PROCEEDINGS OF SCIENCE

The third Gravitational-Wave Transient Catalog (GWTC-3)

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The GWTC-3 catalog is a cumulative catalog of the mergers detected during the first three observing runs of the LIGO-Virgo Collaboration. The catalog contains 90 detected mergers and has been used for several astrophysical applications. The present papers is a short review of the GWTC-3 catalog and its implications.

Frontier Research in Astrophysics – IV (FRAPWS2024)
9-14 September 2024
Mondello, Palermo, Italy

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PoS(FRAPWS2024)014

1. Introduction

The Advanced LIGO and Advanced Virgo have completed three observing runs and have started the fourth run in May 2023. The first direct detection of gravitational waves from the merger of a binary black hole (BBH) system, GW150914, occurred during the O1 run [1]. The detection of the first binary neutron star (BNS) merger, GW170817, occurred during the O2 run [2]; the merger was accompanied by an electromagnetic counterpart [3, 4]. The mergers detected during the O1, O2 runs have been collected in the First Gravitational Wave Transient Catalog, GWTC-1 [5]. During the O3 run. split into O3a and O3b runs, a large number of mergers were detected, mostly BBH mergers, with a few BNS and NSBH (Neutron Star-Black Hole) mergers, showing that all possible combinations of compact objects can merge. The O3 run has delivered three catalogs, GWTC-2 [6] and GWTC-2.1 [7] for the O3a run, GWTC-3 [8] for the O3b run, and some papers for exceptional events. The paper is a concise summary of the O3b run and the GWTC-3 catalog and its impact on astrophysics.

2. The O3 Run

The O3 observing run consisted of the O3a run, from 2019 April 1 to 2019 October 1, and the O3b run, from 2019 November 1 to 2020 March 27. The O3 run marked the start of public gravitational wave alerts, with gravitational wave candidates archived in the Gravitational Wave Candidate Event Database GraceDb [1] and alerts disseminated within minutes using the Gamma-Ray Coordinate Network GCN [2]. The statistics of gravitational wave detections during the O3 run was one order of magnitude larger than the combined statistics of O1 and O2 runs (Fig. 1), leading to a total of 90 detections in the first three runs.

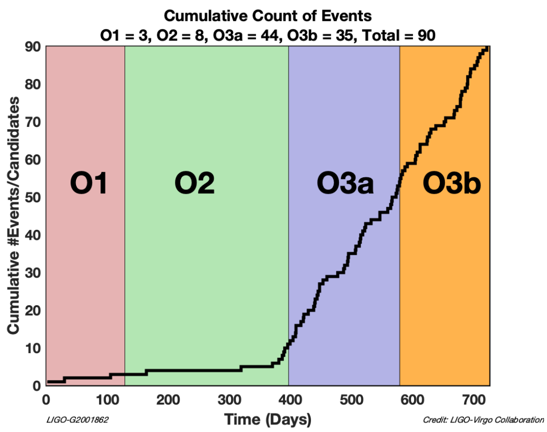

Figure 1: Cumulative counts of events during the O1, O2, O3 runs; the thin vertical lines mark the end of O1, O2, O3a runs. Credits: LVK Collaboration, https://dcc.ligo.org/LIGO-G2102395/public

The interferometer sensitivity is described by the BNS inspiral range, i.e. the average distance at which a 1.4 $M_{\odot}$ + 1.4 $M_{\odot}$ BNS can be detected with a signal-to-noise ratio (SNR) of 8 [9–11].

[1]https://gracedb.ligo.org
[2]https://gcn.gsfc.nasa.gov

The BNS range for O3b run is reported in Fig. 2; the median BNS inspiral ranges for LIGO Livingston, LIGO Hanford, and Virgo were 133, 115, and 51 Mpc, respectively [8].

