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Workshop on gravitational waves and relativistic astrophysics

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Abstract. Discussions related to gravitational wave experiments viz. LIGO and LISA as well as to observations of supermassive black holes dominated the workshop sessions on gravitational waves and relativistic astrophysics in the ICGC-2004. A summary of seven papers that were presented in these workshop sessions has been provided in this article.

Keywords. Gravitational radiation; Laser Interferometer Gravitational-wave Observatory; laser interferometer space antenna; black holes.

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1. Introduction

This workshop saw five presentations in the field of gravitational radiation and two on compact, relativistic self-gravitating systems. Gravitational waves (GWs) and black holes (BHs) are two of the most significant predictions of Einstein's relativistic theory of gravity and, as far as their experimental status is concerned, both of them share a common feature. At the moment, we are tantalizingly close to their actual detection!

Although the inspiralling nature of Hulse-Taylor binary pulsar provides strong evidence for the loss of orbital energy due to gravitational radiation, a direct measurement of GW and its polarization states will not only be a triumph but may also throw up a few surprises on fundamental physics. Excitingly enough, scientific runs of LIGO, so crucial for detection of 'chirp' signals from compact binaries, have been carried out recently. A few of the other ground-based GW detectors are also operational.

Plans to put a sub-Hz GW detector LISA in space, orbiting the sun, is in progress. The sensitivity bandwidth of LISA makes it an ideal detector to observe GW signals from a wide variety of astrophysical sources – from ordinary binary stars to plunging of stars into supermassive BHs to coalescing supermassive binary BHs. Furthermore, a strongly relativistic pulsar J0737-3039, with an orbital period of only $\sim$2.4 h, was discovered a couple of months before this conference began. One hopes that it will turn out to be a promising GW laboratory. Side by side, there have been hectic activities in calculating waveforms at higher orders of accuracy as well as in developing faster algorithms for data analysis.

Coming to black holes, studies of mass functions in several X-ray binaries (e.g. Cygnus X-1) had already suggested that the unseen companions in these systems are stellar size BHs. But a BH is confirmed only when its event horizon is 'seen'! Presently, astronomers have started probing regions close to the last stable orbit around suspected BHs in such X-ray sources, to look for signatures of strong gravitational fields. In particular, quasi-periodic oscillations at frequencies of ∼1 kHz observed in a few of the low mass X-ray binaries may tell us something about the Lense–Thirring precession near rotating BHs.

Active galactic nuclei (AGNs) like quasars and radio-galaxies require supermassive BHs to work as powerful energy generators. Spectroscopic measurements of the motion of stars and ionized gas, using imaging spectrograph STIS of the Hubble space telescope, in the nuclear regions of galaxies consisting of 'elliptical galaxy-like bulge' components reveal the presence of giant 'black holes' with mass $\geq 10^6 M_\odot$. Such studies hold the key to our understanding of the formation and merging of galaxies as well as of the birth of AGNs. Moreover, supermassive BHs are expected to be important sources for LISA, bringing us back to GWs.

The talks in this workshop reflected the excitement discussed above. In what follows, we present summaries of all the seven papers, beginning with the field of GWs that includes discussions on topics ranging from calculation of gravitational radiation waveforms to LIGOs to GW data analysis, and concluding with two brief reports of the work done on supermassive BHs and general relativistic effects around a rotating, magnetized NUT star, respectively.

2. Summaries of the workshop contributions

K G Arun presented a paper (in collaboration with Luc Blanchet and Bala Iyer) on the calculation of gravitational waveforms from inspiralling compact binaries in quasi-circular orbits using the multipolar post-Minkowskian approach developed by Blanchet *et al* [1] at the level of two and a half post-Newtonian (2.5PN) approximation. The crucial new inputs in the computation included the 2.5PN mass octupole, the 2PN current octupole and the 2PN mass hexadecupole. The hereditary terms in the waveform were also computed, leading to the complete waveform with 'plus' and 'cross' polarizations at 2.5PN, extending the results of ready-to-use templates calculated earlier by Blanchet *et al* [2].

Generally, templates for detection employ the so-called restricted waveform (RWF), for which the phase used is calculated up to the highest available PN order while retaining the expression for the amplitude at the Newtonian order. Though for (online) detection RWF may suffice, complete waveform is more useful for estimating parameters (which will be done off-line), since studies using the complete 2PN accurate waveform (which included the contribution from higher harmonics) showed that accuracy plays a vital role in parameter estimation [3]. This work provides waveforms of half a PN order beyond those currently used in gravitational wave data analysis. K G Arun concluded his talk by mentioning that since this 2.5PN waveform includes higher harmonics, one expects that together with the 3.5PN phasing formula obtained by Blanchet *et al* [4], it would provide better parameter estimation.

