A Deep Chandra X-Ray Study of Neutron Star Coalescence GW170817

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Received 2017 September 19; revised 2017 September 22; accepted 2017 September 25; published 2017 October 16

Abstract

We report Chandra observations of GW170817, the first neutron star–neutron star merger discovered by the joint LIGO-Virgo Collaboration, and the first direct detection of gravitational radiation associated with an electromagnetic counterpart, Fermi short γ-ray burst GRB 170817A. The event occurred on 2017 August 17 and subsequent observations identified an optical counterpart, SS17a, coincident with NGC 4993 (~10" separation). Early Chandra (Δt ~ 2 days) and Swift (Δt ~ 1–3 days) observations yielded non-detections at the optical position, but ~9 days post-trigger Chandra monitoring revealed an X-ray point source coincident with SS17a. We present two deep Chandra observations totaling ~95 ks, collected on 2017 September 01–02 (Δt ~ 15–16 days). We detect X-ray emission from SS17a with $L_{0.3–10\text{ keV}} = 2.6^{+0.5}_{-0.4} \times 10^{38}$ erg s$^{-1}$, and a power law spectrum of $\Gamma = 2.4 \pm 0.8$. We find that the X-ray light curve from a binary NS coalescence associated with this source is consistent with the afterglow from an off-axis short γ-ray burst, with a jet angle $\gtrsim 23^{\circ}$ from the line of sight. This event marks both the first electromagnetic counterpart to a LIGO-Virgo gravitational-wave source and the first identification of an off-axis short GRB. We also confirm extended X-ray emission from NGC 4993 ($L_{0.3–10\text{ keV}} \sim 9 \times 10^{38}$ erg s$^{-1}$) consistent with its E/S0 galaxy classification, and report two new Chandra point sources in this field, CXOU J130948 and CXOU J130946.

Key words: galaxies: individual (NGC 4993) – gamma-ray burst: individual (GRB 170817A) – gravitational waves – stars: neutron – X-rays: binaries

1. Introduction

The detection of gravitational waves (GWs) by the Laser Interferometer Gravitational-wave Observatory (LIGO) is one of the most exciting advances in physics in decades. Abbott et al. (2016a) reported the first LIGO detection of GWs, resulting from the merger of two black holes (BHs). The observed waveforms showed a near-perfect match to predictions from general relativity for the inspiral and merger of two BHs, ushering in the era of GW astronomy. Extensive follow-up observations based on this GW event found no robust electromagnetic (EM) counterparts (e.g., Abbott et al. 2016b; Connaughton et al. 2016; Evans et al. 2016; Soares-Santos et al. 2016), consistent with theoretical predictions for stellar-mass BH mergers.

The next frontier is multi-messenger astronomy, where GW sources are associated with an EM emitter, connecting GW astronomy to our rich understanding of astrophysics. Core-collapse supernovae, mergers of two neutron stars (NSs), and mergers of NS–BH binaries are among the EM sources likely to have detectable GW signals. In particular, NS–NS mergers have long been predicted to be the progenitors of short γ-ray bursts (GRBs; Paczynski 1986; Narayan et al. 1992), and may produce kilonovae (Li & Paczynski 1998) that are responsible for the majority of r-process nucleosynthesis in the Universe (Eichler et al. 1989).

