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Multi-messenger from compact binary mergers

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Compact binary mergers are important targets of multi-messenger astronomy. They emit gravitational radiation, which allows us to identify the source as compact object binaries and to infer binary parameters such as the mass and distance. If the binary involves neutron stars, various electromagnetic as well as other high-energy emission could be expected. Here, we summarize the current understanding of multi-messenger emission from compact binary mergers.

KEYWORDS: Gravitational waves, black holes, neutron stars, gamma ray bursts

1. Introduction

Many binary-black-hole merger events are detected with gravitational waves in this few years by Advanced LIGO and Advanced Virgo [1]. Because gravitational waves give us information of the binary components via orbital dynamics encoded on the gravitational-wave phase, we can infer various information of black holes such as the mass and spin. We are starting to understand properties of the cosmological population of stellar-mass black holes [2]. The gravitational-wave amplitude also enable us to derive the luminosity distance to the source thanks to the reliability of general relativity, which is confirmed by these gravitational-wave detections themselves.

Multi-messenger astronomy with binary-neutron-star mergers (as well as black hole–neutron star binary mergers) has also begun with GW170817 [3]. For binary neutron stars, the host galaxy can be determined aided by high localication accuracy of electromagnetic telescopes, and the cosmological redshift can be obtained. This combined with the luminosity distance allows us to conduct novel and robust cosmography to derive cosmological parameters such as Hubble ’ s constant. Furthermore, we may understand the launching mechanism of an ultrarelativistic jet and the production site of *r*-process elements via observations of the short gamma-ray burst and the kilonova/macronova.

However, compact binary mergers have not yet been observed at very high energy. That is, no gamma-rays above MeV, no neutrinos, and no cosmic rays are observed (although their non-detections have been anticipted). In this article, we summarize the current status of multi-messenger astronomy and future prospects for detecting very-high-energy radiation from compact binary mergers.

2. Kilonova/macronova AT 2017gfo and *r*-process nucleosynthesis

When the neutron stars merge, some fraction of the neutron-rich material is likely to be ejected from the system. Nucleons in the ejecta will be synthesized to the so-called *r*-process elements, which occupy about a half of elements heavier than the iron. Associated radioactive decay heats the ejecta so that they shine on a time scale of day, week, and month in the ultraviolet-optical-infrared bands. This unique transient is called the kilonova or macronova. The first confirmed kilonova/macronova, AT 2017gfo, allowed us to conclude that binary-neutron-star mergers are at least partially sites of *r*-process nucleosynthesis, and in addition, to determine the host galaxy of GW170817, NGC 4993 [4].

2.1 Host galaxy and Hubble ' s constant

NGC 4993 turned out to have the cosmological redshift of $z \sim 0.01$. At the same time, gravitational waves GW170817 reveal that the luminosity distance to the source is $\sim 40\,\mathrm{Mpc}$ with moderately large errors. They are combined to derive Hubble ' s constant to be $H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [5]. This value is consistent with both the local and cosmic-microwave-background measurements, where the tension of $\approx 9\%$ between them is vigorously debated as of 2019.

The measurement of Hubble ' s constant with multi-messenger observation will improve in the near future as the number of events increases. It will be possible to test the Hubble tension with this " standard siren " method. However, the source of the error is not limited to statistical ones. Actually, the systematic error assiciated with theoretical models, which is severe for both the local and cosmic-microwave-background measurements, is mostly negligible for the standard siren thanks to the reliability of general relativity. The problem lies in the measurement accuracy of the gravitational-wave amplitude. Currently, it is limited to a few % depending on the frequency [6]. If this is not improved significantly, it may not be straightforward to resolve the Hubble tension with the current gravitational-wave detectors. Taking the fact that the measurement error is associated with specific configurations of ground-based gravitational-wave detectors into account, one way to solve this problem may be to go to space with Laser Interferometer Space Antenna (LISA) [7].

