The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/159675

Please be advised that this information was generated on 2019-08-31 and may be subject to change.

The LIGO Scientific Collaboration and the Virgo Collaboration, the Australian Square Kilometer Array Pathfinder (ASKAP) Collaboration, the BOOTES Collaboration, the Dark Energy Survey and the Dark Energy Camera GW-EM Collaborations, the Fermi GBM Collaboration, the Fermi LAT Collaboration, the GRAVitational Wave InAF TEam (GRAWITA), the INTEGRAL Collaboration, the Intermediate Palomar Transient Factory (iPTF) Collaboration, the InterPlaNetary Network, the J-GEM Collaboration, the La Silla--QUEST Survey, the Liverpool Telescope Collaboration, the Low Frequency Array (LOFAR) Collaboration, the MASTER Collaboration, the MAXI Collaboration, the Murchison Wide-field Array (MWA) Collaboration, the Pan-STARRS Collaboration, The PESSTO Collaboration, the Pi of the Sky Collaboration, the SkyMapper Collaboration, the Swift Collaboration, the TAROT, Zadko, Algerian National Observatory, and C2PU Collaboration, the TOROS Collaboration, and the VISTA Collaboration

(See the end matter for the full list of authors.)

Received 2016 April 27; accepted 2016 May 4; published 2016 July 20

ABSTRACT

This Supplement provides supporting material for Abbott et al. (2016a). We briefly summarize past electromagnetic (EM) follow-up efforts as well as the organization and policy of the current EM follow-up program. We compare the four probability sky maps produced for the gravitational-wave transient GW150914, and provide additional details of the EM follow-up observations that were performed in the different bands.

Key words: gravitational waves – methods: observational

1. PAST AND PRESENT FOLLOW-UP PROGRAM

The first gravitational-wave (GW)-triggered electromagnetic (EM) observations were carried out during the 2009–2010 science run of the initial LIGO and Virgo detectors (Abadie et al. 2012b), featuring real-time searches for unmodeled GW bursts and compact binary coalescences (CBCs; Abadie et al. 2012a, 2012b). GW candidates were identified—typically within 30 minutes—and their inferred sky locations were used to plan follow-up observations with over a dozen optical and radio telescopes on the ground plus the Swift satellite (Gehrels et al. 2004). Tiles were assigned to individual facilities to target known galaxies that were consistent with the GW localizations and that were within the 50 Mpc nominal BNS detectability horizon. Eight GW candidates were followed up. Though none of the GW candidates were significant enough to constitute detections and the EM candidates found were judged to be merely serendipitous sources (Evans et al. 2012; Aasi et al. 2014), the program demonstrated the feasibility of searching in real time for GW transients, triggering follow-up, and analyzing GW and EM observations jointly.

The present program of follow-up of GW candidates involves a large number of facilities and observer teams. Instead of centrally planning the assignment of tiles to facilities, we have set up a common EM bulletin board for facilities and observers to announce, coordinate, and visualize the footprints and wavelength coverage of their observations. The new program builds on the Gamma-ray Coordinates Network (GCN)381 system that has long been established for broadband follow-up of gamma-ray bursts (GRBs). We distribute times and sky positions of event candidates via machine-readable GCN Notices, and participating facilities communicate the results of observations via short bulletins, GCN Circulars. A key difference is that GRB Notices and Circulars are instantly public, whereas GW alert Notices and follow up Circulars currently are restricted to participating groups until the event candidate in question has been published. After four high-confidence GW events have been published, further high-confidence GW event candidates will be promptly released to the public.

