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Gamma Rays and Gravitational Waves

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Abstract:

The first multimessenger observation of a neutron star merger was independently detected with gravitational waves by Advanced LIGO and Advanced Virgo and γ-rays by Fermi-GBM and INTEGRAL SPI-ACS. Gravitational waves are emitted from systems with accelerating quadrupole moments, and detectable sources are expected to be compact objects. Nearly all distant astrophysical γ-ray sources are in fact compact objects. The coïncident observation of these two messengers will elucidate the sources of gravitational waves and γ-rays and enable multimessenger science. This ultimately requires upgrades to the ground-based gravitational wave network and $\sim$keV-MeV γ-ray coverage for observations of neutron star mergers. By simultaneously observing gravitational waves and γ-rays the observation and description of their joint sources can be achieved.

Introduction

The joint detection of γ-rays and gravitational waves (GWs) from merging neutron stars (NSs) ushered in a new era of multimessenger astronomy [1, 2, 3, 4]. This event has led the community to produce on average $>$3 papers/day. NS mergers will continue to be the canonical multimessenger source for the foreseeable future as the joint detections of these events become more common, but they are not the only expected sources of GWs. We summarize here the state of future GW and γ-ray observatories, the potential multimessenger sources, the science they enable, and the science that is achievable in a given mission size.

Gravitational Waves

GWs were first directly detected by Advanced LIGO [5] in 2015 [6]. Advanced LIGO and Advanced Virgo [7] have completed two observing run and published a catalog of events; 10 binary black hole mergers and a binary neutron star merger [8]. Their third observational run started in April of 2019. Searches for GW signals in LIGO and Virgo can be classified according to their methodology, based on the type of GW emission. **Compact Binary Coalescences (CBCs)** are the mergers of compact objects (generally, black holes (BHs) and NSs), have predicted (from general relativity) waveforms, and encompass all GW detections so far. Searches for **Continuous Waves (CWs)** look for persistent sources of GW emission with waveforms predicted by general relativity. The signals are approximately monochromatic, evolve very slowly, and come from rotating non-axisymmetric systems. GW **Burst** searches are sensitive to transients with unmodeled or unspecified waveforms. **Intermediate duration** GWs have timescales in between those of CBC/Burst and CW signals, and are a comparatively new class. Searches for intermediate duration GWs either extend Burst searches to longer timescales or modify CW searches to shorter timescales and more rapid evolution.

Gamma rays

γ-rays are the most energetic form of light. In astrophysics the term is not restricted to photons from nuclear processes; as such, the lower limit of what constitutes γ-rays is somewhat fuzzy, generally set between $\sim$10-100 keV with the overlap sometimes referred to as hard X-rays or soft γ-rays. γ-rays between $\sim$keV-GeV energies can only be observed from space. These instruments are broadly classed as scintillators, coded masks [e.g. 9], Compton [e.g. 10], and pair-conversion telescopes. Higher energy photons are observed indirectly through Cherenkov radiation as the photons pass through water (in enclosed tanks) or the Imaging Atmospheric Cherenkov Telescopes (IACTs). All γ-ray detectors are wide-field survey telescopes, except the IACTs.

In France, and important scientific development for the observation of γ-rays will be the upcoming observations by the Space Variable Objects Monitor (SVOM) [11]. SVOM, a French-Chinese mission, will be one of the major actors in the next decade in the detection of γ-ray bursts and more broadly on the transient sky. This mission is a multi-wavelength observatory with large coded mask imager (ECLAIR) and a gamma-ray spectrometer in the MeV range, associated to two smaller instruments in keV domain (MXT) and visible light (VT). A ground segment will complete the capacities with a large field of view detector in visible range (GWAC, 5000sq deg) but also deeper instruments in visible and IR light (GFTs). The main SVOM objective is to study from the prompt to the afterglow phases and will also increase the number of γ-ray burst with redshift measurement. GW multi-messenger astronomy is also an important aspect of the mission with a dedicated Target of Opportunity program to follow GW or astrophysical neutrinos candidates. For example, X-ray counterpart and kilonova emission will be searched for using the whole range of detectors.

Sources of GWs and γ-rays

NS mergers are important sources for both GW and γ-ray observatories, although they are not the only potential multimessenger sources.

