Research Paper

Volume : 2 | Issue : 1 | Jan 2013 • ISSN No 2277 - 8179

Gravltational Wave and Astronomy : Probing Physics and Astrophysics

Physics

KEYWORDS : LIGO - VIRGO – Gravitational wave astronomy

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ABSTRACT

Kilometer scale Laser Interferometer Gravitational Wave Detectors like LIGO (VIRGO) are online in 2002 (2003). Space Interferometers like LISA are scheduled for 2013. In this talk the possible science Pay offs of these experiments are explored. Starting from the basic properties of gravitational waves and anticipated gravitational wave sources, it highlights the implications of gravitational wave observations for basic physics, astrophysics and cosmology. The current status of theoretical computation of waveforms and templates for data analysis is briefly discussed.

1. Introduction

Gravitational waves (GW) exist. Evidence for their existence is the observed decrease of the orbital period of the Hulse -Taylor binary pulsar 1913+16 which agrees with the predicted decrease due to gravitational radiation damping to better than 3%. These remarkabely accurate observations are an important verification of the lowest order radiative prediction of general theory of relativity (GTR). They are also sensitive to some strong field aspects of GTR since neutron stars have strong internal gravity. However, in spite of this high quality confirmation, the evidence is still indirect. Direct detection of gravitational waves is thus the obvious mandate for upcoming laser interfero metric gravitational wave detectors. The real excitement, however, is the possibility to use GW as an observational tool for basic physics and astrophysics and inaugurate gravitational wave astronomy (Schutz-1999)

Why is gravitational radiation not just 'one more window' to the cosmos? The reason is not too hard to find. Information carried by G W is orthogonal to information carried by electromagnetic waves (EMW) since they arise from fundamentally different physical processes. EMW arise from incoherent superposition of emission from electrons, atoms and molecules. They provide information of the thermodynamic state of the system and its environment. GW arise from a coherent superposition of radiation arising from bulk dynamics of dense mass-energy. They provide information of the system dynamic GS. EMW are oscillations of EM field propogating in space time. GW are oscillations of space time itself. The wavelength of EMW is much smaller than the dimensions of the emitting system and thus they can be used to image these systems in the universe. Gravitational wave lengths on the other hand are much larger than these typical system dimensions. They are useful to listen to the violent motions of astrophysical systems rather than image them. Thus, if EMW provide the video track of the universe, GW provide its stereo sound tracle Exciting times are ahead reminiscent of the revolution from silent moviesto talkies! Gravitational interaction is very weak relative to EM and so, GW interact weakly with matter in contrast to EMW. GW is a dream. come true for theorists offering the possibility to probe the hidden and the dark but a nightmare for the experimenters who have to struggle to pick up strains of the GW symphony. EM detectors are normally intensity detectors while GW detectors are amplitude detectors (one tracks in the phase and builds SNR by coherent superposition of many cycles). Doubling the sensitivity, doubles distances probed, increasing eight fold the volume leading to an eight fold number of events or event rate. In astronomy, observations in new bands throw up

Surprise not imaginable from extra polation from earlier windows. Though the initial sensitivity of GW detectors is marginal, planned upgrades and technology development make them powerful instruments for cosmology in the next decade. LISA in 20ll extends GWA to the entire observable universe. However, one must go through the current sub sensitive phase and learn its lessons to eventually get there!

2. Gravitational Waves in GTR

GTR is the best classical theory of gravitation today and is described by Einstein's equations. GW are wave solutions of these equations. Rigorous theoretical work in the sixties conclusively demonstrated that GW are not mere gauge but carry energy and cause physical effects. GTR is described by a mass less spin two field and consequently GW in this theory are transverse with two polarisation states travelling at the speed of light c. The leading order multipole emission in GTR is quadrupolar. There is no monopole or dipole radiation. GW are produced by accelerating masses. They are travelling tidal disturbances and equivalence principle implies that their effect will be perceived by its action in a system of test masses rather than an isolated test mass. Weakness of gravitational interaction precludes any laboratory Hertz experiment. No terrestrial sources of GW are feasible and one appeal to astronomy for possible sources of GW.

