Gravitational Waves and the 2017 Nobel Prize in Physics

GUNGWON KANG
KOREA INSTITUTE OF SCIENCE AND TECHNOLOGY INFORMATION

ABSTRACT

Gravitational waves (GWs) were directly measured for the first time during the first observation run (O1) of the Laser Interferometer Gravitational-wave Observatory (LIGO) in 2015, i.e., GW150914. Its source turned out to be a merging binary black hole system having about 36 and 29 solar masses at a distance of about 1.3 billion light years. One more observation during O1 and four observations during O2 have been announced. Virgo started its operation on August 1, 2017 and measured two events jointly together with two LIGO observatories, resulting in the sky localization of the source about 10 times better than what would have been obtained by solely two LIGOs. The first four observations were all from stellar-mass binary black holes, and are giving many interesting implications on black hole formation and evolution. The most recently observed GWs were from a merging binary neutron star, and electro-magnetic (EM) signals such as gamma-ray, light, X-ray and radio signals were detected as well through its follow-up searches. We are indeed in the era of GW astronomy. The 2017 Nobel Prize in Physics has been awarded to Rainer Weiss, Kip Thorne and Barry Barish for their pioneering contributions to the LIGO detector and observation of gravitational waves. In this article, the roles of the three winners and some of the main science results obtained in GW observations are briefly summarized. Current activities in GW detection experiments and future perspectives are also discussed briefly, and activities of some groups in Asia are also introduced.

INTRODUCTION

The Newtonian theory of gravitation concerns interactions between matters having masses. It beautifully explained the orbit motions of planets in the solar system. Space and time, on the other hand, was an absolute background frame which was not affected at all by objects or their motions in it. Such a long-standing viewpoint changed when Einstein proposed the theory of general relativity in 1915. He found that spacetime background is affected by the presence of masses and indeed interacts with them dynamically. Gravitation is nothing but geodesic motions of two masses in a curved spacetime whose curvature is caused by the matter.

What is a Gravitational Wave?

When a mass distribution confined in a region changes in time, spacetime responds accordingly. This varying spacetime curvature around will propagate away. Such ripples of spacetime curvature propagating are called gravitational waves (GWs). In 1916, Einstein considered a weak perturbation $h_{\alpha\beta}$ of flat spacetime $\eta_{\alpha\beta}$ in a vacuum [1];

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta} \text{ with } |h_{\alpha\beta}| \ll 1.$$

It turned out that the weakly perturbed metric behaves like massless spin-2 fields propagating at the speed of light c. Namely, Einstein equations are linearized to

$$\left(-\frac{1}{c^2}\partial_t^2 + \partial_x^2 + \partial_y^2 + \partial_z^2\right)h_{\alpha\beta} \approx 0.$$

A gravitational wave is produced by accelerated masses just as an electromagnetic wave is generated when charges are accelerated.

What is the Effect of a GW?

The spacetime metric changes when a GW passes. Consequently, the distance between two positions varies. Any gravitational wave in linearized gravity can be expressed as a sum of two polarizations, namely, plus- and cross-polarizations. When a polarized GW passes on a plane, the distance in one direction shrinks while the distance in the direction perpendicular to it stretches. This becomes reversed and repeats as time goes on. It, however, is not true that deformation due to a GW occurs for all matter in the same way. Consider two separate rings lubricated on a rigid cylindrical bar. Two rings will move almost freely along the bar direction following their geodesic lines in the metric modified by the GW whereas the proper length of the cylindrical bar does not change much due to "repulsive" forces among molecules in it. Then, a passage of a GW will cause motions of the rings relative to the bar, generating some frictional heat in the lubricant. Thus, GWs could carry some sort of "energy" indeed [2]. Strain is defined by the ratio between the variation and its original length, and related to a GW by $\Delta L/L \sim h_{GW}$.

How Strong is the Effect?

A dumbbell of 1 ton mass each at 2-m of distance rotating at the speed of 1 kHz generates a GW of $h \sim 2.6\times10^{-33}/R$ observed at a distance R. A particle accelerator such as LHC in which 10^{11} protons per bunch are orbiting almost at the speed of light produces $h \sim 10^{-43}/R$. These are extremely weak signals, and so we should turn to space for strong sources. Compact binary systems such as black hole binaries, neutron star binaries, and black hole - neutron star systems are good candidates. A binary black hole coalescence of 10 solar masses at about 200Mpc away could produce $h \sim 10^{-21}$. Thus, strengths of GWs from astrophysical sources are enormously large compared to those from surrounding sources on Earth. However, even such astrophysical GWs can cause extremely small variations in length. For instance, for L ~ diameter of the Earth, $\Delta L \sim 10^{-21}\times L \sim 10^{-14}$m, which is the size of a nucleon. Therefore, it is still extremely hard to measure such a tiny variation even in astronomical origin.