2.2 Kilonova/macronova

The observed kilonova/macronova, AT 2017gfo, was consistent with the prediction that quasithermal emission associated with decaying *r*-process elements is bright primarily in infrared bands on a time scale of the week. This uniqueness as an electromagnetic transient owes its origin to atomic properties of lanthanide elements with $Z = 57$–71. Specifically, complicated level structures of lanthanides makes the opacity of ejecta as high as $\sim 10\,\mathrm{cm^2\,g^{-1}}$. Because this value is larger by about two orders of magnitude than the corresponding values for the ejecta made of elements lighter than the iron, the kilonova/macronova tends to become dimmer, longer, and redder than usually expected for the value of the mass and velocity of the ejecta. This confirms that binary-neutron-star mergers can produce some of the *r*-process elements.

It does not necessarily mean that all the *r*-process elements are produced in binary-neutron-star mergers. For example, we are lacking any evidence that the heaviest, trans-uranium elements are produced in this event. Even the existence of third-peak elements such as the gold and platinum has not been confirmed. Although some researchers argue that the late-time emission of AT 2017gfo is explained well if we assume the third-peak elements exist [8], we cannot conclude their existence because of the lacking of theoretical understanding and also of multi-band observations. It is desired to reveal observationally which elements are present in the ejecta in a comprehensive manner, and one possible tool may be early-epoch polarization [9].

2.3 Possible kilonova/macronova remnant

The ejected material will eventually be decelerated by the interstellar material as the supernova ejecta do. Once such deceleration becomes significant, we have a good chance to observe the ejecta again via broadband synchrotron emission induced by particle acceleration and magnetic-field amplification at the blast-wave forward shock. For extreme parameters of the ejecta, e.g., relativistic velocity, it is even possible to detect the inverse Compton emission at GeV–TeV gamma rays [10].

The reverse shock of this blast wave is not likely to be an efficient cosmic-ray accelerator, while the forward shock may be [11]. The reason is that, if cosmic rays are accelerated from the ejecta material at the reverse shock, *r*-process cosmic rays could have been much stronger than the observed amount due to the high velocity of the ejecta. However, this argument does not necessarily mean that the particle acceleration itself is inefficient at the reverse shock. It is possible that the accelerated particle cannot escape without experiencing significant energy loss such as adiabatic expansion.

3. Gamma-ray burst GRB 170817A and magnetars

A black hole surrounded by an accretion disk (or torus) is likely to be formed after merger of binary neutron stars. This system may be able to drive an ultrarelativistic jet, which will be observed as a short gamma-ray burst from the direction along the jet axis. This merger scenario can be confirmed if a short gamma-ray burst is observed at the same time and location as gravitational waves from binary neutron stars. GRB 170817A was detected at 1.7 s after merger inferred from GW170817 by independent observations with gamma-ray satellites, Fermi and INTEGRAL [12]. These simultaneous observations strongly suggest that binary neutron stars are the central engines of short gamma-ray bursts. However, there were debates on the origin of emission, particularly regarding its energy lower by about four orders of magnitude than typical bursts.

3.1 Speed of gravity

Irrespective of whether GRB 170817A is a genuine gamma-ray burst, gamma rays arrived at us with only a 1.7 s delay from gravitational waves. Because the distance to GW170817/GRB 170817A is approximately 10^8 light years, this coincidence means that the speed of gravity must be identical to that of light up to the accuracy of $\sim 10^{15}$ as far as the gamma rays are assumed to be emitted near merger [12].

The fact that the speed of gravity is effectively the same as that of light rejects many modified theory of gravity. For example, if the model Lagrangian contains higher derivatives of a scalar field, the causal structure governing gravitational-wave propagation usually differs from that for electromagnetic waves due to the derivatives of a scalar. Such models are no longer considered to be realistic candidates of the theory of gravity in the real universe.

3.2 Jet or cocoon?

GRB 170817A was exceedingly weak compared to previously observed short gamma-ray bursts. While the detected flux was similar to those of other bursts, the extreme proximity of this event implies its very low luminosity. Thus, it has been speculated that this event may not be a usual gamma-ray burst. Because the afterglow was not detected until 1–2 weeks after merger, it has initially been considered that we had observed a gamma-ray burst from an off-axis direction.