On 2017 August 17 at 12:41:04 UTC, LIGO-Virgo detected event GW170817—its observed waveform traced the distinctive signal of an NS–NS inspiral, and early analysis indicated a luminosity distance of $D_L = 40 \pm 8$ Mpc (LIGO Scientific Collaboration & Virgo Collaboration 2017a, 2017b; Abbott et al. 2017). This discovery is the first in a new class of GW events stemming from NS binary coalescences, which are predicted to produce EM emission. Approximately 2 s after the GW trigger, the Gamma-ray Burst Monitor (GBM) instrument on board the Fermi Gamma-ray Space Telescope was also triggered by the short-duration GRB 170817A (Connaughton et al. 2017; Goldstein et al. 2017a, 2017b; von Kienlin et al. 2017). Thanks to tight localization by LIGO-Virgo, follow-up ground-based optical imaging soon discovered the associated optical transient Swope Supernova Survey 17a (SS17a, Coulter et al. 2017a, 2017b), near the galaxy NGC 4993 at $z = 0.0098$. This discovery initiated rapid follow-up surveillance by X-ray telescopes. The first X-ray observations of the field yielded upper limits from the Monitor of All-sky X-ray Images (MAXI) on board the International Space Station (Sugita et al. 2017) and the X-ray Telescope (XRT) on the Swift Observatory (Evans et al. 2017a). In particular, Swift observations began 0.6 days post-trigger, followed by a cadence of one-to-several observations daily. No X-ray emission was detected at the location of SS17a down to a limiting luminosity of $L_{0.3–10\text{ keV}} = 9.2 \times 10^{38}$ erg s$^{-1}$ (Evans et al. 2017c). Stacked Swift-XRT observations spanning 16 days post-trigger revealed a possible weak source reported in Evans et al. (2017b) that, with refined astrometric corrections and
additional exposure, was localized to R.A. = 13:09:47.65, decl. = −23:23:01.6 with a 90% confidence radius of 3.79″ (Evans et al. 2017c). The Swift position and luminosity, $L_{0.3-10\text{keV}} \sim 4 \times 10^{39}$ erg s$^{-1}$, are consistent with the host NGC 4993, but due to the $\sim 15^\circ$ point-spread function of Swift, it is possible that the nearby X-ray point source CXOU J130948 contaminates both (Figure 1).

Prior to the observations reported here, Chandra also observed the field of NGC 4993. The first observation occurred approximately two days post-trigger and reported a non-detection at the location of SSS17a (Margutti et al. 2017a; 2017b). An observation nine days post-trigger detected a source consistent with SSS17a, though no flux or luminosity values were reported (Troja et al. 2017a, 2017c).

In this Letter, we present two deep Chandra X-ray observations of the field of GW170817. In a $42^\circ \times 42^\circ$ patch centered on NGC 4993 we detect four X-ray sources, including SSS17a and spatially extended X-ray emission from the host galaxy. By constructing a Chandra X-ray light curve of SSS17a using these and earlier Chandra observations, we show that the X-ray emission from this NS–NS merger is consistent with the afterglow from an off-axis short GRB, with a jet axis angle of $\gtrsim 23^\circ$. If confirmed, this makes GRB 170817A the first off-axis short GRB observed to date, in addition to being the first EM counterpart to a LIGO-Virgo GW detection.

The outline of this Letter is as follows. In Section 2, we describe our Chandra observations. In Section 3, we discuss the properties of the X-ray sources in the field of GW170817. In Section 4, we interpret our results and summarize our conclusions. Throughout this Letter, we adopt a standard ΛCDM cosmology with $\Omega_M = 0.31$, $\Omega_{\Lambda} = 0.69$, and $H_0 = 68$ km s$^{-1}$ Mpc$^{-1}$, consistent with the results of Planck Collaboration et al. (2016).

2. Observations

We report the analysis of two 46.69 ks Chandra X-ray observations, ObsID 20899 and ObsID 18988, which cover a patch of the LIGO-Virgo high-confidence localization for GW170817 (LIGO Scientific Collaboration & Virgo Collaboration 2017a, 2017b). ObsID 20899 (PI: Troja) began 2017 September 01 at 15:22:22 (~15 days post-trigger) and ObsID 18988 (PI: Haggard) began approximately 13 hr later on 2017 September 02 at 04:53:25 (~16 days post-trigger). Both observations were acquired using Chandra’s ACIS-S3 chip in VFAINT mode. Data reduction and analysis were performed with CIAO v.4.8 tools (CALDB v4.7.2; Fruscione & Burke 2016). We reprocessed the level 2 events files, applied the latest calibrations via CIAO’s reproc script, and extracted the 0.5–7 keV images and X-ray spectra described in Section 3. Our small field of view (Figure 1) includes the optical transient SSS17a (Coulter et al. 2017a, 2017b), the Swift X-ray detection (Evans et al. 2017a, 2017b), and several other X-ray sources of interest.

