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Anjan Giri
Rukmani Mohanta *Editors*

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Workshop on Frontiers in High Energy Physics 2019

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Preface

In continuation of the practice of publishing the proceedings for conferences covering the latest development, we decided to publish the proceedings for the Frontiers in High Energy Physics 2019 (FHEP 2019). Apart from the excellent talks by the invited speakers, and presentation of new results and discussions, publication of the proceedings constitutes an important aspect of any conference, and the conference under consideration (FHEP 2019) is in no way different. It is very important that we spread the scientific ideas, invited talks, new results, contributed talks, and presentations during the meeting through the proceedings of the conference which will be available to all, not just the conference participants. Beginning researchers and scientists who are working in other related areas will find the present volume very interesting and useful in the sense that most aspects of High Energy Physics currently discussed are nicely covered with interesting articles by experts in the field.

Frontiers in High Energy Physics (FHEP 2019) conference is an outcome of many similar conferences held in the last few years, and from now onward it is going to be held every year at different places. Around 130 physicists and researchers, including many from outside India, participated in FHEP 2019 to discuss the latest advancements in the fields of interest. The area of High Energy Physics is going through an important and crucial phase in the sense that we have understood well the electroweak sector and discovered the last elusive particle, the Higgs boson, but there is no future direction. It actually opens up an ocean of opportunities to hypothesize and test new ideas. Interestingly, observations in the last few decades in this sector not only confirmed to the predictions of the framework of the standard model but also showed there is no evidence against it. Experimental results in the neutrino sector provide us the clue that there is much more unexplored which may give us the clue to many aspects of the Universe we live in. Experiments in the domain of Astroparticle Physics educated us with the hint that most of the total energy budget of the Universe is believed to be Dark Matter or Dark Energy. Accelerator-based Collider experiments allowed us to recreate the Universe at very early stages of evolution (we get to know about the Physics in the very hot and dense state supposed to be prevailing in the very early

Universe, the Quark Gluon Plasma, and the Physics of Heavy Ions). The High Energy experiments are providing us inputs about the Physics related to the standard model and possibly some information/hint beyond it (also known as Energy frontier). Similarly, experiments in Flavor Physics and Neutrino Physics (termed as Intensity frontier) are believed to be very helpful to obtain precision results in this sector and hopefully decipher indirectly the Physics beyond the standard model. Moreover, the observation of Gravitational waves by the LIGO and then also by the Virgo Collaborations confirm to the Century-old prediction by Einstein, where two super-massive Black Holes collide, and as a result the Gravitational waves are produced which eventually are detected by earth-based experiments, as mentioned above. In addition, there are many space-based experiments in Astrophysics and Cosmology which started providing us important information regarding the Universe at large scales (this area is also known as Cosmic Frontier). Needless to mention, there are many ongoing experiments and many future experiments planned in all the three frontiers which cover Physics from the smallest scale to the largest scale possible. Eventually, the development in these frontiers will lead us to the future in Science, Technology, and societal applications. The most important aspect of this conference is that it covered Physics topics associated with the Cosmic, Energy, and Intensity frontiers in one single platform. It is very important that Scientists working in one area should know the development and new ideas discussed and being developed in different related areas for the advancement in the right direction. We truly believe that the topic discussed during the conference and the articles published in these proceedings will be very useful to many in the fields across disciplines and will give impetus to new ideas and interesting developments.

The conference FHEP 2019 was held at the University of Hyderabad, Hyderabad, India, during 14–17 October, 2019, which was jointly organized by the University of Hyderabad and IIT Hyderabad. This volume includes manuscripts from both invited and contributed talks and poster contributions from Gravitation and Cosmology, Neutrino and Dark Matter, Beyond the Standard Model and Collider Physics, QCD and Heavy Ion Physics, and Flavor Physics. Some new results are also presented, including the review talks on the new developments during the past year covering almost all areas of High Energy Physics. The articles in this volume are very nicely written which gives a reader in this area regarding the status, latest results and possible new directions. The book is intended for both young as well as advanced researchers of the field who are actively following the exciting time that we are going through when we are expecting something new to show up either at the energy frontier or maybe at the intensity and cosmic frontiers.

