様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

4版

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

令和　元 年　６ 月 ２０ 日現在

機関番号：１２６０１
研究種目：研究活動スタート支援
研究期間：2016～2017
課題番号：１６Ｈ０６７１４
研究課題名（和文）Low-Latency Compact Object Searches with LIGO, Virgo and KAGRA in O2 and O3

研究課題名（英文）Low-Latency Compact Object Searches with LIGO, Virgo and KAGRA in O2 and O3

研究代表者
カンノン　キップ（Cannon, Kipp）

東京大学・大学院理学系研究科（理学部）・准教授

研究者番号：５０７７７８８６

交付決定額（研究期間全体）：（直接経費）　　2,300,000円

研究成果の概要（和文）：本研究の目的は２つある。(i) 重力波信号を検出するためのパイプライン (GstLAL: https://wiki.ligo.org/Computing/DASWG/GstLAL) を拡張し、日本の検出器 KAGRA からのデータも処理できるようにすること、(ii) 海外の重力波検出器 LIGO と VIRGO の第２回観測期間中にブラックホールと中性子星の合体による重力波信号の探索を行うこと、である。我々はこれらの目標を達成し、更に大きな成果として中性子星連星合体からの重力波信号を GstLAL によって発見した。

研究成果の学術的意義や社会的意義
The discovery of GW170817 altered our understanding of the origin of heavy elements, and showed us that gravity moves at the speed of light, which had a significant impact on our understanding of the nature of gravity.

研究成果の概要（英文）：This project had two main goals: (i) generalize the GstLAL gravitational-wave signal detection system (https://wiki.ligo.org/Computing/DASWG/GstLAL) so that it will be able to process data from the future Japanese KAGRA detector; (ii) search for gravitational waves from black hole and neutron star collisions in Advanced LIGO and Advanced Virgo's second observing run. Both goals were achieved. Notable among the accomplishments was the GstLAL detection system's discovery of GW170817, the first gravitational wave from a neutron star collision.

研究分野：Astrophysics

キーワード：gravitational wave　black hole　neutron star　LIGO　Virgo　KAGRA　signal processing

1　研究開始当初の背景

Gravitational waves are produced by the movement of mass and momentum. They are the gravitational analogue of electromagnetic waves, which are produced by the movement of electric and magnetic charges. Gravitational waves were first detected in 2015, and since then have provided a new, and only, rich, window onto the behaviour of gravity in the strong-field, dynamic, regime. Today, gravitational waves from the collisions of black holes and of neutron stars are observed using three, kilometre scale, gravitational-wave antennas in the United States (two LIGO antennas) and Europe (Virgo antenna). Shortly, Japan will complete the construction and commissioning of the world's 4th kilometre-scale gravitational wave antenna, the KAGRA detector in Gifu prefecture.

To discover gravitational waves from astronomical sources like black hole collisions or neutron star collisions, it is not sufficient to construct a gravitational-wave antenna like KAGRA. The data from the antenna is contaminated with noise, some of which arises from the antenna itself, some arises from mechanical and electrical disturbances from the surrounding environment, and even some gravitational noise is present. Identifying the presence of signals in all of this noise, determining the properties and location of their sources, requires the use of a signal detection software system. One such system is the GstLAL detection system [1, Other].

2　研究の目的

The goals of this project were: (i) to upgrade the GstLAL [1, Other] detection system to be compatible with modern computer systems; (ii) to increase its sensitivity by improving its ability to differentiate signals from noise; (iii) to use the system to search for gravitational-wave signals in the O2 and O3 data-taking runs of the Advanced LIGO and Advanced Virgo detectors; and (iv) to modify the system so that it can be used to analyze data from Japan's KAGRA antenna when the antenna is completed.