Continued monitoring observations of this field with Chandra (as well as Swift) were prohibited by Sun constraints beginning in 2017 mid-September and continuing until early 2017 December (the gray region in the left panel of Figure 4).

3. X-Ray Analysis and Source Properties

In a small, on-axis patch $\sim 0.5'$ on a side (Figure 1), we detected X-ray emission from three point sources and one extended source: (1) point-source X-ray emission at the location of the optical transient SSS17a (Coulter et al. 2017; Fong et al. 2017; Haggard et al. 2017; Troja et al. 2017a, 2017b), (2) another point source, CXOU J130948, near the
Table 1: X-Ray Source Properties

| Source ID | R.A. (J2000) | Decl. (J2000) | Extraction Radius | Chandra ObsID | Power Law$^a$ $\Gamma$ | Flux (0.3–8 keV) $(10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2})$ | Luminosity (0.3–10 keV)$^b$ $(10^{36} \text{ erg s}^{-1})$ |
|-----------|--------------|--------------|------------------|---------------|-------------------|------------------------------------------------|--------------------------------------------------|
| SSS17a    | 13:09:48.077 | −23:22:53.459 | 1$^{o}$968       | 20899         | $2.7_{-0.8}^{+1.0}$ | $0.35_{-0.04}^{+0.04}$                                  | $2.7_{-0.4}^{+0.8}$                              |
|           | 18988        |              |                  | combined      | $2.4 \pm 0.8$     | $0.36_{-0.03}^{+0.03}$                                  | $2.6_{-0.6}^{+0.8}$                              |
| CXOU J130948 | 13:09:48.014 | −23:23:04.917 | 1$^{o}$968       | 20899         | $1.0_{-0.9}^{+0.9}$ | $0.5_{-0.3}^{+0.3}$                                    | $3.7_{-1.1}^{+1.1}$                              |
|           | 18988        |              |                  | combined      | $1.3 \pm 0.8$     | $0.4_{-0.03}^{+0.03}$                                    | $3.1_{-1.4}^{+1.4}$                              |
| CXOU J130946 | 13:09:46.682 | −23:22:06.983 | 1$^{o}$968       | 20899         | $-0.1_{-0.9}^{+0.4}$ | $1.2_{-0.5}^{+0.4}$                                    | $10.5_{-2.9}^{+4.4}$                             |
|           | 18988        |              |                  | combined      | $-0.4_{-0.3}^{+0.3}$                      | $0.9_{-0.4}^{+0.3}$                                    | $7.7_{-2.0}^{+0.9}$                              |
| NGC 4993  | 13:09:47.705 | −23:23:02.457 | 2$^{o}$95        | 20899         | $1.37_{-0.4}^{+0.5}$ | $1.4 \pm 0.2$                                          | $9.1_{-1.4}^{+1.4}$                              |
|           | 18988        |              |                  | combined      | $1.5 \pm 0.4$     | $1.3 \pm 0.2$                                          | $9.0_{-3.8}^{+1.3}$                              |

Notes.
$^a$ The neutral hydrogen absorption was frozen to $N_{\text{H}} = 7.5 \times 10^{20} \text{ cm}^{-2}$ for all spectral fits, based on NGC 4993’s $A_V = 0.338$ (Schlafly & Finkbeiner 2011; see Section 3 for details).
$^b$ A luminosity distance of 42.5 Mpc was assumed for all sources.

The X-ray counterpart of the optical source SSS17a was well-fit with a power law index of $\Gamma \sim 2.4$. Analysis of the spectra reveal a statistical difference in either the flux values or the count rates of SSS17a between the two observations. When we co-added the spectra and response files, the improved statistics yielded an absorbed flux of $\sim 3.6 \pm 0.1 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$. This is consistent with the upper limits observed by Swift (Evans et al. 2017c; see also Figure 2).