Hyderabad, India

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Rukmani Mohanta

Acknowledgements

Organizing a conference like FHEP 2019 (Conference on Frontiers in High Energy Physics 2019) and bringing out the proceedings of the conference is undoubtedly a difficult job, and it would not have been possible to do so without the support and active participation of our colleagues and many students in both the organizing Institutes. The cooperation we received from the Advisory Committee members during the organization of the conference was truly exemplary. We thank all the members of the Advisory Committee from the bottom of our heart for their help in making FHEP 2019 a grand success. We take this opportunity to specially thank Urjit Yajnik, Sukanta Bose, Raghavan Rangarajan, S. Uma Sankar, L. Sriram Kumar, Sridhar Dasu, Karim Trabelsi, and other members in the Advisory committee regarding various organizational aspects including their help in suggesting possible invited speakers and the perfect balance between various topics discussed during the conference which made FHEP 2019 an enjoyable and fruitful meeting. We thank all the members of the Local Organizing Committee for their constant support and encouragement for organizing the conference smoothly. We would also like to thank the members of our Editorial board for their constant support in reviewing the abstracts, finalizing the programs, and finally reviewing the proceedings' drafts. Our special thanks to Narendra Sahu and E. Hari Kumar for innumerable discussions and suggestions during the process for all the support extended to us at critical times. We must also take this opportunity to thank our colleagues in School of Physics, University of Hyderabad, and Department of Physics, IIT Hyderabad. It was indeed a pleasure to work with you all!

The success of a conference depends largely on the exciting discussion, the mesmerizing lectures from the experts, and the fruitful discussions. We would like to express our sincere thanks to all our renowned invited speakers, presenters, and the rest of the enthusiastic participants for making FHEP 2019 a very successful conference. We were lucky to have a large pool of research scholar volunteers who worked relentlessly during the conference. It would have been a Herculean task to organize this event without the active support of our students, in particular, Suchismita Sahoo, Mitesh Behera, Rudra Majhi, Atasi Ray, Aishwarya Bhatt, Dinesh Singha, Akshay Chatla, Manas Mohapatra, Subhasmita Mishra, Seema

Choudhury, Lopamudra Nayak, Rashmi Dhamija, Vishnu Rajagopal, Haritha CP, Sovan Sau, Abhishek Saha, and Karthik Jain M. Thank you all very much for providing the helping hand during the entire duration of preparation till the conclusion. We would also thank the Vice-Chancellor, University of Hyderabad, and the Director, IIT Hyderabad, for their constant support and encouragement and the staff members both at the School of Physics, University of Hyderabad, and Department of Physics, IIT Hyderabad for providing the assistance whenever needed. Needless to say, the conference would not have been possible without the active and financial support from University of Hyderabad and IIT Hyderabad.

We would like to express our sincere thanks to Dr. Loyola D'Silva, Publishing Editor (Springer Nature, Singapore) and Ms. Shalini Monica C., Project Coordinator (Springer Nature, India) for constantly working with us from the beginning to bring out this volume.

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Part I
Gravitation and Cosmology

Chapter 1
Re-visiting Gravitational Wave Events with Pulsars as Weber Detectors

Ajit M. Srivastava

Abstract Many gravitational wave (GW) signals have been detected by LIGO and Virgo. These waves reached earth directly from their respective sources. We consider the possibility that, when these waves travel to different pulsars causing (tiny) transient deformations in the pulsar shape, then the resultant transient change in the pulsar moment of inertia may be detectable by the extremely precisely measured pulsar signals. This is especially likely when the signal frequency is in resonance with some neutron star oscillation mode. In this situation, the pulsars will act as a remotely stationed Weber gravitational wave detector. This technique also allows us to detect past GW events where the direct signals were missed. We have considered various GW events, for example different supernova events as recorded in astronomical records, and have determined specific pulsars whose signals should carry the imprints of these GW events reaching earth in near future.