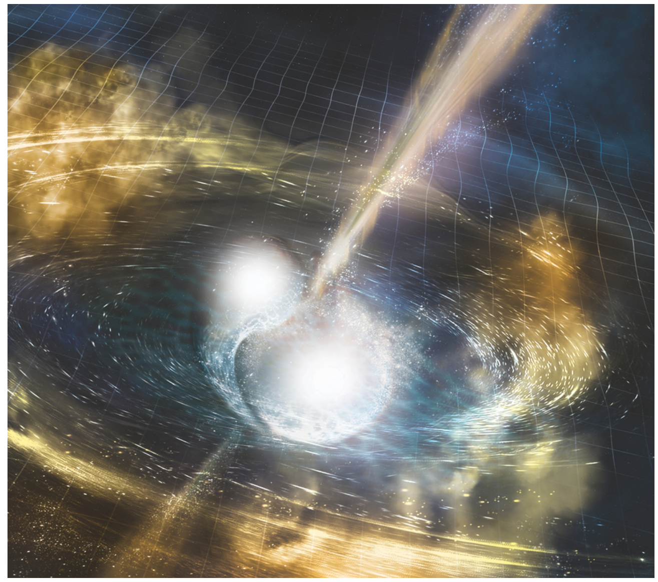
3　研究の方法

1. For the first goal, the GstLAL system was to be converted from using the 0.10 version of the GStreamer signal processing library on which it is built, to the modern 1.x versions of the GStreamer library.
2. The GstLAL system uses a Bayesian classifier to differentiate signals from noise. This system employs a two-step process: firstly, signal candidates are identified in the data streams from the antennas using a basic matched filter system; secondly, a vector of physical parameters describing each signal candidate's appearance in the data is computed and a Bayesian classifier is employed to assess the statistical significance of each parameter vector. For the second goal, the Bayesian classifier was to be generalized to include additional physical characteristics of each potential signal, including the phase of the signal observed in each antenna, and the time delays between its observation in each of the antennas. The classifier was also to be generalized to track the time dependence of some parameters it was already using, including the relative sensitivities of the detectors in the network and their mean glitch (non-Gaussian transient noise) rates.
3. For the third goal, having accomplished the first two goals the new system was to be run on computer systems at the California Institute of Technology and the University of Wisconsin-Milwaukee to search for and detect gravitational-wave signals in the O2 and O3 data from the Advanced LIGO and Advanced Virgo detectors.
4. For the fourth and final goal, the process of generalizing the Bayesian classifier in goal #2 was to be carried out in such a way that the new classifier software would be able to trivially accommodate a new, fourth, detector, the KAGRA detector.

4　研究成果

The goals were almost entirely completed. The GstLAL detection system that has been the focus of this work is publicly available, distributed under a free/libre software license (GPL version 2), and can be downloaded from the project's web page [1, Other].
1. The GstLAL detection system is now compatible with modern computer systems. Since starting this project, the Python 2 language on which the GstLAL system is built has been abandoned by all of the other software

components on which the GstLAL system relies, and so in the future the GstLAL system will need to be converted to the Python 3 language, however the immediate upgrade requirements have been met.
2. & **4.** The GstLAL detection system's Bayesian classifier has been generalized to track time dependence and additional physical parameters of candidate signals, and to accommodate the KAGRA antenna. Descriptions of the theory underlying the work can be found in [22, Papers], [2, Papers].
3. The improved GstLAL detection system was run on Advanced LIGO and Advanced Virgo's O2 data set. Originally the goal was also to analyze O3, but the start date was delayed past the end of the award's funding period, therefore only O2 data was analyzed. This, however, was a great success for the project. **Most notably, the GstLAL detection system discovered the neutron star collision GW170817 [19, Papers], [18, Papers]**. Of the six analysis systems operating at the time, only GstLAL found the signal. The superior sensitivity of the GstLAL system was in part achieved by this project.



Credit: NSF/LIGO/Sonoma State University/A. Simonnet

Other major discoveries of the GstLAL system during O2 include GW170814 [20, Papers], the first gravitational wave detected with the Advanced Virgo detector, and the discovery that established for the first time both the independent reproducibility of the LIGO gravitational-wave observations and also the veracity of the calibration and sensitivity of the Virgo detector. The latter was critical is identifying the location of the source of the GW170817 neutron star collision, allowing its optical counterpart to be identified: since Virgo did not see the GW170817 signal, Virgo's non-detection was used to isolate the source to one of the relatively small sky areas to which the Virgo detector was blind.

5　主な発表論文等

Papers (22)

[1] Soares-Santos, M., ..., Cannon, K. *et al.* (DES Collaboration and LIGO Scientific Collaboration and Virgo Collaboration). First measurement of the Hubble constant from a dark standard siren using the Dark Energy Survey galaxies and the LIGO/Virgo binary–black-hole merger GW170814. *Astrophys. J.*, 876(1):L7, April 2019. doi:10.3847/2041-8213/ab14f1. (refereed, 240th author of 1202), `arXiv:1901.01540 [astro-ph.CO]`.

[2] Hanna, C., Caudill, S., Messick, C., Sachdev, S., Cannon, K., Blackburn, K., Creighton, J. D. E., Fong, H., Godwin, P., Kapadia, S., Li, T. G. F., Magee, R., Meacher, D., Mukherjee, D., Pace, A., Privitera, S., Lo, R. K. L., and Wade, L. Fast evaluation of multi-detector consistency for real-time gravitational wave searches, 2019. (review in progress) `arXiv:1901.02227 [gr-qc]`.