The brightest of the four sources, the host galaxy NGC 4993, was well-fit with a power law index of $\Gamma = 1.5 \pm 0.4$ and an absorbed 0.3–8 keV flux $F_{0.3-8 \text{ keV}} = 1.3 \pm 0.2 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$. The soft energy excess visible in Figure 3 may indicate the presence of thermal emission from a gaseous component in the galaxy. CXOU J130948 has a similar photon index ($\Gamma = 1.3 \pm 0.8$), though it has a lower flux of $F_{0.3-8 \text{ keV}} = 4 \pm 0.1 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$. In
contrast, CXOU J130948 has a very hard spectrum, with $\Gamma \approx -0.4 \pm 0.8$—this hard X-ray emission is also evident in Figure 1, where the source appears visually blue in the three-color image.

Assuming that these four sources are at the distance of the galaxy NGC 4993 ($D_L = 42.5$ Mpc, da Costa et al. 1998), we derive the 0.3–10 keV X-ray luminosities listed in Table 1. NGC 4993’s X-ray luminosity from the combined, deep Chandra observation is $L_{0.3-10 \text{ keV}} = 8.7^{+0.8}_{-0.9} \times 10^{38}$ erg s$^{-1}$, which is consistent with the X-ray luminosity of a lenticular E/S0-type galaxy (e.g., Kim & Fabbiano 2015).

In addition to these two observations ~two weeks post-trigger, Margutti et al. (2017a) reported a non-detection of SSS17a from a ~25 ks Chandra observation two days after the detection of GRB 170817A. Approximately nine days post-trigger, Troja et al. (2017a) subsequently reported a Chandra detection with a 50 ks exposure, though no flux values were reported. The observations all share similar pointings and observing modes. Based on the source (non-)detection status, we were able to use the response files, background spectra, and best-fit spectral parameters from the data reported here to simulate SSS17a emission from the other observations. An upper limit of $F_{0.3-10 \text{ keV}} \approx 3.4 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ was obtained for the non-detection, and we place a lower limit of $F_{0.3-10 \text{ keV}} \approx 2.8 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ on the nine-day post-trigger detection (see Figures 2 and 4). These estimates assume no additional extenuating circumstances during the observation, such as strong solar background flares, bad pixels, etc.

4. Discussion

4.1. X-Ray Evidence for an Off-axis Short GRB

It is challenging to explain our Chandra X-ray detection of the afterglow of GRB 170817a at 16 days post-trigger, in combination with the Chandra non-detection at 2 days post-trigger, and the detection at 9 days post-trigger, as described in Section 2. For short GRBs, standard afterglow models predict that after the prompt emission fades on timescales of $< 2s$ post-burst, and the relativistic jet will be decelerated by the ambient medium. This leads to X-ray emission that decays as $t^{-2}$ on the timescales of $10^{-5}-6$ s; i.e., exactly the timescales covered by our X-ray observations. Figure 4 (left panel) displays our X-ray light curve of the afterglow of GRB 170817a, including the detection at 16 days post-trigger, an upper limit for the non-detection at 2 days post-trigger, and a lower limit for the detection at 9 days post-trigger. Figure 4 (left panel) also displays theoretical 1.5 keV X-ray afterglow light curves for short GRBs for a range of jet axis angles, scaled to the observed flux of our Chandra X-ray observations at 16 days. These light curve models are from the relativistic hydrodynamic simulations of van Eerten & MacFadyen (2011), which include radiative transfer for synchrotron emission, and assume...
that the beaming-corrected total energy in both jets is $10^{48}$ erg, the number density of the ambient medium is $10^{-3}$ cm$^{-3}$, and the jet half-opening angle is 11°. The model light curve in Figure 4 for a jet observed at 0° off-axis (i.e., directly along the line of sight) predicts afterglow X-ray emission that is a factor of $>10^3$ higher than the upper limit from the non-detection at 2 days post-trigger. Thus, the standard on-axis GRB scenario is disfavored by these X-ray observations.

