binaries. The method uses time-reversed filters to discover a multiplicative factor which can be used to correct background estimates from time slide investigations. Investigations of the method and potential issues with it will be discussed.

**Tuesday, May 5, 2009 1:30PM - 3:18PM —**

**Session X5 GGR DAP COM CSWP: Panel Discussion: Women and Minorities in Gravity: Science and Career Paths**

**Governor’s Square 15**

1:30PM X5.00001 Detecting Gravitational Wave Bursts Using Pulsars

ANDREA LOMMEN, Franklin and Marshall College — At the talk of this talk, pulsar timing for gravitational wave detection will be in the midst of becoming an internationally coordinated effort. The North American collaboration is called NANOGrav. I will review the idea of using pulsars to detect a very low-frequency stochastic background of gravitational waves, and discuss current limits that pulsar timing places on the energy density of gravitational waves and what these limits correspond to in terms of cosmological models. The most notably the merger rate of super-massive black holes in the early universe. I have become interested in the possibility of using these ideas farther and using pulsar timing to detect bursts of gravitational radiation from a number of different possible sources, which I will describe.

**1:30PM X5.00001 Simplified Model of Pre-inflationary Remnants held in our Present Epic–Gravitational and Inertial Transfer**

ROBERT EVANS — Scenario pre-inflationary infinite density mass wall transfers as a stationary entity of non-oscillating simultaneity (thought intuitively being “most-perfect-symmetry” at least), but transfers instantaneous - setting the local. This initial condition due to pure bare vacuum attractor (universal constant). Wholeness of order is adjusted titled “Ultiortronics” - based on simple fundamental mathematics from pre-initial conditions to post-remnant conditions. Faster-than-light cryogenic state fractures creating an imbalance of energy. Post bang produces degeneracy of transfer coherence, giving way to present epic speed-of-light limit (quasi-related remnant), utilizing *nautical measure. A bare vacuum attractor nucleus prohibiting entry of convergence past Higgs Field. Perimeter holds to Pauli Exclusion Principle - trapped quantized, with new particle production. Oscillating “back-splash-effect” appears as “particle/wave duality.”

1:42PM X11.00002 Gravitation in 3D Spacetime

JOHN LAUBENSTEIN, KANDI COCKREAM, IWPD Research Center —

3D spacetime was developed by the IWPD Scale Metrics (SM) team using a coordinate system that translates n dimensions to n-1. 4-vectors are expressed in 3D along with a scaling factor representing time. Time is not orthogonal to the three spatial dimensions, but rather in alignment with an object’s axis-of-motion. We have defined this effect as the object’s “orientation” (X). The SM orientation (X) is equivalent to the orientation of the 4-velocity vector positioned tangent to its worldline, where \( X^{-1} = \sin \theta + 1 \) and \( \theta \) is the angle of the 4-vector relative to the axis-of-motion. Both 4-vectors and SM appear to represent valid conceptualizations of the relationship between space and time. Why entertain SM? Scale Metrics gravity is quantized and may suggest a path for the full unification of gravitation with quantum theory. SM has been tested against current observation and is in agreement with the age of the universe, suggests a physical relationship between dark energy and dark matter, is in agreement with the accelerating expansion rate of the universe, contributes to the understanding of the fine-structure constant and provides a physical explanation of relativistic effects.
2:06PM X11.00004 New exact dynamic field solutions of Einstein’s equation, FRANKLIN FELBER, Starmark, Inc. — An exact metric first derived, but not analyzed, by Hartle, Thorne, and Price [1] is used to calculate the exact time-dependent gravitational field of a spherical mass moving with arbitrarily high constant velocity. The exact field solutions [2] confirm that even the weak field of a spherical mass moving faster than $3^{-1/2}c$ is repulsive in the forward and backward directions [3]. The exact threshold conditions required for gravitational repulsion of particles at rest are determined as a function of source speed and field strength and particle position with respect to the relativistic source. The results are consistent with the repulsion of relativistic particles by a weak static Schwarzschild field, discovered 85 years ago by Hilbert [4].