How to Detect GWs?

In the 1960s Joe Weber, at the Univ. of Maryland, pioneered a detection experiment for GWs by using a resonant-mass cylindrical bar. The aluminum bar would vibrate when a GW passes through at the resonant frequency of the bar, ~1657Hz, which may cause some voltage signals in the piezoelectric sensors attached on the bar surface [3]. Its strain sensitivity reached up to $\sim 10^{-16}$ and later $\sim 10^{-19}$ by using cryogenics up to 0.1K. This resonant-bar experiment did not detect GWs, presumably because its sensitivity was not good enough to measure the expected strength from typical astrophysical sources, $\sim 10^{-21}$.

It, however, should be pointed out that the existence of GWs was indirectly confirmed by measuring the periodic radio signals coming from the Hulse-Taylor binary pulsar, PSR B1913+16. Radiation through GWs implies some energy loss from a binary system, resulting in decreases of the orbital period. Indeed, timing measurements over decades showed a very accurate agreement with the theoretical prediction of gravitational radiation damping by general relativity [4].

LIGO AND THREE NOBEL LAUREATES

A new type of GW antenna using a Michelson-like interferometer was also considered during the late 60's and early 70's. The basic concept was to measure the phase difference between two light beams traveling in the interferometer arms whose lengths would be deformed by a passing GW. A leading order calculation actually shows that, for a freely falling observer at the beam splitter, two L-shaped arm lengths change differently when a GW passes whereas the light's wavelength is not affected [5]. Rainer Weiss at the Massachusetts Institute of Technology (MIT) wrote a technical report in 1972 describing the design of such an interferometric detector and detailed analyses of almost all major noise sources [6]. This report became the blueprint for the Laser Interferometer Gravitational-wave Observatory (LIGO).

In the late 60's, Kip Thorne, along with his research group at the California Institute of Technology (Caltech), worked on the theory of gravitational waves and their astrophysical sources, formulating a vision for GW astronomy. After the so-called fateful hotel room discussion with Weiss at Washington D.C. in 1975, Thorne became convinced that GW detection with Weiss's interferometer idea was possible, and later succeeded in creating an experimental group at Caltech led by Ronald Drever, who was recruited from Glasgow in 1979. Based on the "Blue Book" report and the promising results from both MIT and Caltech prototypes, the National Science Foundation (NSF) of the United States in 1984 initiated a Caltech-MIT joint project, which was the beginning of LIGO, led by Weiss, Drever and Thorne. The construction of LIGO was approved in 1990 with a cost of about 300 million US dollars.

LIGO had to be scaled up from a "tabletop" science project, conducted by MIT and Caltech, to a major scientific endeavor with international collaborations. Barry Barish at Caltech, who had experience of leading several large particle physics projects, came to the stage. He led the construction of LIGO facilities at the Hanford and Livingston sites from 1994 to 1998, and then oversaw the installation and commissioning of its initial interferometers from 1999 to 2002 and the first data-taking science runs from 2002 to 2005. In 1997, he also created the LIGO Scientific Collaboration (LSC) in which the most qualified researchers from other universities and countries were given equal opportunities to conduct technical and scientific research and data analysis.

LIGO started its upgrade to Advanced LIGO (aLIGO) after the sixth science run (S6) in 2010, which took about five years. The sensitivity of aLIGO reached a level that was 3 to 4 times better than that of the initial LIGO. The first direct observation of GWs occurred on September 14, 2015, just two days after the first observation run (O1) started its operation [7]. Weiss's pioneering design and noise analysis, Thorne's theoretical support and vision, and Barish's brilliant organization finally led to this LIGO discovery in 2015. Due to their decisive contributions to the LIGO detector and the resultant observation of GWs, Rainer Weiss, Kip Thorne and Barry Barish were awarded the 2017 Nobel Prize in Physics.