GRB jets observed off-axis can produce afterglow emission that is faint at early times, but becomes luminous and observable as the jet beaming becomes less severe and the jet opening angle spreads into the line of sight (Granot et al. 2002). Figure 4 (left panel) also displays model light curves at a range of jet axis angles from the line of sight. Our observed X-ray light curve is consistent with afterglow models for an off-axis short GRB, with a jet axis angle of $>23°$. If confirmed, this makes GRB 170817A the first observed off-axis short GRB, in addition to the first electromagnetic counterpart to a GW event.

Further X-ray monitoring of GRB 170817A can tightly constrain the jet axis angle. If the jet axis angle is at $>23°$, the X-ray afterglow has already reached its peak and will continue to fade. However, at larger jet axis angles, the X-ray afterglow can still be brightening (e.g., see the model light curve for a 46° axis angle in Figure 4), until reaching a peak at up to 430 days post-burst for a jet at a 90° axis angle, using our assumed model parameters. Deep Chandra observations after sunblock (~2017 December; Figure 4) could easily distinguish between these possibilities.

The off-axis GRB scenario also predicts emission other multi-wavelength properties, including late-time radio emission from the afterglow that peaks on timescales of order 10 days after the X-ray peak. Indeed, a previously undetected radio source associated with SSS17a was reported approximately 15 days post-burst (Corsi et al. 2017; Mooley et al. 2017). Thus, continued multi-wavelength monitoring of GRB 170817A will be key to unveiling its nature and understanding its properties.

4.2. Gamma-Ray Evidence for an Off-axis Short GRB

Our off-axis short GRB interpretation of GRB 170817A may also be supported by the low luminosity of its prompt $\gamma$-ray emission. The prompt emission from off-axis GRBs is likely to be under-luminous in comparison with on-axis GRBs, and it is strongly beamed. Figure 4 (right panel) compares the $\gamma$-ray peak isotropic luminosity ($L_{\text{iso}}$) and $\gamma$-ray rest-frame spectral peak energy ($E_{\text{peak}}$) of GRB 170817A to a sample of 8 short GRBs from Tsutsui et al. (2013) and a sample of 12 short GRBs from D’Avanzo et al. (2014). The $L_{\text{iso}}$ and $E_{\text{peak}}$ of GRB 170817A are based on Fermi GBM observations over the 10-1000 keV range reported by Goldstein et al. (2017), which encompasses the 128 keV spectral peak. The prompt $\gamma$-ray emission of GRB 170817A appears to be strongly under-luminous in comparison with other short GRBs, although GRB 170817A is at much lower redshift ($z = 0.009$) compared to these other samples ($z \sim 0.5$–1). The minimum luminosity of short GRBs is not well-constrained observationally, making it difficult to definitively distinguish off-axis GRBs from faint on-axis GRBs. However, the fact that the luminosity of GRB 170817A is a factor of $>10^3$ fainter than the next faintest short GRB, while having $E_{\text{peak}}$ that is not unprecedented, suggests that GRB 170817A is not simply a faint on-axis short GRB, but is instead consistent with the observation that it is viewed off-axis.

We dedicate this work to the memory of Neil Gehrels, one of the original PIs for our Chandra proposal and an active participant in the early months of the program. Neil’s stewardship of Swift has influenced our entire community—this short $\gamma$-ray burst and its coincidence with a LIGO-Virgo GW source would have thrilled him. The authors also owe a debt of gratitude to Belinda Wilkes and the Chandra scheduling, data processing, and archive teams. Their incredibly fast work was essential to making these time-sensitive observations possible. We also thank our anonymous referee for their timely review and useful comments. We thank Sean McWilliams for his useful input. This work was...
supported by Chandra Award Number GO7-18033X, issued by the Chandra X-Ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration (NASA) under contract NAS8-03060. D.H. acknowledges support from the Canadian Institute for Advanced Research (CIFAR). M.N. and J.J.R. acknowledge funding from the McGill Trottier Chair in Astrophysics and Cosmology. D.H., M.N., and J.J.R. also acknowledge support from a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant and a Fonds de recherche du Québec-Nature et Technologies (FRQNT) Nouveaux Chercheurs Grant. P.A.E. acknowledges UKSA support. J.A.K. acknowledges the support of NASA grant NAS5-00136.