2. COMPARISON OF GRAVITATIONAL-WAVE SKY MAPS

In the main Letter (Abbott et al. 2016a), we introduced four GW sky maps produced with different methods: cWB (Klimenko et al. 2016), LIB (Lynch et al. 2015), BAYESTAR (Singer & Price 2016), and LALInference (Veitch et al. 2015). cWB and LIB treat the GW signal as an unmodeled burst; BAYESTAR and LALInference assume that the source is a CBC. The LALInference sky map should be regarded as the authoritative one for this event. Table 1 shows that the areas of the 10%, 50%, and 90% confidence regions vary between the algorithms. For this event, cWB produces smaller confidence regions than the other algorithms. While cWB produces reasonably accurate maps for typical binary black hole (BBH) signals, it can systematically misestimate the sizes of large confidence regions (Essick et al. 2015). The other algorithms are self-consistent even in this regime. Only the LALInference results account for calibration uncertainty (systematic errors in the conversion of the photocurrent into the GW strain signal). Because systematic errors in the calibration phase affect the measured arrival times at the detectors, the main effect is to broaden the position uncertainty relative to the other sky maps.

Table 1 also shows the intersections of the 90% confidence regions as well as the fidelity $F(p, q) = \int \sqrt{pq} \, d\Omega \in [0, 1]$ between the two maps $p$ and $q$. All these measures show that

--

381 http://gcn.gsfc.nasa.gov
Notes.

\(^a\) Area of credible level (deg\(^2\)). Note that the LALInference area is consistent with but not equal to the number reported in Abbott et al. (2016b) due to minor differences in sampling and interpolation.

\(^b\) Fidelity (below diagonal) and the intersection in deg\(^2\) of the 90% confidence regions (above diagonal).

\(^c\) Mean and 10% and 90% percentiles of polar angle in degrees.

\(^d\) The sky maps are similar but not identical. Typically, this level of quantitative disagreement is distinguishable by eye and has been observed in large simulation campaigns (Singer et al. 2014; Berry et al. 2015; Essick et al. 2015) for approximately 10%–20% of the simulated signals. This even includes the bi-modality of LIB’s \(\theta_{\text{ml}}\) distribution (see the inset of Figure 2 of the main paper), which is associated with a degeneracy between sky location and the handedness of the binary orbit projected on the plane of the sky. Similar features were noted for BNS systems as well (Singer et al. 2014).}

### 3. Gamma-Ray and X-Ray Observations

The Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009), INTEGRAL (Winkler et al. 2003), and the Inter Planetary Network (IPN; Hurley et al. 2010) searched for prompt high-energy emission temporally coincident with the GW event. Although no GRB in coincidence with GW150914 was reported, an offline analysis of the Fermi GBM (8 keV–40 MeV) data revealed a weak transient with a duration of \(\sim 1\) s (Connaughton et al. 2016). A similar analysis was performed for the instruments on board INTEGRAL (Winkler et al. 2003), particularly the spectrometer’s anticoincidence shield (SPI-ACS; von Kienlin et al. 2003, 75 keV–1 MeV)\(^{382}\). No significant signals were detected, setting upper limits on the hard X-ray fluence at the time of the event (Savchenko et al. 2016). Data from the six-spacecraft, all-sky, full-time monitor IPN, (Odyssey–HEND, Wind–Konus, RHESSI, INTEGRAL–SPI-ACS, and Swift–BAT\(^{383}\)) revealed no bursts around the time of GW150914 apart from the weak GBM signal (K. Hurley et al. 2016, in preparation).

The Fermi Large Area Telescope (LAT), MAXI, and Swift searched for high-energy afterglow emission. The LIGO localization first entered the Fermi LAT field of view (FOV) at 4200s after the GW trigger and was subsequently observed in its entirety over the next 3 hr and every 3 hr thereafter at GeV energies (Fermi-LAT Collaboration 2016). The entire region was also imaged in the 2–20 keV X-ray band by the MAXI Gas Slit Camera (Matsuoka et al. 2009) aboard the International Space Station from 86 to 77 minutes before the GW trigger and was re-observed during each subsequent \(~92\) minute orbit (N. Kawai et al. 2016, in preparation). The Swift X-ray Telescope (XRT; Burrows et al. 2005) followed up the GW event starting 2.25 days after the GW event, and covered five tiles containing eight nearby galaxies for a total \(~0.3\) deg\(^2\) area in the 0.3–10 keV energy range. A 37 point tiled observation of the Large Magellanic Cloud was executed a day later. The Swift UV/Optical Telescope (UVOT) provided simultaneous ultraviolet and optical observations, giving a broadband coverage of 80% of the Swift XRT FOV. Details of these observations are given in Evans et al. (2016).