[3] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Search for transient gravitational-wave signals associated with magnetar bursts during Advanced LIGO's second observing run. *Astrophys. J.*, 874(2):163, April 2019. doi:10.3847/1538-4357/ab0e15. (refereed, 153th author of 1130), `arXiv:1902.01557 [astro-ph.HE]`.

[4] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Search for gravitational waves from a long-lived remnant of the binary neutron star merger GW170817. *As-*

trophys. J., 875(2):160, April 2019. doi:10.3847/1538-4357/ab0f3d. (refereed, 166th author of 1163), `arXiv:1810.02581 [gr-qc]`.

[5] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Low-latency gravitational wave alerts for multi-messenger astronomy during the second Advanced LIGO and Virgo observing run. *Astrophys. J.*, 875(2):161, April 2019. doi:10.3847/1538-4357/ab0e8f. (refereed, 154th author of 1136), `arXiv:1901.03310 [astro-ph.HE]`.

[6] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Constraining the p-mode–g-mode tidal instability with GW170817. *Phys. Rev. Lett.*, 122(6):061104, February 2019. doi: 10.1103/PhysRevLett.122.061104. (refereed, 167th author of 1162), `arXiv:1808.08676 [astro-ph.HE]`.

[7] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Properties of the binary neutron star merger GW170817. *Phys. Rev. X.*, 9(1):011001, January 2019. doi: 10.1103/PhysRevX.9.011001. (refereed, 167th author of 1172), `arXiv:1805.11579 [gr-qc]`.

[8] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs, 2019. (review in progress) `arXiv:1811.12907 [astro-ph.HE]`.

[9] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Binary black hole population properties inferred from the first and second observing runs of Advanced LIGO and Advanced Virgo, 2019. (review in progress) `arXiv:1811.12940 [astro-ph.HE]`.

[10] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Search for subsolar-mass ultracompact binaries in Advanced LIGO's first observing run. *Phys. Rev. Lett.*, 121(23):231103, December 2018. doi:10.1103/PhysRevLett.121.231103. (refereed, 167th author of 1161), `arXiv:1808.04771 [astro-ph.CO]`.

[11] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW170817: Measurements of neutron star radii and equation of state. *Phys. Rev. Lett.*, 121(16):161101, October 2018. doi:10.1103/PhysRevLett.121.161101. (refereed, 167th author of 1174), `arXiv:1805.11581 [gr-qc]`.

[12] Abbot, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Constraints on cosmic strings using data from the first Advanced LIGO observing run. *Phys. Rev.*, D97(10):102002, May 2018. doi:10.1103/PhysRevD.97.102002. (refereed, 150th author of 1064), `arXiv:1712.01168 [gr-qc]`.

[13] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW170817: Implications for the stochastic gravitational-wave background from compact binary coalescences. *Phys. Rev. Lett.*, 120(9):091101, February 2018. doi:10.1103/PhysRevLett.120.091101. (refereed, 156th author of 1120), `arXiv:1710.05837 [gr-qc]`.

[14] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Search for post-merger gravitational waves from the remnant of the binary neutron star merger GW170817. *Astrophys. J.*, 851(1):L16, December 2017. doi:10.3847/2041-8213/aa9a35. (refereed, 157th author of 1126), `arXiv:1710.09320 [astro-ph.HE]`.

[15] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). On the progenitor of binary neutron star merger GW170817. *Astrophys. J.*, 850(2):L40, December 2017. doi: 10.3847/2041-8213/aa93fc. (refereed, 155th author of 1116), `arXiv:1710.05838 [astro-ph.HE]`.

[16] Albert, A., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Search for high-energy neutrinos from binary neutron star merger GW170817 with ANTARES, IceCube, and the Pierre Auger observatory. *Astrophys. J.*, 850(2):L35, November 2017. doi:10.3847/2041-8213/aa9aed. (refereed, 1011th author of 1973), `arXiv:1710.05839 [astro-ph.HE]`.

[17] Abbot, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, 1M2H Collaboration, Dark Energy Camera GW-EM Collaboration and the DES Collaboration, DLT40 Collaboration, Las Cumbres Observatory Collaboration, VINROUGE Collaboration, MASTER Collaboration). A

gravitational-wave standard siren measurement of the Hubble constant. *Nature*, 551:85–88, November 2017. doi:10.1038/nature24471. (refereed, 167th author of 1422), `arXiv:1710.05835 [astro-ph.CO]`.

[18] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration, the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech- NRAO, TTU-NRAO, NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS, RATIR, SKA South Africa/MeerKAT). Multi-messenger observations of a binary neutron star merger. *Astrophys. J.*, 848(2):L12, October 2017. doi:10.3847/2041-8213/aa91c9. (refereed, 157th author of 3673), `arXiv:1710.05833 [astro-ph.HE]`.