CURRENT STATUS OF GW OBSERVATIONS

There were two detections of GWs during O1 (Sept. 12, 2015 ~ Jan. 12, 2016) and four during O2 (Nov. 30, 2016 ~ Aug. 25, 2017). Table 1 shows astrophysical parameter values estimated from the signal waveforms of these events. Advanced Virgo joined O2 from Aug. 1st to 25th in 2017, improving LIGO's sky localization to a level that was approximately 10 times better. GWs in all the first five events turned out to have come from coalescences of stellar-mass binary black holes at luminosity distances of 340~880 Mpc. The component mass appeared to have ~36 M⊙, at largest, which was much larger than the maximum mass of what had been believed, ~20 M⊙, in many scenarios of stellar-mass binary black hole formations. Data analyses in detail have shown that all results are in good agreement with the predictions in general relativity.

The latest GW detection event GW170817 was observed on Aug. 17, 2017 with a merger time at 12:41:04 UTC, which lasted for about 100 s. This event was especially important because it was, for the first time, from a binary neutron star merger. A colliding neutron star binary system is highly expected to emit various signals in the form of electromagnetic waves as well after the emission of GWs, and it is of interest to see how the follow-up search has been done. On 2017 August 17 12:41:06 UTC a gamma-ray burst (GRB 170817A) was independently observed by the Fermi Gamma-ray Burst Monitor (Fermi-GBN), and a Gamma-ray Coordinates Network (GCN) Notice was issued ~16 s later. Then, about 6 minutes later, a GW trigger was registered by LIGO Hanford only in low latency, showing its signal consistent with coalescence of a binary neutron star with a merger time, 1.7 s before GRB 170817A. A GCN Circular was issued about 40 minutes after the merger, reporting that a significant GW candidate was associated with the GRB time. An extensive electro-magnetic (EM) follow-up search campaign was launched using traditional observing facilities in response to the Fermi-GBM and LIGO-Virgo detections. About five hours later, the data from two LIGOs and Virgo were jointly analyzed to produce a well constrained sky localization map for the source having mass range of binary neutron stars (BNS), namely, a region of ~31 deg^2 centered around (12^h57^m, $-17^\circ51'$) at a luminosity distance of ~40 Mpc. Notice that the Fermi-GBM only gave a sky region of ~1100 deg^2, which was too broad to locate the source quickly. The follow-up searches led to multiple observations of optical transients from the same location near NGC 4993, including the first one by Swope about 11 hours after the merger. Subsequently, emissions - infrared by Gemini, ultraviolet by Swift, X-ray by Chandra and radio by VLA - were first detected ~13 hr, ~15 hr, ~9 days and ~16 days after the merger, respectively. However, ultra-high-energy

Table 1: Parameters estimated for GW sources. BBH: Binary Black Hole and BNS: Binary Neutron Star.

	GW150914	GW151226	GW170104	GW170608	GW170814	GW170817
Source	BBH	BBH	BBH	BBH	BBH	BNS
Signal-to-noise ratio	23.7	13	13	13	13.7	32.4
Primary mass (M⊙)	$35.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	$31.2^{+8.4}_{-6.0}$	12^{+7}_{-2}	$30.5^{+5.7}_{-3.0}$	1.36-1.60
Secondary mass (M⊙)	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	$19.4^{+5.3}_{-5.9}$	7^{+2}_{-2}	$25.3^{+2.8}_{-4.2}$	1.17-1.36
Chirp mass (M⊙)	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$21.1^{+2.4}_{-2.7}$	$7.9^{+0.2}_{-0.2}$	$24.1^{+1.4}_{-1.1}$	
Final mass (M⊙)	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	$48.7^{+5.7}_{-4.6}$	$18^{+4.8}_{-0.9}$	$53.2^{+3.2}_{-2.5}$	
Final spin	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.64^{+0.09}_{-0.20}$	$0.69^{+0.04}_{-0.05}$	$0.70^{+0.07}_{-0.05}$	
Luminosity distance (Mpc)	420^{+150}_{-180}	440^{+180}_{-190}	880^{+450}_{-390}	340^{+140}_{-140}	540^{+130}_{-210}	40^{+8}_{-14}
Tidal deformability						≤800
Remark	O1	O1	O2	O2	O2 & Virgo	O2 & Virgo

gamma-rays and neutrinos were not detected. All these observations strongly indicate that GW170817 was produced by a binary neutron star merger near NGC 4993 followed by a short gamma-ray burst and a kilonova [8]. The coinciding observations of a GW and a gamma-ray burst support the long-held hypothesis that a binary neutron star merger is a progenitor of short gamma-ray bursts. By combining the distance measured purely from GWs with the redshift of NGC 4993 measured from EM data, the Hubble constant was also estimated to be $H_0 = 70.0^{+12.0}_{-8.0}\ km/sMpc$, independent from previous measurements [9].