### 4. Optical and Near-IR Observations

The optical and near-infrared observations fell into roughly two stages. During the first week, wide FOV (1–10 deg\(^2\)) telescopes tiled large areas to identify transient candidates, and then larger but narrower FOV telescopes obtained classification spectroscopy and further photometry. The Wide FOV instruments included DECam on the CTIO Blanco telescope (Flaugher et al. 2015; Dark Energy Survey Collaboration et al. 2016), the Kiso Wide Field Camera (KWFC, J-GEM; Sako et al. 2012), La Silla QUEST (Baltay et al. 2007), the Global Master Robot Network (Lipunov et al. 2010), the Palomar 48 inch Oschin telescope (P48) as part of the intermediate Palomar Transient Factory (iPTF; Law et al. 2009), Pan-STARRS1 (Kaiser et al. 2010), SkyMapper (Keller et al. 2007), TATOL-La Silla (Boër et al. 1999, node of the TATOL-Zadko-Algerian National Observatory-C2PU Collaboration), and the VLT Survey Telescope (VST@ESO; Capaccioli & Schiappi 2011, Graz|ational Wave Inaf TeAm, Emerson et al. 2006)\(^{384}\) in the optical band, and the Visible and Infrared Survey Telescope (VISTA@ESO; Emerson et al. 2006)\(^{385}\) in the near-infrared. They represent different classes of instruments ranging in diameter from 0.25 to 4 m and reaching apparent magnitudes from 18 to 22.5. About one-third of these facilities followed a galaxy-targeted observational strategy, while the others tiled portions of the GW sky maps covering 70–590 deg\(^2\). A narrow (arcminute) FOV facility, the 1.5 m EABA telescope in Bosque Alegre operated by the TOROS Collaboration (M. Diaz et al. 2016, in preparation), also participated in the optical coverage of the GW sky maps. Swift UVOT observed simultaneously with XRT, giving a broadband coverage of 80% of the Swift XRT FOV.

A few tens of transient candidates identified by the wide-field telescopes were followed up on the 10 m Keck II telescope (using the DEIMOS instrument; Faber et al. 2003), the 2 m Liverpool Telescope (LT: Steele et al. 2004), the Palomar 200 inch Hale telescope (P200; Bracher 1998), the 3.6 m ESO New Technology Telescope (within the Public ESO Spectroscopic Survey of Transient Objects, PESSTO; Smartt et al. 2015), and the University of Hawaii 2.2 m telescope (SuperNovae Integral Field Spectrograph, SNIIFS). The follow-up observations of the candidate counterparts are summarized in Table 3 of the main paper.

An archival search for bright optical transients was conducted in the CASANDRA-3 all-sky camera database of BOOTES-3 (Castro-Tirado et al. 2012) and the all-sky survey of the Pi of the Sky telescope (Mankiewicz et al. 2014), both covering the entire southern sky map. The BOOTES-3 images

\(^{382}\) INTEGRAL’s coded-mask imager (IBIS, Ubertini et al. 2003, 20–200 keV) was pointed far outside the GW localization region.

\(^{383}\) The Swift Burst Alert Telescope did not intersect the GW localization at the time of the trigger.

\(^{384}\) ESO proposal ID:095.D-0195.095.D-0079.

\(^{385}\) ESO proposal ID:095.D-0771.
are the only observations simultaneous to GW150914 available to search for prompt/early optical emission. They reached a limiting magnitude of 5 due to poor weather conditions (GCN 19022). The Pi of the Sky telescope images were taken 12 days after GW150914 and searched for transients brighter than $R < 11.5$ mag (GCN 19034).