3. GW Spectrum and Sources

The spectrum of known and expected sources extend over 20 decades of frequency between Hz comparable to the EMW spectrum extending between 10^7- 1027 Hz. Promising sensitivities are in the following 4 frequency bands referred to and designated as extreme low frequency. (ELF), very low frequency (VLF), low frequency (LF) and high frequency (HF) respectively:

ELF	10^{-15}- 10^{-18}	CMBR anisotropy
VLF	10^{-7}- 10^{-9}	Pulsar Timing
LF	10^{-1}- 10^{-4}	Doppler tracking of Spacecraft, LISA
HF	1 - 10^4	Weber Bars Laser Interferometers: LIGO, VIRGO, GEO, TAMA

The first generation detectors would be sensitive to only extremely violent astrophysical processes. These include, coalescence of compact binaries (CB) of neutron stars (NS) and black holes (BB), and stellar core collapse in supernovae (SN). These are extremely energetic but short lived events. The GW luminosity of CB reaches the theoretical maximum of c^5 /G ~10^{59}erg/sec for several x(10^{-2} - 10-3)sec and is then brighter than any thing in the sky. For the next generation detectors, continuous GW emitters, like pulsars, accreting neutron stars, stochastic background are also possible sources. Joint analysis With neutrino, gamma ray and X-ray detectors offer new insights due to multiple radiation channels. The hope eternal is the possibility of significant signals from unknown and unexpected sources .Compact Binaries are the best understood sources of GW. They are made of NS or BB. Many NS-NS binaries have been observed in the galaxy. Orbital periods of the order of hours lead to GW frequency of about 10-4Hz. Information of NS-BH or BB- BH come from population synthesis of main sequence stars. Large uncertainity still remain due to uncertain physics details, though calculations are 'matched' to NS-NS observational data. Thus data from GW detectors can ha.ve impact on understanding stellar solution and CB formation. For CB systems, there are three distinctive epochs: slow inspiral, late inspiral, plunge, and merger, and finally ringdown. Though early inspiral (Blanchet-2002) and ringdown are well-understood by analytical techniques, late inspiral and merger is the most important open problem right now, providing impetus to Numerical Relativity (Lehner-200l). The reason is as follows: For NS-NS only inspiral waves are accessible to laser interferometers (LI) on earth; special configurations may extract the higher frequency merger. N8-NS signals are we(!.k due to their small mass; a signal-to-noise(SNR) of 5 obtains at 20 Mpc. Thus N8-NS detections by first generation detectors is plausible but not likely. With upgrades that will span 300 Mpc detection is likely and quite non detection very surprising!! BH-BH binaries on the other hand, are more massive and emit stronger signals, but in a lower frequency range. Hence in LIGO only the late inspiral and merger is visible. However this phase is poorly understood and motivates all the large activity in NR as mentioned earlier. H one succeeds one can detect signals upto z ~ 5 - 1. An useful estimate of the frequency of inspiral waves is f ≤ 400 Hz[10 Mo/(1+z)M] while for Ring down waves one has (1200 - 3200) Hz [10 Mo/(1+z)M]

All current data analysis for inspiralling CB uses 2PN templates computed by (Blanchet et al1995, Blanchet, Damour & lyer 1995, Will & Wiseman 1996, Blanchet et al1996). The 3.5PN templates are only partially complete due to arbitrary parameters arising due to incompleteness of the Hadamard self-energy regularisation (Blanchet, lyer and Jo.puet 2002, Blanchet et al 2002). Resummation techniques have been used to improve the convergence of the PN templates and effective-one-body templates have been constructed to model the late inspiral, plunge and merger beyond the adiabatic approximation (Damour, lyer & Sathyaprakash 1998, 2000,2001).

Stochastic Background refers to random GW arising from a large number of independent uncorrelated sources not individually resolvable. Dynamics of the early universe (EU) can lead to an all sky GW background like the CMBR in EMW. It is caused by amplification of primordial fluctuations of geometry, phase transitions as unified interactions separate, or condensation of brane from higher dimensional space. Phase transitions peak at a temperature f peak ~ 100Hz (T/105Tev) so that energy scales of electroweak theory T~ 100 - 1000 Gev. are possible sources in the LISA band On the other hand, extra dimensions of scale b yield f peak ~ 10-4Hz (1 mm/b) 1/2 so that branes lie in the LISA range while LIOO probes b~ 10-15m scales .Core Collapse of Massive stars: Super novae involve highly energetic dense matter dynamics. However this is ill-understood and hence GW emission is uncertain. There will be a major thrust towards coincident observations with neutrino, gamma ray, and optical. GW detectors could provide triggers and cross-checks. SN in our galaxy can be easily detected by neutrino and GW detectors. Though rare it has large SNR and it would be instructive to track the relative evolution in the neutrino and GW channels.

Periodic Sources refer to GW emitters radiating at (nearly) constant frequency. The detection is attempted by coherently following the periodic source's phase evolution to build power in the weak signal over the noise. The obstacle to this is that the signal is strongly modulated by earth's rotation and orbital motion which smears waves over multiple frequency bands degrading the signal strength. The search requires demodulating detector motion and is thus computation intensive since modulation is different for every sky position. NS accreting matter from close companion in LMXB's have maximum spin frequency since they are braked by GRR torques. These are promising targets since their sky position is known. Sources for LISA Galactic binaries (NS binaries, cataclysmic binaries or close white dwarf binaries) are sure sources for LISA. More speculative sources include merging massive black holes or inspiralling compact stars around massive black holes. Above 1 m Hz there are about 108(mostly WD) CB. Below this frequency individual binaries are not resolvable and become part of the confusion noise.