Shrirang Deshingkar described a new scheme for extracting gravitational radiation that has been developed jointly with Nigel Bishop. The method employed Bondi News function within the null cone or characteristic approach to numerical relativity where space-time was foliated by a sequence of null hypersurfaces. The procedure was based on explicit coordinate transformation to the Bondi coordinate system in which one could express the News function in a simple form so as to obtain the GW constraint. The new method was claimed to be technically and conceptually much simpler than the earlier method. When it was implemented computationally and was applied to certain test problems, second-order convergence of the News to the corresponding analytic value was observed.

Biplab Bhawal gave a detailed account of the time domain simulation of LIGO interferometer. Since an interferometric gravitational wave detector like LIGO is a complex, nonlinear and coupled dynamical system, the time-domain description of its physics is essential to achieve a good insight into the operation of such a complex system. Hence, a simulation package called the end-to-end (E2E) program has been developed to model the full LIGO detector, its subsystems as well as its advanced design-variants in collaboration with Matt Evans, Virginio Sannibale and Hiro Yamamoto.

The main purpose of E2E software is to: (i) study detector diagnostics during the commissioning and operating phases, (ii) help in trouble-shooting hardware or unknown noise sources, (iii) generate pseudo-data for running and testing data analysis techniques, and to (iv) design advanced detectors.

The E2E package simulates time evolution of fields, optics, mechanical structures as well as electronics and control systems. It works as a software toolbox, like MATLAB, where complex systems can be simulated by combining various building blocks housed in different modules. E2E is written in C++ and its modular design makes it possible to simulate a wide variety of experimental configurations and processes (with different description files), using the same simulation engine. A JAVA-based graphical user interface has been developed, using which it is easy to create, modify and maintain the simulation configuration setup even for complex systems such as LIGO interferometer with all its optical, mechanical and control system components. The flexibility of the underlying simulation environment makes it easy to maintain, extend or introduce new physics or functionalities in a streamlined manner.

The simulation effort needs to take care of at least the following issues and complexities:

(i) Complex hardware – pre-stabilised laser, input optics, core optics, seismic isolation system on moving ground, stacks, suspension system, sensor and actuators.
(ii) Feedback loops – length and alignment control, feedback to laser.
(iii) Nonlinearity – cavity dynamics to actuators.
(iv) Field – Gaussian or non-Gaussian field propagation through imperfect mirrors and lenses, effects of thermal lensing and misalignments.

(v) Noise – mechanical, thermal, sensor, amplitude and frequency noise of laser; their creation, propagation and coupling.

(vi) Wide dynamical range – $\sim 1 \times 10^{-20}$ to $\sim 1 \times 10^{-6}$ m.

A simulation setup of the Hanford 2 km LIGO interferometer played a crucial role in the first lock-acquisition design of the interferometer. Another recently built LIGO simulation setup contains all the important hardware and software features of the LIGO detector. This is capable of generating realistic noise spectra as well as studying both the length control and alignment control through wave-front sensors. E2E played an important role in understanding or resolving various issues encountered during commissioning or operation of LIGO interferometers. E2E could also provide important feedbacks or insights to the LIGO commissioning team to resolve physics-related issues on a number of occasions.

Biplab Bhawal concluded by mentioning that for more documents and details describing E2E software package and its design, models based on the package and physics behind E2E's simulation modules etc., one can visit the website: http://www.ligo.caltech.edu/e2e

Sanjeev Dhurandhar started with a general introduction to laser interferometric space antenna (LISA) and then demonstrated how elements of algebraic geometry could be used to analyse the time-delay data expected from this detector. It is virtually impossible to remove noise at low frequencies (below 10 Hz) from ground-based detectors, as it is dominated by gravity gradient noise. The solution, therefore, lies in building a detector in space. LISA is a space-based interferometric gravitational wave detector designed for observing low frequency gravitational waves. It consists of three spacecrafts going round the sun, exchanging laser beams over a separation of $\sim 5 \times 10^6$ km, and working as a six-armed interferometer.

LISA is sensitive in the frequency range of $\sim 10^{-5}$–10^{-1} Hz. Sanjeev Dhurandhar pointed out that cancellation of laser frequency noise in interferometers is crucial for attaining the requisite sensitivity of the triangular 3-spacecraft LISA configuration. Raw laser noise is several orders of magnitude above the other noises and hence, it is essential to bring it down to the level of noises such as shot, acceleration, etc. Since it is impossible to maintain equal distances between the spacecrafts, cancellation of laser noise must be achieved by suitably combining the six beams with appropriate time-delays. It has been shown in several recent papers that such combinations are possible. A rigorous and systematic formalism based on algebraic geometrical methods involving computational commutative algebra has been developed, which generates in principle all the data combinations, cancelling the laser frequency noise. The relevant data combinations form the first module of syzygies, as it is called in the literature of algebraic geometry. Specifically, several sets of generators for the module was listed in the talk. This formalism can be extended in a straight forward way to cancel other systematic noises such as those due to optical bench motions and ultra-stable oscillator (USO).