5. RADIO OBSERVATIONS

The radio telescopes involved in the EM follow-up program have the capability to observe a wide range of frequencies with different levels of sensitivity, and a range of FOVs covering both the northern and southern skylines (Tables 2 and 3 of the main paper). The Low Frequency Array (LOFAR; van Haarlem et al. 2013) and the Murchison Wide-field Array (MWA; Tingay et al. 2013) are phased array dipole antennas sensitive to meter wavelengths with large FOVs ($\approx 50$ deg$^2$ with uniform sensitivity for the LOFAR observations carried out as part of this follow-up program; and up to 1200 deg$^2$ for MWA). The Australian Square Kilometer Array Pathfinder (ASKAP; Schinckel et al. 2012) is an interferometric array composed of 36 12 m diameter dish antennas. The Karl G. Jansky Very Large Array (VLA; Perley et al. 2009) is a 27 antenna array, with dishes of 25 m diameter. Both ASKAP and VLA are sensitive from centimeter to decimeter wavelengths.

MWA started observing 3 days after the GW trigger with a 30 MHz bandwidth around a central frequency of 118 MHz and reached an rms noise level of about 40 mJy beam$^{-1}$ in a synthesized beam of about 3'. The ASKAP observations used the five-element Boolardy Engineering Test Array (BETA; Hotan et al. 2014), which has an FOV of $\approx 25$ deg$^2$ and FWHM synthesized beam of 1'–3'. These observations were performed with a 300 MHz bandwidth around a central frequency of 863.5 MHz, from $\approx 7$ to $\approx 14$ days after the GW trigger, reaching rms sensitivities of 1–3 mJy beam$^{-1}$. LOFAR conducted three observations from $\approx 7$ days to $\approx 3$ months following the GW trigger, reaching a rms sensitivity of $\approx 2.5$ mJy beam$^{-1}$ at 145 MHz, with a bandwidth of 11.9 MHz and a spatial resolution of $\approx 50''$. ASKAP, LOFAR, and MWA all performed tiled observations aimed at covering a large area of the GW region.

The VLA performed follow-up observations of GW150914 from $\approx 1$ to $\approx 4$ months after the GW trigger, and targeted selected candidate optical counterparts detected by IPTF. VLA observations were carried out in the most compact array configuration (D configuration) at a central frequency of $\approx 6$ GHz (primary beam FWHP of $\approx 9'$, and synthesized beam FWHP of $\approx 12''$). The rms sensitivity of these VLA observations was $\approx 8$–10 $\mu$Jy beam$^{-1}$.

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO 600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS), and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector, and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Spanish Ministerio de Economía y Competitividad, the Conselleria d’Economia i Competitivitat and Conselleria d’Educació Cultura i Universitats of the Govern de les Illes Balears, the National Science Centre of Poland, the European Commission, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the National Science and Engineering Research Council Canada, Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, and Innovation, Russian Foundation for Basic Research, the Leverhulme Trust, the Research Corporation, Ministry of Science and Technology (MOST), Taiwan, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS, and the State of Niedersachsen/Germany for provision of computational resources.

The Australian SKA Pathfinder is part of the Australia Telescope National Facility which is managed by CSIRO. The operation of ASKAP is funded by the Australian Government with support from the National Collaborative Research Infrastructure Strategy. Establishment of the Murchison Radio-astronomy Observatory was funded by the Australian Government and the Government of Western Australia. ASKAP uses advanced supercomputing resources at the Pawsey Supercomputing Centre. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatoire site.

A.J.C.T. acknowledges support from the Junta de Andalucía (Project P07-TIC-03094) and Univ. of Auckland and NIWA for installing of the Spanish BOOTES-3 station in New Zealand, and support from the Spanish Ministry Projects AYA2012-39727-C03-01 and 2015-71718R.