[19] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW170817: Observation of gravitational waves from a binary neutron star inspiral. *Phys. Rev. Lett.*, 119(16):161101, October 2017. doi:10.1103/PhysRevLett.119.161101. (refereed, 159th author of 1144), `arXiv:1710.05832 [gr-qc]`.

[20] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW170814: A three-detector observation of gravitational waves from a binary black hole coalescence. *Phys. Rev. Lett.*, 119(14):141101, October 2017. doi:10.1103/PhysRevLett.119.141101. (refereed, 157th author of 1128), `arXiv:1709.09660 [gr-qc]`.

[21] Abbott, B. P., ..., Cannon, K. *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, Fermi Gammay-Ray Burst Monitor, and INTEGRAL). Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. *Astrophys. J.*, 848(2):L13, October 2017. doi:10.3847/2041-8213/aa920c. (refereed, 157th author of 1177), `arXiv:1710.05834 [astro-ph.HE]`.

[22] Messick, C., Blackburn, K., Brady, P., Brockill, P., Cannon, K., Caudill, S., Chamerlin, S. J., Creighton, J. D. E., Everett, R., Hanna, C., Lang, R. N., Li, T. G. F., Meacher, D., Pankow, C., Privitera, S., Qi, H., Sachdev, S., Sadeghian, L., Sathaprackash, B., Singer, L., Thomas, E. G., Wade, L., Wade, M., and Weinstein, A. Analysis framework for the prompt discovery of compact binary mergers in gravitational-wave data. *Phys. Rev.*, D95(4):042001, February 2017. doi:10.1103/PhysRevD.95.042001. (refereed, 5th author of 27), `arXiv:1604.04324 [astro-ph.IM]`.

Presentations (15)

[1] Cannon, K., 2018-10-07, Conference (invited), Taipei Gravitational-Wave Group Conference, "Identification and Significance Assessment of Compact Object Merger Candidates."

[2] Cannon, K., 2018-05-22, Conference (invited Dunlap Prize lecture), Canadian Astronomical Society Annual Meeting, "The Unlikely Dawn of Joint Gravitational-Wave and Electromagnetic Astronomy."

[3] Cannon, K., Yokoyama, J., 2018-03-27, Lecture (public talk), University of Tokyo, "Discovery of Gravitational Waves from a Neutron Star Collision."

[4] Cannon, K., 2018-03-24, Conference (invited), Japan Physics Society Meeting, Kashiwa, "Back story of GW170817 and Electromagnetic Follow-up Observations."

[5] Cannon, K., 2018-02-20, Lecture (presented to high school students), Central Toronto Academy, "Gravitational Waves."

[6] Cannon, K., 2018-02-05, Conference (invited), Physics and Astronomy at the eXtreme (PAX), Pennsylvania State University, "Low-Latency Compact Object Detection: Technical Summary."

[7] Cannon, K., 2017-12-19, Conference (invited), Cherenkov Telescope Array Meeting, University of Tokyo, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral."

[8] Cannon, K., 2017-12-15, Conference (invited), CosPA, Kyoto University, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral."

[9] Cannon, K., 2017-11-20, Colloquium, University of Tokyo, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral."

[10] Cannon, K., 2017-11-15, Colloquium, RIKEN, Wakoshi, "Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA."

[11] Cannon, K., 2017-11-09, Conference (invited), Astrophysical Big Bangs, RIKEN, Wakoshi, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral."

[12] Cannon, K., 2017-10-20, Lecture (public talk), Nerd Nite, Tokyo, "Gravitational Radiation, or: How I Learned to Stop Worrying and Love Black Hole Collisions."

[13] Cannon, K., Flaminio, R., Shigeyama, T., 2017-10-17 Press Conference, University of Tokyo, "Discovery of a new kind of gravitational wave source."

[14] Cannon, K., 2017-09-19, Seminar (presented to high school students), Ryerson University, Toronto, "The Significance of the Detection of Gravitational Waves."

[15] Cannon, K., 2017-07-12, Conference (invited), Dark Side of the Universe, Daejeon, "Status of LIGO and Virgo and Future Prospects."

Books and Magazines (0)

Industrial Products (0)

Other (1)

[1] Cannon, K., Hanna, C., *et al.* GstLAL. `https://wiki.ligo.org/Computing/DASWG/GstLAL`.

6 研究組織

1. Collaborators

   N/A

2. Associate Members

   N/A

科研費による研究は、研究者の自覚と責任において実施するものです。そのため、研究の実施や研究成果の公表等については、国の要請等に基づくものではなく、その研究成果に関する見解や責任は、研究者個人に帰属されます。