4. Status of Tests of GTR, Basic physics issues

Empirical support .of GTR is very strong but most tests are solar system tests probing weak field, slow motion, non radiative regimes. GTR is not tested deeply in radiative and strong regimes except in the Hulse Taylor test and alternative theories of gravitation exist consistent with available experiments. Important tests of GW and their properties are still undone and aspects of GW to be tested include, polarisation content of waves, speed of GW and back reaction of radiation on evolution of the source. Polarisation : General theories of gravitation have up to six states of polarisation: Three transverse (2 quadrupolar deformations+ 1 monopole breathing mode), and three longitudinal (2 quadrupolar deformations+ 1 axially symmetric stretching). Scalar tensor theories have all the three transverse polarisations. GTR on the other hand has only the two transverse quadrupolar modes of polarisation. Speed: GTR predicts C; if the 'graviton' is massive, other theories predict different speeds .Back reaction: NS have strong internal self gravity. Alternate scalar tensor theories lead to dipole gravitation radiation emission whose back reaction on the orbit is very different.GTR predicts no such effect. Binary pulsar bounds on dipole radiation are weak since it is a very symmetric system of 2 NS. WD-NS or NS-BH systems are better for this test. Strong field Tests: Quasi-Normal mode oscillations of BH ; Uniqueness of BH; No hair Theorem. Nonlinear effects like tails.

NS EOS: NS tidal disruption is sensitive to NS size and hence to NS EOS. Deviation of gravitational waveforms from the point particle predictions can reveal NS structure and hence discriminate between NS EOS

5. Contributions to Astrophysics and Cosmology

Inspiralling binaries could be standard candles and provide accurate estimation of distances, masses, spins, direction to binary NS, stellar mass or 5MBH. It can provide data on galactic compact binary population, NS population in the local universe, and dark matter in the universe. Are MACHO binaries .5M0 BH?? One can examine the association of GW sources and gamma ray bursts, or X-ray Ray sources like Sco-Xl. NS seismology via. r-modes can yield data about fundamental modes of NS and NS EOS. The waveforms will carry information about spin induced precession in binaries; Lense Thirring effect ,nature of orbits of spinning and non-spinning masses around rotating and non-rotating BH, eccentricity effects on LISA sources and effects of periastron precession (Will and Wiseman 1996, Gopakumar and Iyer 1997). Possible contributions to cosmology comprise an accurate measurement of the Hubble parameter and its variation with red shift, galaxy interactions at high red shift and implications for structure formation models. The photons of CMBR offer us a glimpse of the universe of 100,000 yrs old. Neutrinos do immensely better and reveal it just a second young. GW are even more incredible. They take us to unbelievably short time scales of 10-43 sec. The determination of primordial stochastic background of GW could thus the universe100, 000 yrs old. Neutrinos do immensely better and reveal it just a second young.GW are even more incredible. They take us to unbelievably short time the universe 100,000 yrs old. Neutrinos do immensely better and reveal it just a second young. GW are even more incredible. They take us to unbelievably short time scales of 10^{-43} sec. The determination of primordial stochastic background of GW could thus allow one to differentiate models of EU based on string model choices or inflation brands! Waves from standard inflation are too weak for LISA, LIGO or pulsar timing in the next fifteen years. Crude string models of big bang have stronger G W backgrounds.

6. Conclusions

The detection of GW will be a striking confirmation of GTR. It will help check properties predicted by GTR, constrain gravitation theories and probe unification physics beyond the standard model. imprints of strong gravitation phenomenon provides tests of GTR in strong field limit. GW observations coupled with theoretical analysis and simulations of observed sources should bring surprises in astrophysics and cosmology. Routine detection of GW will transform astronomy and astrophysics touching upon BH mergers, WD binaries, mass-energy flows, dynamics of MBH formation at galactic centers, evolution of binary systems mechanism of neutrino driven SN explosion, EU, EOS of NS matter, LMXB's, Gamma ray bursts and NS seismology. GW detection is an effort that 'strains' all resources: best technology, best data archiving, best theoretical templates, best data analysis, and best computing. It 'stresses' the symbiotic relation between basic sciences and applied technology on one hand and theory, experiment and computation on the other. We are in an epoch where experiments are driving the theory.

Volume : 2 | Issue : 1 | Jan 2013 • ISSN No 2277 - 8179

Computations reminiscent of Lamb shift in QED seem crucial to test the theory! We are seeing the emergence of another window and hearing the stirrings of a new astronomy. When it comes of age, more than ever before, General Relativity would have found its true home.

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