Funding for the DES Projects has been provided by the United States Department of Energy, the United States National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência, Tecnologia e Inovação, the Deutsche Forschungsgemeinschaft, and the Collaborating Institutions in the Dark Energy Survey.
The Collaborating Institutions are Argonne National Laboratory, the University of California at Santa Cruz, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil Consortium, the University of Edinburgh, the Eidgenössische Technische Hochschule Zürich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l’Espai (IEEC/CSIC), the Institut de Física d’Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig-Maximilians Universität München and the associated Excellence Cluster universe, the University of Michigan, the National Optical Astronomy Observatory, the University of Nottingham, The Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, and Texas A&M University.

The DES data management system is supported by the National Science Foundation under Grant Number AST-1138766. The DES participants from Spanish institutions are partially supported by MINECO under grants AYA2012-39559, ESP2013-48274, FPA2013-47986, and Centro de Excelencia Severo Ochoa SEV-2012-0234. Research leading to these results has received funding from the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007-2013) including ERC grant agreements 240672, 291329, and 306478.

The Fermi LAT Collaboration acknowledges support for LAT development, operation, and data analysis from NASA and DOE (United States), CEA/Inrfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. The Fermi GBM Collaboration acknowledges the support of NASA in the United States and DRL in Germany.

GRAWITA acknowledges the support of INAF for the project “Gravitational Wave Astronomy with the first detections of adLIGO and adVirgo experiments.”

This work exploited data by INTEGRAL, an ESA project with instruments and science data center funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), and with the participation of Russia and the USA. The SPI ACS detector system has been provided by MPE Garching/Germany. We acknowledge the German INTEGRAL support through DLR grant 50 OG 1101.

IPN work is supported in the US under NASA Grant NNX15AU74G.

This work is partly based on observations obtained with the Samuel Oschin 48 in Telescope and the 60 in Telescope at the Palomar Observatory as part of the Intermediate Palomar Transient Factory (iPTF) project, a scientific collaboration among the California Institute of Technology, Los Alamos National Laboratory, the University of Wisconsin, Milwaukee, the Oskar Klein Center, the Weizmann Institute of Science, the TANGO Program of the University System of Taiwan, and the Kavli Institute for the Physics and Mathematics of the universe.

M.M.K. and Y.C. acknowledge funding from the National Science Foundation PIRE program grant 1545949. A.A.M. acknowledges support from the Hubble Fellowship HST-HF-51325.01. Part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

J-GEM is financially supported by KAKENHI Grant No. 24103003, 15H00774, and 15H00788 of MEXT Japan, 15H02069 and 15H02075 of JSPS, and the “Optical and Near-Infrared Astronomy Inter-University Cooperation Program” supported by MEXT.

The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias with financial support from the UK Science and Technology Facilities Council.

LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, which are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy. R. Fender acknowledges support from ERC Advanced Investigator Grant 267697.

MASTER Global Robotic Net is supported in parts by Lomonosov Moscow State University Development programm, Moscow Union OPTICA, Russian Science Foundation 16-12-00085, RFBR15-02-07875, National Research Foundation of South Africa.

We thank JAXA and RIKEN for providing MAXI data. The MAXI team is partially supported by KAKENHI grant Nos. 24103002, 24540239, 24740186, and 23000004 of MEXT, Japan.

This work uses the Murchison Radio-astronomy Observatory, operated by CSIRO. We acknowledge the Wajarri Yamatji people as the traditional owners of the observatory site. Support for the operation of the MWA is provided by the Australian Government Department of Industry and Science and Department of Education (National Collaborative Research Infrastructure Strategy: NCRIS), under a contract to Curtin University administered by Astronomy Australia Limited. The MWA acknowledges the iVEC Petabyte Data Store and the Initiative in Innovative Computing and the CUDA Center for Excellence sponsored by NVIDIA at Harvard University.

Pan-STARRS is supported by the University of Hawaii and the National Aeronautics and Space Administration’s Planetary Defense Office under grant No. NNX14AM74G. The Pan-STARRS-LIGO effort is in collaboration with the LIGO Consortium and supported by Queen’s University Belfast. The Pan-STARRS1 Sky Surveys have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg, and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen’s University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, and the National Aeronautics and Space Administration under grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), and the Los Alamos National Laboratory. This work is based
(in part) on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile as part of PESSTO, (the Public ESO Spectroscopic Survey for Transient Objects Survey) ESO programs 188.D-3003, 191.D-0935.