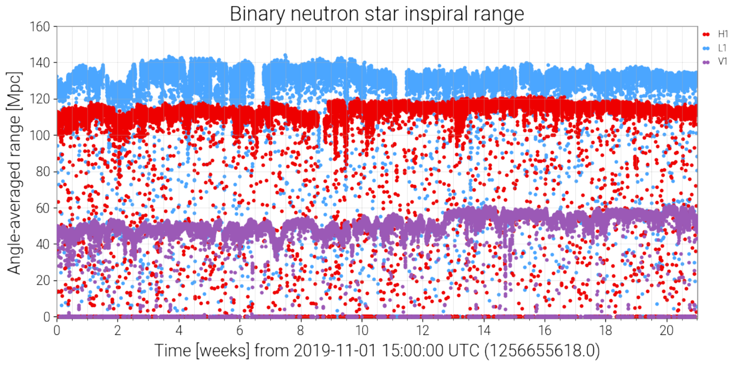

Figure 2: Sensitivity to a BNS merger during the O3b run; Credits: https://gwosc.org/detector_status/O3b/

3. The GWTC-3 Catalog

The mergers observed during O3 have been reported in three catalogs: GWTC-2 [6] and GWTC-2.1 [7] for O3a run, GWTC-3 [8] for O3b run. The series of O3 catalogs started the full gravitational naming using the UTC time appended after an underscore to the GWyymmdd prefix including the date.

Candidate searches during O3b run were performed on two timescales, in low latency and offline, and included both modeled searches with template waveforms, and unmodeled searches. The modeled searches used four independent pipelines: GstLAL, MBTA, PyCBC Broad, PyCBC BBH. The events were identified as compact binary coalescences (CBC) using matched filtering and banks of template waveforms. The search considered coincidences between the LIGO Hanford and LIGO Livingston interferometers, of Virgo with each LIGO interferometer and the triple coincidence of the two LIGO interferometers and Virgo; GstLAL allowed also for single detector candidates. The key parameters of the searches are the chirp mass $\mathcal{M}_c$ [12, 13]:

$$\mathcal{M}_c = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \tag{1}$$

and the effective inspiral spin χ_{eff} [14, 15]:

$$\chi_{eff} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \hat{L}_N}{(m_1 + m_2)} \tag{2}$$

where $\vec{\chi}_i$ are the dimensionless spin of the components, $\hat{L}_N$ is the unit vector in the direction of the orbital angular momentum.

The cWB pipeline performs unmodeled searches identifying excess power in coincident strain data of all possible pairs of LIGO Hanford, LIGO Livingston and Virgo. This search algorithm can potentially identify non-CBC sources.

The significance of events is assessed using the False Alarm Rate (FAR) or the probability of physical origin $p_{astro} = p_{BNS} + p_{NSBH} + p_{BBH} = 1 - p_{terr}$, where p_{BNS}, p_{NSBH}, p_{BBH} are the probabilities of BNS, NSBH, BBH mergers, p_{terr} the probability of terrestrial origin. The False Alarm Rate defines how often noise is expected to produce a trigger with the same ranking statistics, but is does not take into account any astrophysical information. The p_{astro} parameter is a Bayesian odds comparing the astrophysical and terrestrial hypothesis [16, 17], assessing the significance by comparing the foreground and background ranking statistics, with the information of the estimated astrophysical rates. The three O3 catalogs have been built using different criteria for selecting events. The GWTC-2 catalog, that included 39 detections (26 reported as public alerts) during the O3a run, used a FAR threshold of two per year [6]. The GWTC-2.1 catalog included a deeper list of candidates with a FAR threshold of two per day [7]. A selection of 44 candidates had a probability of astrophysical origin $p_{astro} > 0.5$, among them 36 candidates had previously reported in the GWTC-2 catalog. The threshold for inclusion in the main event list of the GWTC-3 catalog was $p_{astro} > 0.5$ in at least one pipeline, for CBC sources, giving a total number of 35 events [8]. In addition, there were 7 marginal events with $p_{astro} < 0.5$ and FAR < 2 per year and 1041 deep subthreshold events with FAR < 2 per day [8].

The properties of candidates with a probability of astrophysical origin $p_{astro} > 0.5$ detected during the O3b run are reported in Fig. 3, where the credible region contours are showed in the plane of mass ratio $q = m_2/m_1$ versus the total mass M [8]. The majority of events are BBH mergers, whose total mass covers an order of magnitude, ranging from about 14 $M_\odot$ to about 150 $M_\odot$.