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References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016a, PhRvL, 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016b, ApJL, 826, L13
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, PhRvL, https://doi.org/10.1103/PhysRevLett.119.161101
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17
Connaughton, V., Blackburn, L., Briggs, M. S., et al. 2017, GCN, 21506
Connaughton, V., Burns, E., Goldstein, A., et al. 2016, ApJL, 826, L6
Corsi, A., Hallinan, G., Mooley, K., et al. 2017, GCN, 21815
Coulter, D. A., Kilpatrick, C. D., Siebert, M. R., et al. 2017a, GCN, 21529
Coulter, D. A., et al. 2017b, Sci, https://doi.org/10.1126/science.aap9811
da Costa, L. N., Willmer, C. N. A., Pellegrini, P. S., et al. 1998, AJ, 116, 1
D’Avanzo, P., Salvaterra, R., Bernardini, M. G., et al. 2014, MNRAS, 442, 2342
Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, Natur, 340, 126
Evans, P. A., Kennea, J. A., Barthelmy, S. D., et al. 2016, MNRAS, 460, L40
Evans, P. A., Kennea, J. A., Breeveld, A. A., et al. 2017a, GCN, 21550
Evans, P. A., Kennea, J. A., Keneko, S. B., et al. 2017b, GCN, 21612
Evans, P. A., et al. 2017c, Sci, https://doi.org/10.1126/science.aap9580
Fong, W., Margutti, R., & Haggard, D. 2017, GCN, 21786
Fruscione, A., & Burke, D. 2016, ChNew, 23, 29
Goldstein, A., Veres, P., Burns, E., et al. 2017b, ApJL, https://doi.org/10.3847/2041-8213/aa8f41
Goldstein, A., Veres, P., von Kienlin, A., et al. 2017a, GCN, 21506
Granot, J., Panaitescu, A., Kumar, P., & Woosley, S. E. 2002, ApJL, 570, L61
Güver, T., & Özel, F. 2009, MNRAS, 400, 2050
Haggard, D., Nynka, M., Kalogera, V., et al. 2017, GCN, 21528
Kim, D.-W., & Fabiano, G. 2015, ApJ, 812, 127
Li, L.-X., & Paczynski, B. 1998, ApJL, 507, L59
LIGO Scientific Collaboration & Virgo Collaboration 2017a, GCN, 21505
LIGO Scientific Collaboration & Virgo Collaboration 2017b, GCN, 21509
Margutti, R., Berger, E., Fong, W., et al. 2017b, ApJL, https://doi.org/10.3847/2041-8213/aa0577
Margutti, R., Fong, W., Berger, E., et al. 2017a, GCN, 21648
Mooley, K., Hallinan, G., & Corsi, A. 2017, GCN, 21814
Narayan, R., Paczynski, B., & Piran, T. 1992, ApJL, 395, L83
Paczynski, B. 1986, ApJL, 308, L43
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Soares-Santos, M., Kessler, R., Berger, E., et al. 2016, ApJL, 823, L33
Sugita, S., Kawai, N., Serino, M., et al. 2017, GCN, 21555
Tsvetkova, K., Cobo, L., Panaitescu, A., et al. 2017a, GCN, 21523
Tsvetkova, K., Cobo, L., Panaitescu, A., et al. 2017b, GCN, 21545
Tsvetkova, K., Cobo, L., Panaitescu, A., et al. 2017c, GCN, 21648
Tsutsui, R., Yonetoku, D., Nakamura, T., Takahashi, K., & Morihara, Y. 2013, MNRAS, 431, 1398
van Eerten, H. J., & MacFadyen, A. I. 2011, ApJL, 733, L37
Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, ApJ, 465, 487
von Kienlin, A., Meegan, C., Goldstein, A., et al. 2017, GCN, 21520
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914