Some of the data presented herein were obtained at the Palomar Observatory, California Institute of Technology.

S.J.S. acknowledges funding from the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007-2013)/ERC Grant agreement No. [291222] and STFC grants ST/L001123/1 and ST/L000709/1. M.F. is supported by the European Union FP7 programme through ERC grant No. 320360. K.M. acknowledges support from the STFC through an Ernest Rutherford Fellowship.

F.O.E. acknowledges support from FONDECYT through postdoctoral grant 3140326.

Parts of this research were conducted by the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO), through project No. CE110001020.

Funding for Swift is provided by NASA in the US, by the UK Space Agency in the UK, and by the Agenzia Spaziale Italiana (ASI) in Italy. This work made use of data supplied by the UK Swift Science Data Centre at the University of Leicester. We acknowledge the use of public data from the Swift data archive.

The TOROS Collaboration acknowledges support from Ministerio de Ciencia y Tecnología (MinCyT) and Consejo Nacional de Investigaciones Científicas y Tecnoológicas (CONICYT) from Argentina and grants from the USA NSF PHYS 1156600 and NSF HRD 1242090.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

VST and VISTA observations were performed at the European Southern Observatory, Paranal, Chile. We acknowledge ESO personnel for their assistance during the observing runs.

This is LIGO document LIGO-P1600137-v2.

Software: Astropy (Robitaille et al. 2013), HEALPix (Górski et al. 2005).

REFERENCES


Bracher, K. 1998, Mercu, 27, 4
Capaccioli, M. & Schipani, S. 2011, Mgrs, 146, 2
Emerson, J., McPherson, J., & Sutherland, W. 2006, Mgrs, 126, 41
Keller, S. C., Schmidt, B. P., Bessell, M. S., et al. 2007, PASA, 24, 1
Klimenko, S., Vedovato, G., Drago, M., et al. 2016, PhRvD, 93, 042004
Singer, L. P., & Price, L. R. 2016, PhRvD, 93, 024013
Tingay, S. J., Goeke, R., Bowman, J. D., et al. 2013, PASA, 30, e007
Veitch, J., Raymond, V., Farr, B., et al. 2015, PhRvD, 91, 042003

M. T. Botticella\textsuperscript{285}, T.-W. Chen\textsuperscript{220}, M. D. Valle\textsuperscript{128}, N. Elías-Rosa\textsuperscript{283}, M. Fraser\textsuperscript{355}, C. Inserra\textsuperscript{349}, E. Kankare\textsuperscript{349}, T. Kupfer\textsuperscript{301}, J. Harmannen\textsuperscript{358}, L. Galbany\textsuperscript{353,359}, L. Le Guillou\textsuperscript{360,361}, J. D. Lyman\textsuperscript{325}, K. Maguire\textsuperscript{349}, A. Mitra\textsuperscript{361}, M. Nicholl\textsuperscript{171}, A. Razza\textsuperscript{353,359}, G. Terreran\textsuperscript{283,349}, S. Valentí\textsuperscript{362,363}, A. Gal-Yam\textsuperscript{364} (The PESSTO Collaboration),

A. Ćwiek\textsuperscript{110}, M. Ćwiök\textsuperscript{365}, L. Mankiewicz\textsuperscript{366}, R. Opiela\textsuperscript{366}, M. Zaremba\textsuperscript{365}, A. F. Żarnecki\textsuperscript{365} (The Pi of the SKY Collaboration),

C. A. Onken\textsuperscript{20,135}, R. A. Scalzo\textsuperscript{20,135}, B. P. Schmidt\textsuperscript{20,135}, C. Wolf\textsuperscript{20,135}, F. Yuan\textsuperscript{20,135} (The SKYMapper Collaboration),