2:18PM X11.00005 A brief crack of light between two eternities of darkness: DM and DE explained, JAMES BEICHLER, Retired — I have previously presented a geometrical explanation of Dark Matter and Dark Energy that is falsifiable, but the model was criticized for being non-mathematical. In this structure, the four-dimensional space-time of relativity is extrinsically curved in a higher spatial dimension. Dark Matter is curvature in the higher dimension that is not directly associated with local matter, but instead results from an interaction between the curvature of local matter and the global curvature due to all matter in the universe. The earlier criticism has now been overcome by looking at the possible particulate source of galactic halos and a simple yet revolutionary algebraic formula has been derived. The algebraic formula implies a five-dimensional unified field structure such as that developed by Kaluza in 1921 and extended by Einstein and his colleagues in the late 1930s. Others, such a H.T. Flint, have developed more complete mathematical models of similar five-dimensional structures. The new equation also shows how gravity can be quantized on the basis of relativity without hypothesizing the discrete nature of matter, i.e., the existence of specific “particles” of gravity, inherent in quantum mechanics, the Standard Model and other quantum models.

2:30PM X11.00006 Apparent sizes of black holes and their alternatives$^1$, JAMES GRABER, LC — Observers recently made a non-trivial measurement of the apparent diameter of Sagittarius A*, the black-hole candidate at the center of the Milky Way (Doeleman, et al., Nature, 4 September 2008). At face value, this measurement appears to be more than two sigma smaller than predicted. Better measurements are anticipated within the next five to 10 years, or perhaps much sooner. This presents an opportunity for a new, further (imprecise, to be sure, but qualitatively independent) test of the predictions of general relativity. We present a few mathematical formulae relevant for predicting the apparent size of black holes or the equivalent collapsed objects in all metric theories of gravity, including general relativity.

$^1$Affiliation for identification only. Support/endorsement not implied.

2:42PM X11.00007 Quantum Gravity of IED Particles, J. ZHENG-JOHANSSON — The internally electrodynamic (IED) model$^2$ developed based on overall experimental observations since 2000, briefly states that a simple material particle like electron is composed of an oscillatory charge of a characteristic frequency $\Omega$ and zero rest mass, generally also traveling at velocity $v$, and the resulting Doppler-effected electromagnetic waves ($E$, $B$)'s. Based on first principles solutions for the IED processes a range of basic particle equations/properties have become predictable. One prediction is: two IED particles of masses $M_1$ and $M_2$ ($=M_1/c$, $i=1,2$) and charges $q_i, q_2$ separated at $r$ apart in a dielectric vacuum act always on one another an attractive force $F = \sqrt{P_{ij} P_{ji}} = \frac{C M_1 M_2}{4\pi \epsilon_0 r^2}$, where $P_{ij} = q_i v_{pj} \times B_i$, is the Lorentz or depolarization radiation force on $q_j$ due to the radiation depolarization field $E_{pi} = -\sum_{i=0}^{C_B} E_i$ of $q_i$, electric field $E_i$, and magnetic field $B_i$, with $E_{pi}$ driving $q_j$ into motion at velocity $v_{pj} = \sum_{i=1}^{C_B} E_i$, $i,j = 1,2$;

$C = \frac{2 \pi h^2 \epsilon_0 c}{\epsilon_0 h^2 \pi l}$ with $q_1, q_2 = \pm e$ and $\epsilon_0, h$ fundamental constants of the usual meaning. $F$ resembles directly Newton’s gravitational force. The fields $E_i, B_i$ are by nature quantized at the scale of Planck constant $h$; consequently $E_{pi}$ and therefore $F$ are each quantized at the scale $h$. The present work gives a formal quantum electrodynamic re-derivation of this force.

$^2$See e.g. a) arxiv:0812.3951, b) J Phys Conf Ser128. 012019, 2008.