PROCEEDINGS OF SCIENCE

Multi-messenger astrophysics in the gravitational-wave era

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The observation of GW170817, the first binary neutron star merger observed in both gravitational waves (GW) and electromagnetic (EM) waves, kickstarted the age of multi-messenger GW astronomy. This new technique presents an observationally rich way to probe extreme astrophysical processes. With the onset of the LIGO–Virgo–KAGRA Collaboration's O4 observing run and wide-field EM instruments well-suited for transient searches, multi-messenger astrophysics has never been so promising. We review recent searches and results for multi-messenger counterparts to GW events, and describe existing and upcoming EM follow-up facilities, with a particular focus on WINTER, a new near-infrared survey telescope, and TESS, an exoplanet survey space telescope.

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1. Introduction

Multi-messenger astrophysics with gravitational waves (GWs) is a young but rapidly growing field, spurred on by GW detectors such as the LIGO-Virgo-KAGRA (LVK) network [1–3] and a variety of electromagnetic (EM) follow-up instruments. Many possible sources of multi-messenger emission exist, but the most promising are compact binary coalescences involving neutron stars, such as neutron star–black hole (NSBH) and binary neutron star (BNS) mergers. These mergers produce a wide range of EM phenomena headlined by the kilonova, a thermal transient powered by the radioactive decay of heavy elements synthesized in the merger. We discuss efforts to search for multi-messenger emission and highlight two follow-up facilities: the Wide-field Infrared Transient ExploreR (WINTER), a new infrared survey telescope, and the Transiting Exoplanet Survey Satellite (TESS), a space telescope primarily designed for the discovery of exoplanets.

2. GW170817, O3, and O4

The discovery of the BNS merger GW170817, its companion gamma-ray burst (GRB), and resulting kilonova during the LIGO–Virgo O2 observing run kickstarted GW multi-messenger astrophysics. This single event has led to important advances in cosmology, dense matter equation of state physics, tests of general relativity, r-process nucleosynthesis, and neutron star astrophysics [4, 5, and references within]. The subsequent O3 observing run was successful, with the discovery of the first NSBH mergers and the detection of many binary black hole (BBH) mergers, as well as upper limits on multi-messenger GW emission from sources such as GRBs [6] and fast radio bursts [7]. However, no new multi-messenger sources were discovered, and the uncertainty in the BNS merger rate (representing the most promising source of GW multi-messenger events) continues to span orders of magnitude [8]. The current LVK observing run, O4, has thus far also not yielded any multi-messenger events, but the upcoming addition of Virgo to the detector network will improve its sensitivity and localization prospects.

3. Current and upcoming follow-up facilities

Multi-messenger astrophysics is by its very nature a synergistic effort. In addition to the LVK GW detectors, EM follow-up instruments across the wavelength spectrum are an integral part of multi-messenger science. Optical all-sky surveys such as ZTF and ATLAS and dedicated follow-up networks like GRANDMA and GOTO are joined by X-ray and gamma-ray telescopes such as Fermi and Swift as well as radio arrays in searching for EM counterparts to GW events [9–11, and references within]. In the coming years, new instruments such as the gamma-ray and X-ray telescope SVOM [12] and the Vera Rubin Observatory [13] will add to the GW follow-up landscape. We will focus here on introducing two instruments to the multi-messenger realm: WINTER and TESS.

3.1 WINTER

WINTER is a newly commissioned 1 sq. deg. infrared survey instrument mounted on a 1-meter telescope at Palomar Observatory [14]. It observes in the Y, J, and Hs (shortened H, ending at 1.7 μm) bands and has a current limiting magnitude of $\sim$ 18.5 mag in the J band, with planned sensitivity