P. A. Evans\textsuperscript{367}, J. A. Kennea\textsuperscript{72}, D. N. Burrows\textsuperscript{72}, S. Campana\textsuperscript{284}, S. B. Cenko\textsuperscript{39,368}, P. Giommi\textsuperscript{288}, F. E. Marshall\textsuperscript{39}, J. Nousek\textsuperscript{72}, P. O’Brien\textsuperscript{367}, J. P. Osborne\textsuperscript{367}, D. Palmer\textsuperscript{369}, M. Perri\textsuperscript{282,288}, M. Siegel\textsuperscript{72}, G. Tagliaferri\textsuperscript{284} (The SWIFT Collaboration),

A. Klotz\textsuperscript{370}, D. Turpin\textsuperscript{370}, R. Laugier\textsuperscript{53} (The TAROT, ZADKO, ALGERIAN NATIONAL OBSERVATORY, and C2PU Collaboration),

M. Beroiz\textsuperscript{85,371}, T. Peñuela- Larger\textsuperscript{85,372}, L. M. Macri\textsuperscript{373}, R. J. Oelkers\textsuperscript{373}, D. G. Lambas\textsuperscript{374}, R. Vrech\textsuperscript{374}, J. Cabral\textsuperscript{374}, C. Colazo\textsuperscript{374}, M. Dominguez\textsuperscript{374}, B. Sanchez\textsuperscript{374}, S. Gurovich\textsuperscript{374}, M. Lares\textsuperscript{374}, J. L. Marshall\textsuperscript{373}, D. L. DePoy\textsuperscript{373}, N. Padilla\textsuperscript{375}, N. A. Pereyra\textsuperscript{85}, M. Bencaciquista\textsuperscript{85} (The TOROS Collaboration),

AND

N. R. Tanvir\textsuperscript{367}, K. Wiersema\textsuperscript{367}, A. J. Levan\textsuperscript{325}, D. Steeghs\textsuperscript{325}, J. Hjorth\textsuperscript{305}, J. P. U. Fynbo\textsuperscript{305}, D. Malesani\textsuperscript{305}, B. Milvang-Jensen\textsuperscript{305}, D. Watson\textsuperscript{305}, M. Irwin\textsuperscript{355}, C. G. Fernandez\textsuperscript{355}, R. G. McMahon\textsuperscript{355}, M. Banerji\textsuperscript{355}, E. Gonzalez-Solares\textsuperscript{355}, S. Schulze\textsuperscript{355}, A. de U. Postigo\textsuperscript{305,376}, C. C. Thoene\textsuperscript{376}, Z. Cano\textsuperscript{376}, and S. Rosswog\textsuperscript{306} (The VISTA Collaboration)