Neutron Star Mergers

BNS and probably some NSBH mergers, collectively referred to as NS mergers, produce short gamma-ray bursts (SGRBs) as well as kilonovae. These events have GW signals in the $\sim$Hz-kHz range and are found with CBC searches. SGRBs are observed from $\sim$keV-MeV energies in their prompt phase. Prompt emission is followed by afterglow that has been observed from radio to GeV energies, and may soon be detected in the TeV regime based on the MAGIC detection of the long GRB 190114C [12] and the sensitivity improvement with the CTA. There is also the report that for GRB 180720B HESS observed 440 GeV γ-rays 10 hours after the burst [13]; GRB 190829A is another interesting event but HESS has not yet reported on the energy of the observed photons [14]. As SGRBs arise from collimated jets [e.g. 15], they are not expected to be detectable for the majority of NS mergers; GWs are omnidirectional but not isotropic [16]. Accounting for these effects, about 10-15% of GW-detected NS mergers will produce SGRBs with Earth in the jet opening angle. However, the joint observation of GW170817 / GRB 170817A [3] has shown that SGRB can emit gamma-rays even outside the jet opening angle albeit with several orders of magnitude lower flux.

Joint GW-GRB detections of NS mergers give unique insights into relativistic jets, astroparticle physics, and the equation of state (EOS) of supranuclear matter, and provide precise tests of fundamental physics. A more in-depth summary of the science enabled by the multimessenger observations of these events is available in [17, 18]. Because SGRB prompt emission occurs within a few seconds of merger, this science requires serendipitous observations of mergers. Therefore, the first SGRB figure of merit is the average sky coverage, corresponding to the probability a merger will be observed. The second figure of merit is the known or predicted rate of SGRB detections, which directly corresponds to the likelihood of joint detections. Currently, this figure of merit is limited by the GW detector sensitivity for on-axis SGRBs and by γ-ray detector sensitivity for moderately off-axis SGRBs. Lastly, joint searches for GWs and GRBs will result in more confirmed GWs, GRBs, and joint detections, and enable a near real-time combination of localization information. These capabilities aid the coordinated follow-up effort, helping with their use in cosmology as standard sirens (with GRBs breaking inclination-distance correlations), the origin of heavy elements, and a fuller understanding of the NS EOS [see, e.g. 17, 18, and references therein]. Therefore, localization accuracy is the last SGRB figure of merit. Localization with γ-ray instruments can occur in two ways: autonomous real-time prompt SGRB localization by a single detector (which can be improved with follow-up by other instruments on the same spacecraft) or the detector's use in the InterPlanetary Network (IPN) [19] for timing annulus localizations. We note that instruments in Low Earth Orbit (LEO) require distant instruments for these annuli to be constraining, given the limited timing accuracy from SGRB observations.

Other Possible Joint Sources

A critical topic in astrophysics is the identification of sources of GWs and γ-rays. Here, we list most of the putative GW sources and their expected γ-ray emission. Beyond identifying the sources themselves, such detections could give insight into the formation processes of NSs and BHs, the formation channels of the binaries, the NS EOS, and the evolutionary pathways of supermassive BHs and galaxy formation. The serendipitous joint observations of these two messengers can be the catalyst for coordinated follow-up. Multimessenger science may be key to identifying GW sources, by providing a known position, time of interest, or directly measuring frequency evolution. Joint sources that require long-term EM monitoring cannot be studied by scintillators, can be studied by coded masks and IACTs, and are best studied with Cherenkov, Compton, and Pair-conversion survey telescopes. For such sources the two figures of merit are (total) sky coverage and cadence.