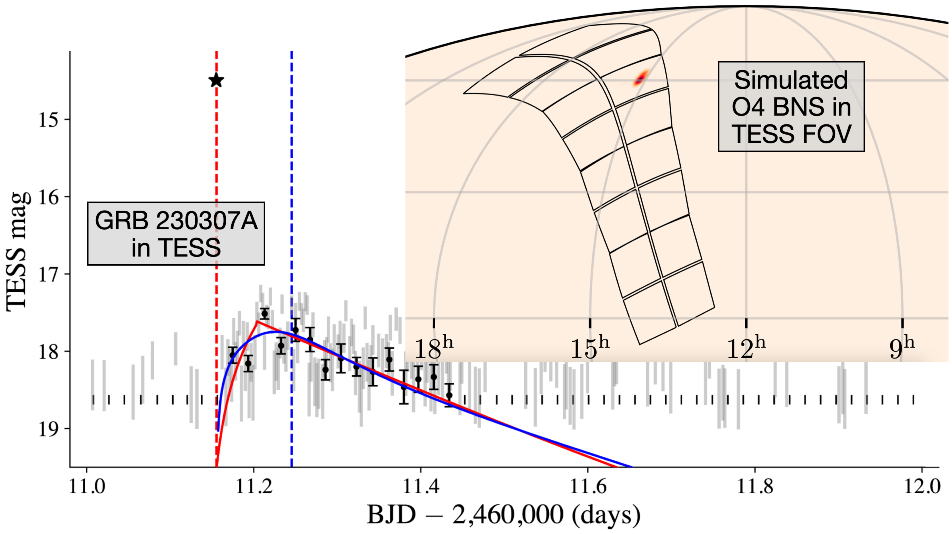

Figure 1: Example scenario for a TESS detection of a kilonova resulting from a BNS merger discovered in GWs. The lightcurve shows the TESS observation of GRB 230307A, including the prompt optical emission coincident with the GRB (dashed red line) and the subsequent rise and decay of the GRB afterglow. The inset shows a simulated LVK localization of a BNS merger using projected O4 GW sensitivity curves (as described in [17]), overlaid with the FOVs of the 16 TESS CCDs. The entire GW localization area is contained within one TESS CCD. If a resulting kilonova lightcurve is similarly luminous to that from GW170817, TESS will sample it as finely as it did for GRB 230307A's afterglow. Figure modified from [17, 18].

upgrades. One of its main science objectives is the discovery of kilonovae through the follow-up of GW events. The *r*-process elements synthesized in BNS mergers have dense line transitions at optical wavelengths, pushing the peak of the kilonova emission into the near-infrared (NIR). Similarly, compared to in the optical, the NIR emission is expected to be longer-lived, and to depend less on the viewing angle of the kilonova [15]. WINTER's NIR sensitivity combined with its relatively wide 1 sq. deg. field-of-view (FOV) fill a unique niche in the parameter space of follow-up instruments. A simulation study of a WINTER follow-up campaign of LVK BNS mergers using design sensitivities for WINTER and LVK O4 finds that WINTER could discover up to ten kilonovae per year under ideal circumstances [16]. Despite both the LVK network and WINTER currently falling short of their projected sensitivities, WINTER's NIR capabilities and its FOV are why it remains a powerful tool for multi-messenger discovery and characterization.

3.2 TESS

Another promising follow-up facility is TESS, which was originally designed for the discovery of exoplanets around M-dwarf stars. With its 2304 sq. deg. FOV, it has proven to be valuable for transient science as well [19]. TESS observes its FOV for approximately one month at a time with a fixed schedule, taking an image every 200 s in a single filter spanning from 600 nm to 1000 nm. Each 200 s integration has a limiting magnitude of about 17.5 in the TESS band, but stacking exposures can increase TESS's sensitivity to 20.5 mag for an 8 hour stack. Due to its large FOV (equivalent to about 5% of the sky), TESS is likely to make serendipitous observations of GW skymaps, and, if it is bright enough, any counterpart optical/NIR emission.

Simulations of BNS mergers and their resulting kilonova lightcurves have shown that TESS can detect up to two kilonovae per year from BNS found in GWs. The simulations also show the importance of performing searches for kilonovae in TESS data, even without a GW event: as many as eight BNS per year may be too quiet in GWs to result in an LVK trigger, but can produce kilonovae bright enough to be detectable in TESS [17]. If a GW170817-like BNS occurs within its FOV, TESS will provide exquisite photometric measurements of the kilonova. Fig. 1 shows this example scenario using a well-localized simulated O4 BNS and the TESS observation of the afterglow of GRB 230307A as an example light curve [18]. The above predictions depend strongly on BNS merger rates, which are a large source of uncertainty in simulations like these.

4. Conclusion

As O4 continues and follow-up instruments across the EM spectrum such as WINTER and TESS realize their potential, prospects for multi-messenger observations remain bright. In addition to the BNS mergers we know can result in EM counterparts, there is also the possibility of unveiling new multi-messenger science from NSBH and BBH mergers, as well as potentially from other sources of GWs such as core-collapse supernovae or magnetars. Beyond O4, instruments such as LSST on the Vera Rubin Observatory promise to revolutionize time-domain astronomy as a whole, driving forward the horizon of multi-messenger astrophysics.

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