1 LIGO, California Institute of Technology, Pasadena, CA 91125, USA; lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.eu
2 Louisiana State University, Baton Rouge, LA 70803, USA
3 Università di Salerno, Fisciano, I-84084 Salerno, Italy
4 INFN, Sezione di Napoli, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy
5 University of Florida, Gainesville, FL 32611, USA
6 LIGO Livingston Observatory, Livingston, LA 70754, USA
7 Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France
8 Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Hannover, Germany
9 Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands
10 LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
11 Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, SP, Brazil
12 INFN, Gran Sasso Science Institute, I-67100 L’Aquila, Italy
13 INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
14 Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India
15 International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bangalore 560012, India
16 University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA
17 Leibniz Universität Hannover, D-30167 Hannover, Germany
18 Universität di Pisa, I-56127 Pisa, Italy
19 INFN, Sezione di Pisa, I-56127 Pisa, Italy
20 Australian National University, Canberra, Australian Capital Territory 0200, Australia
21 The University of Mississippi, University, MS 38677, USA
22 California State University Fullerton, Fullerton, CA 92831, USA
23 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
24 Chennai Mathematical Institute, Chennai, India
25 Università di Roma Tor Vergata, I-00133 Roma, Italy
26 School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK
27 Universität Hamburg, D-22521 Hamburg, Germany
28 INFN, Sezione di Roma, I-00185 Roma, Italy
29 Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany
30 APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
31 Montana State University, Bozeman, MT 59717, USA
32 Università di Perugia, I-06123 Perugia, Italy
33 INFN, Sezione di Perugia, I-06123 Perugia, Italy
34 European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
35 Syracuse University, Syracuse, NY 13244, USA
36 SUPA, University of Glasgow, Glasgow G12 8QQ, UK
37 LIGO Hanford Observatory, Richland, WA 99352, USA
38 Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thége Miklós út 29-33, Hungary
39 NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
40 Columbia University, New York, NY 10027, USA
336 Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan
337 MAXI team, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
338 Department of Physics, Nihon University, 1-8-14 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan
339 JEM Mission Operations and Integration Center, Human Spaceflight Technology Directorate, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan
340 Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan
341 Department of Earth and Space Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan
342 University of California, Berkeley, Astronomy Dept., 501 Campbell Hall #3411, Berkeley, CA 94720, USA
343 Eureka Scientific, Inc., 2452 Delmer Street Suite 100, Oakland, CA 94602, USA
344 Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
345 International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia
346 Dunlap Institute for Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada
347 School of Chemical & Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand
348 Observatorio di Radio Astronomia, Istituto Nazionale di Astrofisica, Bologna, I-40123, Italy
349 Astrophysics Research Centre, School of Mathematics and Physics, Queens University Belfast, Belfast BT7 1NN, UK
350 Institute for Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA
351 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
352 Department of Physics, Harvard University, Cambridge, MA 02138, USA
353 Millennium Institute of Astrophysics, Casilla 36-D, Santiago, Chile
354 Departamento de Ciencias Fisicas, Universidad Andres Bello, Avda. Republica 252, Santiago, Chile
355 Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
356 Institut d’Astrophysique de Paris, CNRS, and Université Pierre et Marie Curie, 98 bis Boulevard Arago, F-75014, Paris, France
357 European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile
358 Tuorla Observatory, Department of Physics and Astronomy, University of Turku, Väisäläntie 20, FI-21500 Piikkiö, Finland
359 Departamento de Astronomía, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
360 Sorbonne Universités, UPMC Univ. Paris 06, UMR 7585, LPMHE, F-75005, Paris, France
361 CNRS, UMR 7585, Laboratoire de Physique Nucleaire et des Hautes Energies, 4 place Jussieu, F-75005 Paris, France
362 Las Cumbres Observatory Global Telescope Network, 6740 Cortona Dr., Suite 102, Goleta, CA 93117, USA
363 Department of Physics, University of California Santa Barbara, Santa Barbara, CA 93106, USA
364 Benoziyo Center for Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel
365 Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland
366 Center for Theoretical Physics of the Polish Academy of Sciences, 02-668 Warszawa, Poland
367 Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK
368 Joint Space-Science Institute, University of Maryland, College Park, MD 20742, USA
369 Los Alamos National Laboratory, B244, Los Alamos, NM, 87545, USA
370 L’Institut de Recherche en Astrophysique et Planétologie, CNRS UMR 5277/UPS, 14 avenue Edouard Belin, F-31400 Toulouse, France
371 University of Texas at San Antonio, San Antonio, TX, USA
372 Ludwig Maximillan Universitat München, Faculty of Physics, Schellingstrasse 4, D-80799 Munich, Germany
373 Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, 4242 TAMU, College Station, TX 77843, USA
374 Universidad Nacional de Córdoba, IATE, Laprida 854, Córdoba, Argentina
375 Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
376 Instituto de Astrofísica de Andalucía, Consejo Superior de Investigaciones Científicas, Glorieta de la Astronomía s/n, E-18008 Granada, Spain
377 Centre for Astrophysics and Cosmology, Science Institute, University of Iceland, 107 Reykjavik, Iceland
378 NASA Postdoctoral Program Fellow, USA
379 Hubble Fellow
380 Emeritus