PERSPECTIVES

Up to now, LIGO has been extremely successful and the joint operation with Virgo could provide a quick alert with good sky localization for a binary neutron star merger, opening up a new kind of multi-messenger astronomy with GWs. Its third observation run (O3) is planned to be held sometime in the fall of 2018 with improved sensitivity. Peak sensitivity, as designed, will be achieved in 2019. The simultaneous LIGO-detector observing time during O2 was 117 days and there were four detections of GWs in total. It means that about one detection per month can be achieved in ideal operations. The sensitivity of LIGO detectors at O3 will be 2~4 times better than that of O2, which means that LIGO would be able to cover an approximately 8~64 times larger volume. In O3, consequently, there could be about 3~25 observations per month assuming about 40% of the duty cycle. Therefore, frequent observations of GWs are anticipated, and GW observatories on Earth could routinely be used for gravitational wave astronomy like traditional telescopes for EM signals. This new way of doing astronomy, however, will produce enormous scientific outcomes, and could uncover parts of the universe that were previously unexplored.

Finally, activities on GW sciences in some Asian countries are briefly summarized. The Japanese GW detection experiment KAGRA finished its initial operation early in 2016, and baseline-KAGRA will be ready for operation by March in 2020. The LIGO-India Project (IndIGO) was approved by the Indian government right after the announcement of the first detection of GWs in 2016. Its site selection has been completed, and its operation will begin sometime in the middle of the 2020s. (See the web sites for more information in detail [10].) Some of other major activities in Asian region are quoted below.

The Korean Gravitational Wave Group (KGWG), led by Hyung-Mok Lee: KGWG is a research consortium consisting of about 30 members working at universities or government funded institutes. The number of the LSC members is 16 and that of KAGRA ~15. Many of them are co-members. For LSC they have been working mainly on GW data analysis such as parameter estimation, waveform modeling and detector characterization in the CBC (Compact Binary Coalescence) group since 2009. For KAGRA instrumental works are also involved such as developing a tilt sensor for initial mirror alignment and measuring Newtonian noise with an atom interferometer in addition to developing the parameter estimation pipeline in KAGALI (KAGRA Algorithmic Library). Some of the members are also doing a pilot study for SOGRO (Superconducting Omni-directional Gravitational-wave Observatory) which is a new type of terrestrial tensor GW detector at bandwidth of 0.1~10 Hz using SQUID sensors to measure tiny differential motions of superconducting test masses levitated magnetically [11]. KISTI-GSDC LDG Tier-3 center is a computing facility supporting works on GW data analysis for LIGO and KAGRA experiments. It has 864 CPU cores and 550 TB storage [12]. (Web site: http://www.kgwg.org/)

The Group at Beijing Normal University, led by Zong-Hong Zhu: GW research within Beijing Normal University (BNU) is spearheaded by the astronomy department, under the formal banner of the “Gravitational Wave and Cosmology Laboratory”. Presently, there are six faculty members and around twenty students partaking in GW-related projects, in addition to two visiting faculty members from the University of Glasgow. The group members are actively engaged with KAGRA in the high frequency end, FAST (China’s Five hundred-meter Aperture Spherical Telescope) in the nano-hertz band through its pulsar timing program, and China’s CMB (cosmic microwave background) B-mode experiment at Ngari on the Tibetan plateau.

Previously, efforts were mainly concentrated in theoretical analyses, on such topics as stochastic GW background, the application of GW to cosmology, its lensing effects, laser cavity parametric instability, electromagnetic counterpart modeling, numerical relativity and waveform template construction. The group has nevertheless been training students with the aforementioned experimental collaborations. BNU has trained six LIGO members who are presently very active in different countries. As of 2014, we have been leading the intra-BNU inter-disciplinary project on gravitational wave astronomy. Together with our partners from the physics, computer sciences and system sciences departments, we have begun the construction of a data center for FAST, as well as clean rooms reserved for the development of laser technology relating to the third generation ground-based GW observatories. We are also in charge of the key program of the National Natural Science Foundation of China, entitled "GW Astronomy", and one branch ("Numerical Relativity and GW Templates") of its major program "Physics Relating to GW". (Web site: http://astrowww.bnu.edu.cn/)