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1.1 Introduction

Detection of gravitational waves (GW) by LIGO and Virgo has allowed us to observe remarkable events of coalescing black holes (BH) as well as neutron stars. We discuss a new class of GW detectors [1]. We consider the deformations caused by the gravitational wave (GW) passing through a pulsar. This leads to variation in its moment of inertia affecting spin rate of the pulsar as well as its pulse profile. Careful monitoring of extremely precisely measured pulses from the pulsars can reveal the arrival of GW signals on those pulsars. The effect will be most pronounced at resonance. The pulsars thus act as remotely stationed Weber detectors of gravitational waves with their signals being monitored on earth [1]. A very important use of this technique will be in detection of those GW events whose direct GW signal reached earth in

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past. Knowing the GW source, and the locations of different pulsars allows us to predict when the imprints of that particular GW event can be seen on the specific pulsar signal in future. This allows for re-visiting the same source again and again via different pulsars giving us opportunity to make detailed investigations of that GW source, along with the properties of the relevant pulsar interiors. It is known that a typical supernova event can be a powerful source of GW emission [5]. With the location and date of these events known, our technique allows us to directly observe that specific supernova event, in some sense allowing us to visit past events. Clearly there will be numerous GW events (supernova events, merger events etc.) which are not even identified by any known records. Continuous monitoring of pulsar signals for such transient perturbations can reveal existence of such GW sources.

The most crucial element underlying this proposal is extreme accuracy with which pulsar signals are monitored on earth. We will start by discussing the basic features of the pulsar signals in the next section. We will also briefly recall our earlier work [2] where it was proposed that this extreme precision of pulsar observations can be used to monitor density fluctuations occurring inside pulsar cores, e.g. those occurring during a phase transition. We will also discuss that these density fluctuations can lead to rapidly changing quadrupole moment of the pulsar leading to GW emission. In subsequent section we will then discuss the response of the neutron star (NS) to external GWs and show that it can act as a Weber detector at resonance. We will then discuss specific past GW events and make predictions of specific dates on which such past GW events can be seen imprinted on different pulsar signals.

1.2 Pulsars and Phase Transitions

We start by recalling basic properties of a pulsar which is a rapidly rotating neutron star. Neutron stars typically form in supernova explosions. Their masses are typically in the range of 1–2 solar mass, and radius about 10–15 km. Central density of NS can be as high as 5–10 times the nuclear equilibrium density of $0.16/\text{fm}^3 \simeq 10^{14}$ grams/cm^3. It is believed that there is a superfluid phase of nucleons in the interior of neutron stars. Observational evidence for this superfluid nucleonic phase arises from pulsar observations. Pulsars are rapidly rotating neutron stars, detected by their periodic pulses (electromagnetic waves), which are beamed emission from the magnetic poles of the neutron star. Superfluid phase in the pulsar interior allows for vortex lattice to form. These vortices are pinned at the interface with the pulsar crust. Many pulsars show the phenomenon of glitches which is a rapid increase in the rotation speed of the pulsar, followed by a slow relaxation. The most consistent explanation for these glitches is in terms of vortex depinning from crust. We mention here that there have been observations of anti-glitches (sudden slowing down of pulsar) which cannot be accounted for by this vortex-depinning mechanism.

Pulsar timings are extremely precisely measured, indeed they are the best clocks available in space. For example, the pulsar J0437-4715 has a pulse time period P = 0.005757451936712637 sec. This is known with the error of 1.7×10^{-17} sec. We use this incredible precision for detecting changes occurring in the configuration of a neutron star. We have argued that this extreme accuracy of pulsar timings can be used to probe various phase transitions occurring inside the pulsar core, for example transitions to exotic phases of QCD, or nucleonic superfluidity [2]. We used association of phase transitions with density fluctuations which inevitably arise during phase transitions. Importantly, the statistical properties of the density fluctuations crucially depend on the nature of the phase transition. Any density fluctuations in the neutron star will have observational effects. It will affect its moment of inertia (MI) and quadrupole moment Q which can be detected by precision measurements of pulse shape/timing. Note that these changes in MI and Q can have both signs, + and $-$. Random density fluctuations will lead to changes in all components of MI tensor. Changes in the diagonal components of MI will result in rapid changes in the rotation of pulsar. As density fluctuations dissipate away, leading to a uniform new phase in the core, some part of change in MI will be restored, but not fully. This is exactly the pattern of glitches and anti-glitches where often only few percent of the change in rotation is recovered. Also, as we find changes of both $+$ and $-$ sign in MI, glitches and anti-glitches are both naturally accommodated in this picture. Importantly, there has to be also transient change in the off-diagonal components of MI and Q. These are distinctive predictions of our model. Changes in off-diagonal components will lead to wobbling of star (on top of any present initially). This will lead to modulation of pulse intensity as the direction of radiation emission wobbles. We have made estimates of the changes in MI and Q for specific models, e.g. first order phase transition with specific bubble sizes, formation of QCD Z(3) strings/domain walls, as well as formation of superfluid vortices in a nucleon superfluid phase transition. We estimate fractional changes of various components of MI and Q caused by density fluctuations in these cases. Due to large range of distance scales involved (from relevant correlation lengths to pulsar core size), one needs to extrapolate the results. With these limitations we expect fractional changes in various moment components of order ranging from 10^{-14} to 10^{-10}.