- **Core Collapse Supernovae** in the Milky Way may produce detectable GW burst emission, and are expected to occur once every few decades. γ-rays in the $\sim$MeV range measure the production of radioactive elements that probe both stellar convection and the supernova engine. Some extreme CCSN also power long GRBs, which may produce significantly stronger GW emission [20, 21]. Neutrinos from collapse events are also detectable, and joint GW, neutrino, and γ-ray detections would constrain both the understanding of the supernova engine and the physics behind it [22], but to do so requires improved sensitivity to both the ground-based GW network and MeV γ-ray observatories.
- **Pulsars** are rapidly rotating neutron stars with large magnetic fields from which we observe pulsed electromagnetic emission. Any non-axisymmetric deformation in the object would cause it to emit $\sim$Hz-kHz CWs, generally at twice the rotational frequency [see, e.g. 23, for a review]. γ-ray monitoring of pulsars provide accurate timing solutions that enable deep searches for CWs. Further, γ-ray observatories have also provided dozens of well-behaved pulsars for use in PTAs.
- **Accreting NSs** are promising sources of intermediate duration GWs. Small deformations may survive on short timescales at the regions of accretion [24, 25]. γ-ray observations can measure the frequency change and inform on the accretion rate. A possible example are transitional pulsars which spin up during accretion but otherwise have normal spin-down behavior.
- **Pulsar Glitches** are sudden changes in the rotation period and period derivative of the pulsar, with recovery timescales of hours to months. Glitches are thought to be caused by interactions at the core-crust interface, which could produce GWs during the recovery period. All-sky γ-ray monitors with localization capability can constrain the glitch time of γ-ray pulsars to an accuracy of $\sim$minutes, as was recently done for a Vela pulsar glitch [26]. This precision enables sensitive follow-up searches for intermediate-duration GW searches by providing both a start time and a known frequency evolution.
- **Giant Magnetar Flares** are short, bright flashes of γ rays, followed by quasi-periodic oscillations (QPOs) for hundreds of seconds [see, e.g. 27, 28, 29]. They could result in non-axisymmetric deformations of the magnetar through crust-cracking or magnetic field-induced structural changes [30]. The prompt flare may produce GW burst emission,

and the QPOs provide a known frequency to search for intermediate-duration GWs [31, 32]. Joint observations can inform on the NS structure and the emission mechanism for magnetar flares.

- **Supermassive Black Holes Binaries** (SMBHBs) and their mergers are key sources for PTAs and LISA. The evolutionary pathways to creating SMBHBs are intricately tied to galaxy formation, but poorly understood. Long timescale observations of active galactic nuclei can reveal periodicity that may be related to future GW sources. The BL Lac object PG 1553+113 has an apparent 2.2 year cycle that has been observed for $\sim$5 periods by the Fermi LAT, which could arise from a SMBHB system [33, 34]. Observations of MeV blazars would allow for multimessenger constraints on the formation of SMBHBs, without necessarily observing the same individual sources.
- **Something Unexpected.** Among the most interesting options for GW and multimessenger sources are those that we do not predict. One such example may be the creation of a SGRB following stellar-mass binary black hole mergers [e.g. 35], which is generally unexpected due to the lack of available matter. Because of the low rate of γ-ray transients and γ-ray detectors being all-sky monitors, they are promising EM partners for the unexpected, and could reliably prove association even without prior statistical assumptions.

Summary

Joint γ-ray and GW searches will identify the sources of both of these messengers and initiate the coordinated follow-up efforts. The all-sky monitoring capability of γ-ray and GW facilities, and the expected source types, make them synergistic partners in the multimessenger era.

There was an important lesson that was learned from GW170817 / GRB 170817A. A SGRB can be observed by γ-ray detectors even if Earth is not in the jet opening angle, and the emission is very dim. There is still no scientific consensus as to know how far away from the jet there is still emission, or what is the jet structure (cocoon emission, or whatever made the γ-ray emission of GRB 170817A). For events like GRB 170817A the γ-ray satellites' horizon is actually smaller (40 to 80Mpc) than the LIGO/Virgo horizon. Consequently, there are two ways to increase the joint detection rate:

- increase the LIGO/Virgo horizon and observing time to detect more standard SGRBs in coincidence with GW events;
- increase the γ-ray satellite sensitivity to find more slightly off axis SGRBs like GRB 170817A that are already within the LIGO/Virgo horizon.

The science possible with NS mergers is incredible. To ensure success, it will be essential to have a vigorous upgrade timeline for the ground-based GW network and continued and improved $\sim$keV-MeV γ-ray coverage. In addition, the creation of a coherent GRB network analogous to the ground-based GW network is also scientifically crucial. Small-scale missions can contribute critical sky coverage, sensitivity, and localizations for SGRB studies, though not at the same time. High energy missions that do not have GW counterparts as prime science drivers will provide important coverage and capabilities for joint γ-ray and GW science.

To study longer-duration transients generally requires larger-scale missions that can study individual sources in detail. Any new joint detection will uncover another class of GW sources, and will enable unique science. To capture the full range of multimessenger sources, broad coverage of the γ-ray sky from keV to TeV energies in partnership with broad coverage of the GW spectrum must be a goal for the coming years of observations.

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