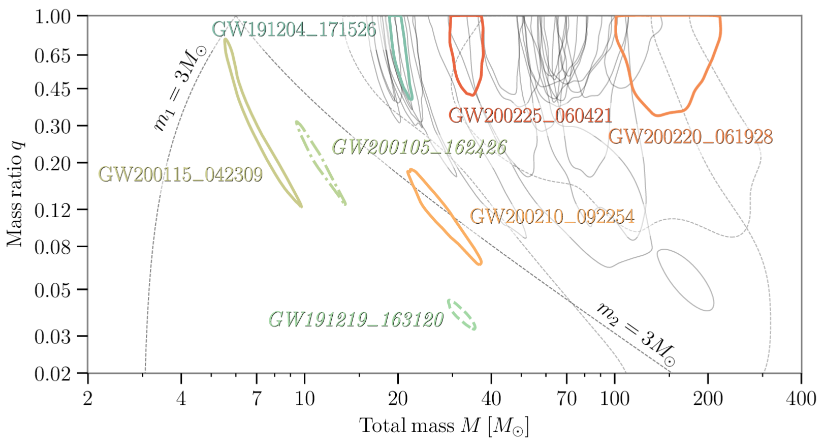

Figure 3: Credible region 90% contours for all O3b candidates with $p_{astro} > 0.5$ and for GW200105 in the plane of mass ratio q and total mass M. Highlighted candidates include: NSBH mergers GW200105, GW200115 (discussed in the text), GW191219_163120, the low mass BBH/NSBH system GW200210_092254, the heaviest system GW200220_061928, the systems GW200225_060421 and GW191204_171526 with negative and positive effective spins. Adapted from [8]

From the point of view of mass, the extreme events are GW200220_061928, the most massive O3b candidate with M = 148 $M_\odot$, and GW200115_042309, the less massive O3b candidate, with M = 7.4 $M_\odot$. The range of redshifts spans from z = 0.06 of event GW200105_162426 to z = 1.04

of event GW200308_173609.

GW200105 and GW200115 were the first detected NSBH mergers [18]; this class of events could potentially show electromagnetic emission [19]. The luminosity distances of both mergers were large ($0.27^{+0.12}_{-0.11}$ Gpc for GW200105 and $0.29^{+0.15}_{-0.10}$ Gpc for GW200115). In addition, the sky localization regions were poorly constrained (9600 deg^2 for GW200105, 720 deg^2 for GW200115) [8]. Both factors contributed to make the detection of electromagnetic counterparts less likely. The component masses for the two systems were $m_1 = 9.1^{+1.7}_{-1.7}$ $M_\odot$ and $m_2 = 1.91^{+0.33}_{-0.24}$ $M_\odot$ for GW200105, and $m_1 = 5.9^{+2.0}_{-2.5}$ $M_\odot$ and $m_2 = 1.44^{+0.85}_{-0.28}$ $M_\odot$ for GW200115 [8]. For both events the mass of primaries and of secondaries are consistent with the masses of black holes and neutron stars, respectively. The NSBH merger GW200105 was classified as a marginal event in the GWTC-3 catalog due to its low p_{astro} value [8]. GW200105 and GW200115 have been the targets of electromagnetic and neutrino follow-up observations [20–31], but no counterpart was detected.

For completeness, the follow-up observations in the electromagnetic and neutrino domains during the O3 run involved more than one hundred collaborations, and included optical and infrared photometry [21–23, 25, 32–39], radio observations [40–43], X-rays and gamma-rays (coverage from keV to TeV energies) [26–29, 44–49], neutrino observations (from MeV to PeV energies) [30, 31, 50–54]. No confirmed counterpart has been detected.

In addition to the follow-up, there have been searches of coincidences between gravitational events occurring during O3b and/or high energy events, without any observed coincidence: gravitational emission associated with Gamma-Ray Bursts detected by Fermi and Swift during the O3a and O3b runs [55, 56]; joint Fermi-GBM and Swift-BAT Analysis [57] and Swift-BAT GUANO follow-up [58] of gravitational mergers; searches for magnetar bursts [59]; search for coincident optical and high energy candidates in Swift and gravitational observations [48]; search for precursors of Gamma-ray Bursts associated to BNS mergers with time modulation [60], as in GRB 211211A [61–63].