This formalism was used to maximise signal-to-noise ratios of monochromatic GW sources and also to optimally track sources with known positions. This research work was done in collaboration with K Rajesh Nayak, A Pai, P Aldo Moro and J-Y Vinet.

Anand S Sengupta reported a new hierarchical detection strategy developed jointly with S V Dhurandhar and Albert Lazzarini. The basic motivation arose from the observation that if GW signal is present in the data then power spectral density tends to have a power law dependence on the frequency in such a manner that most of the signal power lies at low frequencies, e.g. it was found that for LIGO detectors more than 90% of the signal power is well within 512 Hz limit. Therefore, it makes sense to employ a two stage strategy in which: (a) first, there is a cursory stage where data is sampled coarsely (at 1 kHz) and matched filtering is carried out by a template bank with a template density that is significantly less than that in regular search, and then followed by (b) a stage involving data sampling at a higher rate of 4 kHz and use of templates covering the parameter space more densely. However, the second stage search is restricted to a much smaller parameter space because it is carried out locally around those putative events which cross the first stage cross-correlation threshold.

By adopting such a strategy, (a) the cost of FFT operations that scales as N log N (where N is the number of sampled points) falls by a factor of 4 to 5, in the first stage, while the signal-to-noise ratio is not compromised since more than 90% of the signal power is retained at the lower sampling frequency, (b) there are fewer cycles of the inspiral waveform in the first stage so that the templates can be placed further apart without significant loss in the cross-correlations (as such the mismatch between templates is comparatively less sensitive to mismatch in parameters) and (c) the speed can go up, over a naive implementation of matched filtering, by a factor of $\sim$60. Anand Sengupta also presented Monte Carlo studies of the LIGO data analysis (LDAS) implementation of this search pipeline as well as preliminary results regarding efficiency and errors in parameter estimation.

C D Ravikumar presented a paper on estimating the masses of the supermassive black holes at the centres of galaxies across the Hubble sequence using photometric data and the correlation between the velocity dispersion of the spheroidal bulge component and the mass of the nuclear black hole observed in a large number of the early-type spirals belonging to a different sample. By carrying out detailed and accurate surface photometry of 33 early type galaxies in two clusters, Abell 2199 and Abell 2634, it was shown for the first time that there exists a four-dimensional hyperplane for the early type galaxies. This hyperplane and the well-known fundamental plane relations were independently used for obtaining the central velocity dispersions for the spheroidal bulge components of galaxies.

Comparison of the velocity dispersion measurements for a sample of bulges of early-type spirals with those estimated using the fundamental and hyperplane relations for ellipticals in rich clusters revealed that this method works at an accuracy of about 12%. These velocity dispersion estimates were further used for calculating the masses of supermassive black holes present at the centres of the galaxies belonging to Abell 2199 and 2634. This method relies on pure photometry alone, and hence, is an economical alternative (in telescope time and data reduction) to other methods like reverberation mapping, which involve detailed spectroscopic analysis. This work was carried out in collaboration with Ajit Kembhavi, V C Kuriakose and Bahram Mobasher.

B J Ahmedov presented analytic general relativistic expressions for the electromagnetic fields external to a slowly rotating magnetized NUT star with non-vanishing gravitomagnetic charge. Solutions for the electric and magnetic fields were obtained after separating the Maxwell equations in the external background space-time of the star into angular and radial parts at the lowest order approximation. The star was assumed to be isolated and in vacuum and two distinct models for stellar magnetic field were considered, (1) monopolar magnetic field and (2) dipolar magnetic field aligned with the axis of rotation. It was shown that the general relativistic corrections due to the dragging of inertial frames and gravitomagnetic charge appear not in the form of magnetic fields but emerge only as electric fields. In particular, the frame-dragging effect and the gravitomagnetic charge were shown to provide an additional induced electric field, which is analogous to the one introduced by the rotation of the star in the flat space-time limit. This research work was done jointly with A V Khugaev.

References

[1] L Blanchet, B R Iyer and B Joguet, *Phys. Rev.* **D65**, 064005 (2002)
[2] L Blanchet, B R Iyer, C M Will and A G Wiseman, *Class. Quantum Gravit.* **15**, 89 (1998)
[3] R W Hellings and T A Moore, *Class. Quantum Gravit.* **20**, S181 (2003)
[4] L Blanchet, G Faye, B R Iyer and B Joguet, *Phys. Rev.* **D65**, 061501(R) (2002)