Multi-messenger astronomy

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Modern astrophysics utilizes data from a wide variety of channels extending beyond the conventional optical, radio and X-ray observations. Technological developments have augmented electromagnetic (EW) observations with data from cosmic ray detectors, neutrino detectors and recently from gravitational wave (GW) observatories – together forming the core of multi-messenger astronomy. Each 'messenger' carries complementary information about various physical processes occurring in an astrophysical source. Combining data from all these channels makes it possible to piece together a more detailed understanding of sources than any single channel can. In this article I discuss multi-messenger astronomy with emphasis on joint EM and GW studies.

Keywords: Astrophysical source, complementary information, electromagnetic and gravitational waves, multi-messenger astronomy.

Introduction

ASTRONOMERS had long relied on visible light as a means of understanding the universe. As the tools of the trade became more sophisticated over time and expanded to include wavelength bands from radio to gamma rays, our understanding of the cosmos improved manyfold[1]. In recent decades, astroparticle studies – cosmic rays and neutrinos – opened up a completely new line of astrophysical study. The discovery of gravitational waves (GWs) has ushered a new era of astrophysics. Put together, light, particles and GWs form the complete toolbox of multi-messenger astronomy at our disposal for unravelling the mysteries of the universe.

Much as multi-wavelength studies transformed astronomy in the 20th century, today multi-messenger astronomy holds immense potential for pushing the boundaries of our understanding of the universe[2–4]. For instance, observations and theoretical models of short gamma ray bursts indicate that their progenitors are the merger of two neutron stars. The direct detection of GWs from such a source will provide the final unambiguous proof of such a model[5]. Detection of neutrinos from nearby supernovae or gamma ray bursts will provide vital inputs to state-of-the-art models of these explosions[6]. While the importance of such multi-messenger observations has been long acknowledged, it is only now that technological developments have brought us on the verge of actually making these observations.

This rapid development of multi-messenger astronomy is fuelled by both evolutionary and revolutionary advancements in facilities around the world. Advanced LIGO[7,8] will soon be joined in its observations of GWs by VIRGO, Kagra and LIGO-India, and eventually by LISA. The coming decade will see the development of 30 m class telescopes that will far surpass the performance of the current 8–10 m class telescopes. Surveys like ZTF, Pan-STARRs, LSST will provide exquisite time-domain data on nearly the entire sky. Radio facilities are getting a tremendous boost with observatories like uGMRT, ALMA and SKA. High-energy astrophysics is progressing with space-based instruments like AstroSat, POLAR, as well as ground-based developments like MACE. Neutrino detectors like Icecube and the Indian Neutrino Observatory complete the repertoire.

The potential scientific returns from multi-messenger observations are far too many to discuss in a single article. Instead, here I focus on the sub-field which is most active: the synergy between GWs and electromagnetic (EM) observations.

Shedding light on gravitational wave sources

Advanced GW detectors are routinely undertaking observations[9], and will be joined by projects like LIGO-India in the coming years[10]. These observatories will measure GWs from a multitude of sources, which can be broadly classified as compact binary coalescences, burst sources, continuous wave sources and stochastic background. Several sources from the first three categories may be accompanied by EM emission. This arises from a different set of physical processes in the same source – giving us access to complementary information that cannot be gleaned from the GW signal alone. With decades of efforts to detect GWs finally bearing fruit, this is an opportune moment for the searches for EM counterparts to unravel the true nature of these sources.

It is widely agreed that the detection and study of the anticipated EM counterparts will vastly enrich the science returns for the field of GW astronomy. For compact binary coalescence events involving a neutron star, the photometric discovery of the EM counterpart will give a precise location and a spectrum of the host galaxy will

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give a precise redshift. This will enable a more accurate measurement of basic astrophysical properties such as the luminosity and energetics of this strong-field gravity event. If the spectrum is timely, it may also solve the longstanding mystery of the unknown sites of *r*-process nucleosynthesis – we might finally pinpoint the heavy element mines.

A potential 'burst' source of GWs is supernova explosion. Observations of supernova remnants have indicated that there might be a high degree of asymmetry in the explosion (see for instance refs 11, 12). Such asymmetric explosions will emit GWs, which may be detectable for nearby core collapse supernovae[13].

Searches for GWs from 'continuous wave' sources benefit immensely by data from various EM bands. The LIGO Scientific Collaboration[14] searched for GW emission by neutron stars (NS) using the location and spin parameters from radio data. While no GWs were detected, the measured upper limits on GW energy loss from eight pulsars were more stringent than the indirect upper limits from just spin-down considerations. Another promising source of continuous GW are accreting NS binaries. In such systems, gas flowing from a companion star gets channelled to the magnetic poles of the NS, where it may accumulate for a while before spreading over the surface. As the magnetic poles of NS are often offset from their rotational poles, these mounds provide the necessary time-variable quadrupole moment necessary for the emission of GWs. The search for GWs from these sources is complicated by the fact that time-variable accretion rates produce unpredictable changes in the spin periods of these NS (Messenger *et al.*[15] and references therein). This hurdle can be alleviated by using X-ray instruments like Large Area X-ray Proportional Counter (LAXPC) and Scanning Sky Monitor (SSM) on AstroSat to monitor the spin periods and generate an ephemeris to assist GW searches.