Continiued power-law brightening of the afterglow up to ≈ 160 day after merger rejected the top-hat jet seen off-axis [13]. The reason is that the brightning and subsequent dimming must be rapid for such a jet. One of remaining possibilities is that we observed an ultrarelativistic jet with an angular structure from off-axis. Another possibility is that GRB 170817A was not, despite its appearance, associated with ultrarelativistic motion. Instead, it could have been driven by a quasispherical outflow, so-called cocoon, with a radial structure. If the latter is true, GW170817 and GRB 170817A do not give us the evidence of the merger scenario for short gamma-ray bursts. Thus, distinguishing these two models is definitely important for understanding the gamma-ray burst.

The solution came from two late-time features. First, the radio emission was spatially resolved and found to move with an apparent velocity of $\approx 4c$ [14]. The emission region itself was not resolved and was consistent with a point source. This superluminal motion strongly indicates the relativistic motion of a jet with $\Gamma \approx 4$, where the Lorentz factor should have been larger at early times. Second, the decay of the light curve after the peak is so steep that it is consistent with the jet emission [15]. By contrast, the luminosity should have decreased much slowly if the emission comes from a quasi-spherical cocoon. The current understanding is that GRB 170817A and its afterglow are consistently explained by the emission from an ultrarelativistic and structured jet seen from an off-axis direction. This suggests that the angular structure is an important ingredient of ultrarelativistic jets driving short gamma-ray bursts and must be accounted for in theoretical modeling of central engines.

3.3 Magnetar scenario

A central engine of the short gamma-ray burst alternative to a black hole–accretion disk system includes a magneter formed after merger. If the maximum mass of a neutron star is large, the merged object does not collapse into a black hole on a short time scale of $\lesssim 1$ s and it could survive as a massive neutron star on the spin-down time scale (or even permanently). Magnetic fields in the remnant massive neutron star are expected to be amplified substantially by Kelvin-Helmholtz instability, magnetic winding, and magnetorotational instability, and thus the merged remnant could become a magnetar. It has been argued that the magnetar can launch a jet via magnetic processes.

Some researchers reported late-time X-ray emission from GRB 170817A near the peak of the afterglow, ≈ 160 day after merger [16]. Although this excess emission is not very significant, it could indicate that a magnetar evaded collapse at least until this epoch. If such a long-lived remnant exist, it may be possible to detect assocaited GeV gammay rays from the magnetar [17]. Thus, late-time high-energy gamma rays could serve as confirmation of the magnetar scenario of short gamma-ray bursts.

Thermal neutrinos from the merged object could also be detected if it evades the collapse for $\gtrsim 1$ s in the foreseeable future [18]. The detection will support the existence of a massive neutron star and enable us to infer the energy scale of thermal emission from the merged object. Furthermore, comparison of arrival times of gravitational waves and neutrinos could possibly be used to put an upper limit of $\sim O(10)$ meV on the mass of neutrinos in the lightest eigenstate.

4. Future prospect

KAGRA will join the gravitational-wave detector network in the near future. By increasing the number of detectors, we may be able to constrain extra degrees of freedom, i.e., polarization modes, of gravitational waves. This will serve as an important test of general relativity, in which only two polarization modes should exist.

On 2030 ’ s, LISA and possibly other space-based gravitational-wave detectors will be launched. They are typically sensitive at ~ 1 mHz. The most promising target will be the merger of supermassive black holes in the center of galaxies. Their detection will occur at a very high signal-to-noise ratio. Thus, it will allow us to test general relativity and no hair theorem of black holes at very high accuracy. We may also be able to study cosmological evolution of large scale structures via observing the merger history of galaxies.

IceCube collaboration has reported possible simultaneous detection of a neutrino IC170922A and gamma rays from a blazer TXS 0506+056 [19]. Although intense neutrino emission from a blazar may not be very typical, this might suggest a possibility of novel multi-messenger observation with gravitational waves, neutrinos, and electromagnetic waves simultaneously.

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