3.1 GWTC-3 Catalog Implications

The improved statistics collected during the O3 run has allowed to investigate the populations of black holes and neutron stars, using 74 compact binary mergers detected up to the end of O3b run (70 BBH, two BNS and two NSBH mergers) [64]. The mass distribution of primary black holes is a power law with features at about 10 and 35 $M_\odot$ and possibly also at about 18 $M_\odot$ [64]. The mass distribution of neutron stars observed in gravitational mergers favors high masses, compared to the double peak distribution of Galactic radio/X-ray detected pulsars [64]. The maximum neutron star mass in the gravitational sample lies between 1.8 to 2.3 $M_\odot$, consistent with pulsar observations. However, extra-galactic populations producing the observed mergers could be different from the Galactic population. The merger rates of compact objects have been updated as 10-1700 Gpc^{-3} yr^{-1} for BNS, 7.8-140 Gpc^{-3} yr^{-1} for NSBH, 17.9-44 Gpc^{-3} yr^{-1} for BBH at the fiducial redshift z=0.2 [64].

The GWTC-3 catalog has been used for testing General Relativity (GR) in the strong field regime, finding no evidence for deviations [65]: consistency of post-Newtonian coefficients with GR predictions, of spin-induced quadrupole moments of BBH components with those of Kerr black holes, of the final mass and final spin values estimated from the pre-merger and post-merger parts of the signal; behavior of the remnant black hole; dispersion of gravitational waves; presence of

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non standard polarization modes. The upper limit on the mass of the graviton has been constrained at 1.27×10^{-23} eV/c^2 [65].

Gravitational waves can provide an estimation of the Hubble parameter independent from the electromagnetic estimates. Presently, there is tension between the values of the Hubble parameter H_0 obtained using observations from the Cosmic Microwave Background (CMB) [66] and observations from Cepheids and type Ia supernovae [67]. The investigation of the cosmic expansion requires an independent measurement of the source redshift. The detection of the gravitational waves from the BNS merger GW170817 [2] and of the associated EM emission [3] has provided the first standard siren measurement [68] of the Hubble constant [69], $70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}. The redshift of the host galaxy can be estimated in presence of a confirmed electromagnetic counterpart [68, 70–73], but when a counterpart is missing statistical methods are used, including: redshift estimation using galaxy catalogs [68]; comparison of the redshifted mass distribution with a source mass distribution [74]; source redshift distribution [75]; spatial clustering between gravitational sources and galaxies [76]. The Hubble parameter has been estimated using 47 mergers of GWTC-3 catalog (42 BBHs, 2 BNSs, 2 NSBHs and GW190814) [77], and both excluding [78] or including [79] the information of galaxy catalogs. The joint fit of the cosmological parameters with the BBH population yielded $H_0 = 68^{+12}_{-7}$ km s^{-1} Mpc^{-1} when combined with the GW170817 H_0 estimation, and $H_0 = 50^{+37}_{-30}$ km s^{-1} Mpc^{-1} when using BBHs mergers only. The association of each merger event with a candidate galaxy in the GLADE+ catalog [80] produced $H_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}. A review of the Hubble parameter estimation with gravitational waves has been presented by [81].

4. Conclusions

The GWTC-3 catalog has greatly improved out knowledge of the merging processes and of the population of black holes and neutron stars, and has allowed a new estimation of the Hubble constant with standard sirens.

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ASKAP, Las Cumbres Observatory Group, OzGrav, DWF (Deeper Wider Faster Program), AST3, CAASTRO, VINROUGE, MASTER, J-GEM, GROWTH, JAGWAR, CaltechNRAO, TTU-NRAO, NuSTAR, Pan-STARRS, MAXI Team, TZAC Consortium, KU, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS, BOOTES, MWA, CALET, IKI-GW Follow-up, H.E.S.S., LOFAR, LWA, HAWC, Pierre Auger, ALMA, Euro VLBI Team, Pi of Sky, Chandra Team at McGill University, DFN, ATLAS Telescopes, High Time Resolution Universe Survey, RIMAS, RATIR, SKA South Africa/MeerKAT collaboration, *Multi-messenger Observations of a Binary Neutron Star Merger*, *Astrophys. J. Lett.* **848** (2017) L12 [1710.05833].

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