Electromagnetic follow-up around the world

The first campaigns to search for EM counterparts to GW event candidates was executed with initial LIGO and Virgo detectors and several EM observatories in 2009 and 2010 (refs 16–18). In preparation for the first observing run of the advanced GW detectors, the LIGO–Virgo Collaboration invited interested groups to sign Memoranda of Understanding (MoUs) for entering into a partnership for the EM counterparts of GW sources[19]. Information about any GW candidates would be shared with these MoU partners so that they could undertake the search for EM counterparts. Sixty-three groups signed such MoUs before the first observing run O1, of which 25 teams partook in the search for an EM counterpart to the first GW source: GW150914 (refs 20, 21). Similar engagement was seen in the case of GW151226, and many groups have active MoUs for EM follow-up during the ongoing second observing run, O2.

The follow-up strategies in O1 varied significantly across teams. Missions like Fermi, AstroSat-CZTI and IceCube continuously acquire data for large parts of the sky, which can be post-processed to identify any burst coincident with the GW event. Wide-field ground-based telescopes like ATLAS and MASTER undertook rapid wide but shallow imaging of the GW localization region, while surveys like Pan-STARRS and iPTF went progressively deeper. Any potential transients were reported on a private GCN network. Various teams collaborated in the process, and often obtained photometric and spectroscopic measurements of sources discovered by others. The timescales for candidate radio transients range from weeks to months; hence radio telescopes continued their searches for longer periods of time[20]).

The GW events reported in O1 were coalescences of binary black holes; hence the detection of any EM counterparts was unlikely. The only candidate counterpart was reported by Fermi[22] – a flash in gamma rays coincident with the GW trigger. While a few models have been proposed for emission of EM radiation in a binary black hole merger[23,24], this gamma ray event has not been conclusively identified as the counterpart to GW150914.

Follow-up in India

Two Indian teams – an IUCAA optical observers group, and part of the AstroSat CZTI instrument team – were among the 63 that initially entered an EM follow-up MoU with the LIGO–Virgo Collaboration. The optical observers group collaborated with the intermediate Palomar Transient Factory Collaboration to follow-up GW triggers in O1 (refs 25, 26). Rana *et al.*[27] developed an enhanced scheduling algorithm that increases the odds of discovering an EM counterpart from a ground-based survey. This algorithm is being used by the iPTF group for scheduling follow-up observations[28], and also being adapted for a radio searchs using the Jansky Very Large Array.

The Cadmium–Zinc–Telluride detector on-board AstroSat serves as an all-sky monitor at energies above ~100 keV (refs 29 and 30). Bhalerao *et al.*[31] utilized this capability to put stringent upper limits on any X-ray emission coincident with the second GW detection, GW151226.

India is one of the seven partner countries in a project titled 'GROWTH': Global Relay of Observatories Watching Transients Happen[32]. GROWTH is a collaboration of longitudinally well-distributed observatories around the world to obtain uninterrupted observations of any sources of interest. As a part of this project, funding has been provided for a new robotic telescope by the Science and Engineering Research Board of the Department of

Science and Technology, Government of India. The GROWTH-India telescope will be a fully autonomous 0.7 m telescope located at Hanle, Ladakh, and is expected to be installed in late 2017. The search for optical counterparts to GW sources is one of the key projects planned for this telescope. Fully autonomous functioning, a modest aperture, and a wide 1° field of view will make this telescope well suited for the task.

Discussion

The first observing run of the advanced GW detectors demonstrated the capabilities of the global multi-messenger astronomy network. The events detected were coalescences of black holes, with a low probability of having any associated EM emission. Indeed, no confirmed counterpart could be found for these GW sources. The LIGO detectors started their second science observing run in late 2016, and are expected to be joined by Virgo in 2018. This network with increased sensitivity may soon detect GW events that are likely to have EM counterparts. The active follow-up community around the world will undoubtedly capitalize on this opportunity to obtain detailed observations. Detection, or even upper limits from non-detection of EM counterparts to GW sources will go a long way in improving our understanding of these extreme gravity events.

In the coming decade, facilities like the Zwicky Transient Facility (ZTF; ref. 33) and the Large Synoptic Survey Telescope (LSST; ref. 34) will drastically improve the odds of discovering the elusive optical counterparts to GW sources. The Square Kilometre Array will provide unprecedented capabilities for radio searches and studies of such counterparts[35]. Accurate source positions from any band will enable a slew of multi-wavelength observations for source characterization. With the advent of 30 m class telescopes, we will be able to study in detail the photometric evolution of the afterglows, spectral properties of these sources and even the environments of the progenitor. X-ray and gamma-ray studies of these sources will suffer due to the very short duration of these transients at high energies. This can be averted by augmenting the existing set of space telescopes to provide continuous coverage of the entire sky at high sensitivity.

The advent of GW astrophysics has added a long-awaited messenger to the toolbox of astronomers. We are tantalizingly close to solving riddles that have been unanswered for decades – exciting times lie ahead!

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