The Group at National Tsing Hua University, led by Shiuh Chao: Prof. Shiuh Chao's group at National Tsing Hua University in Taiwan focuses on low loss coatings development. The group currently has one post-doc, two PhD students and nine master degree students. There is an in-house ion-beam sputter coater, room temperature and cryogenic mechanical loss measurement facilities for cantilever samples and a photo-thermal common path interferometer for optical loss measurement. Numerous facilities on chemical-vapor-deposition (CVD) and material characterization at the nearby National Nano-device Laboratory (NDL) are available to the group. Several subjects toward novel deposition methods, materials and layer structure are undertaken: developing low loss silicon-nitride thin films by using chemical vapor deposition (CVD) methods; developing and characterizing nanometer layer structures with TiO2-SiO2 pairs deposited by an ion-beam-sputter method in collaboration with the University of Sannio of Italy and California State University at Los Angeles of USA; and developing double-side coated, thin film suspended, "cat-flap" optomechanical devices in collaboration with the University of Western Australia. (Web site: http://crystal04.ee.nthu.edu.tw)

The Group at the Research Institute of Information Technology, Tsinghua University, led by Junwei Cao: The LIGO Scientific Collaboration research group at Research Institute of Information Technology, Tsinghua University has been working on gravitational-wave data analysis and computing infrastructure since 2009. These areas of research include GPU acceleration and optimization of online pipelines for compact binary coalescence searching, applying deep learning methods for real-time gravitational-wave data analysis, applying virtualization and cloud computing for gravitational-wave data platforms, etc. (Web site: http://elop.org.cn/)

The Group at the Chinese University of Hong Kong, led by Tjonnie Li: The gravitational-wave group at the Chinese University of Hong Kong consists of 15 members and has been making strong contributions to the key science goals of the LIGO Scientific Collaboration. We broadly study fundamental physics and astrophysics so that we can learn from the mergers of compact objects. This includes probing the strong field nature of gravity, measuring the nuclear equation of state that governs the properties of neutron stars, uncovering the effects of gravitational lensing by intervening compact objects, and understanding the origin of black holes. Moreover, we are actively contributing to the core analysis infrastructures such as the low-latency detection of gravitational-wave signals. (Web site: http://www.phy.cuhk.edu.hk/~tgfli/)

Acknowledgements: GK would like to thank Zong-Hong Zhu, Shiuh Chao, Junwei Cao and Tjonnie Li for providing brief descriptions of their respective groups' work on GW research.

References

[1] A. Einstein, Näherungsweise Integration der Feldgleichungen der Gravitation, Sitzungber. Preuss. Akad. Wiss. Berlin, part 1, 688 (1916).
[2] H. Bondi, Nature 179, 1072 (1957); R.P. Feynman in Proc. conf. on the role of gravitation in physics, Chapel Hill, North Carolina, Jan 18-23, 1957, Cecile M. DeWitt and Dean Rickles (eds.), www.edition-open-sources.org /sources/5/; F.A.E. Pirani, Phys. Rev. 105, 1089 (1957); J. Weber, ibid 117, 306 (1960).
[3] J. Weber, Phys. Rev. Lett. 17, 1228 (1966).
[4] J.M. Weisberg, D.J. Nice and J.H. Taylor, Astrophys. J. 722, 1030 (2010).
[5] K.S. Thorne and R.D. Blandford, Modern Classical Physics, Princeton University Press, p.1352 (2017).
[6] R. Weiss, Quarterly Progress Report of Research Laboratory of Electronics (MIT) 105, 54 (1972).
[7] B.P. Abbott et al., Phys. Rev. Lett. 116, 061102 (2016).
[8] LIGO Scientific Collaboration et al., Astrophys. J. Lett. 848, L12 (2017).
[9] LIGO Scientific Collaboration et al., Nature 551, 85 (2017).
[10] KAGRA: http://gwcenter.icrr.u-tokyo.ac.jp/en/, IndIGO: http://www.gw-indigo.org.
[11] H.J. Paik et al., Class. Quantum Grav. 33, 075003 (2016).
[12] Configurations of this facility may be found on http://watchtower.phys.uwm.edu/ganglia-webfrontend/?c=LDG-KISTI&m=load_one&r=year&s=by%20name&hc=4&mc=2.

Gungwon Kang is a member of LIGO and KAGRA and a Principal Researcher at Supercomputing Center of Korea Institute of Science and Technology Information (KISTI). After studying at Yonsei University and at University of Maryland for Ph.D. in theoretical general relativity, he worked at various places including Raman Research Institute, KEK and KIAS. He is currently working on GW physics and pilot study for SOGRO, and also serves as the coordinator of the International Block of LSC Fellows Program.