An important implication of these density fluctuation is that rapid changes in quadrupole moment Q will lead to gravitational waves. We get a small value of Q/I arising from density fluctuations of order 10^{-10} which is much smaller than the value of 10^{-6} typically invoked from structural deformation in a neutron star. However, it is more than compensated by the very short time scale of microseconds when gravitational wave (GW) power is calculated as GW power is proportional to the square of third time derivative of the quadrupole moment. Fastest time scale for conventional mechanism of gravitational wave emission is milliseconds (from pulsar rotation), with the largest values of Q/I of order 10^{-3}. In our case, for phase transitions, Q/I is very tiny, of order 10^{-10}. However, here the time scale is at most microseconds. In fact, for topological defect induced density fluctuations, the time scale can be much shorter as initial defect network coarsens very fast. This very short time scale can lead to powerful GW bursts even for such tiny changes in Q/I thereby providing a new source of gravitational radiation.

1.3 Pulsars as Weber Detectors

Now we discuss changes in pulsar due to external influence. A gravitational wave passing through a pulsar will cause (very) tiny deformations in the pulsar shape, affecting its rotation. The effect will be most pronounced at resonance and may be detectable by accurate observations of the pulsar signal. We will argue below that resonance is likely with pulsar equation of state and tidal deformability constrained by recent BNS merger event. The pulsar, thus, acts as a remotely stationed Weber detector of gravitational waves whose signal can be monitored on earth [1].

Consider a pulsar under influence of external gravitational waves (GW), coming, say, from a merger event far away. For simplicity, we take the equilibrium configuration of the pulsar to be spherical. Under the influence of external gravitational wave, the pulsar will undergo quadrupolar deformations. Deformation of neutron star in the Tidal field E_{ij} of the gravitational wave is given by

$$Q_{ij} = -\lambda_d E_{ij} \ . \tag{1.1}$$

E_{ij} is the tidal field of the external GW and λ_d is the tidal deformability given by $\lambda_d = \frac{2}{3}k_2\frac{R^5}{G}$. k_2 is known as the second Love number. Recent BNS mergers have put constraints on the value of k_2 to be in the range $k_2 \simeq 0.05 - 0.15$ [3]. $E_{ij} = R_{i0j0}$ ($R_{\mu\nu\lambda\rho}$ being the Riemann curvature tensor) can be written in terms of GW strain amplitude for a specific polarization in the transverse traceless (TT) gauge. For a GW with wavelength λ, denoting the strain h_+ for the $+$ polarization by h, the amplitude of resulting E_{ij} is given by

$$E_{xx} = -E_{yy} = \frac{2\pi^2 hc^2}{\lambda^2}, \tag{1.2}$$

For simplicity, we take the initial NS configuration to be spherically symmetric, and the deformation to be ellipsoidal, with the dimension in the direction of GW propagation remaining unchanged. Then using (1.1) and (1.2), we get the change in the moment of inertia of the NS to be [1]

$$\frac{\Delta I_{xx}}{I} = -\frac{\Delta I_{yy}}{I} \simeq \frac{k_2}{3}\frac{R^3c^2}{GM\lambda^2}20h \tag{1.3}$$

Here M is the mass of NS and R is its equilibrium radius. We will use sample values $M = M_{Sun}$ and R = 10 km. Highest sensitivity will be reached for smallest values of λ (we mention that the above equations are valid for static case, this requires λ to be much larger than NS radius. Range of frequencies we consider are below kHz, so this approximation holds).

As a typical astrophysical source of GW, we take binary neutron Star (BNS) merger, such as the one detected by LIGO/Virgo The highest value of GW frequency being about 1 kHz, and we use k2 = 0.1 as a sample value. This gives $\frac{\Delta I_{xx}}{I} = 10^{-2}h$.