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Multi-Messenger Astrophysics

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Most astronomy observations are made by sensing light in a variety of wavelength bands, but a growing suite of sensitive detectors are opening up our ability to detect different astrophysical "messengers", namely neutrinos, ultra-high-energy cosmic rays, and gravitational waves. Detecting these different emissions from the same astrophysical event gives us complementary information and can provide novel insights into source objects, physical processes such as relativistic jet formation, and fundamental tests of gravity and nuclear astrophysics. In this article, I outline the promise and also the challenges of multi-messenger astronomy and astrophysics. I then illustrate a range of current multi-messenger research efforts with highlights from presentations given by various speakers in ICHEP2018 parallel sessions, and I also mention the case of the blazar TXS 0506+056. Finally, I relate some of the findings from the binary neutron star merger GW170817 that was detected by the LIGO and Virgo gravitational-wave detectors and by gamma-ray instruments in orbit, and subsequently studied in great detail by astronomers and instruments around the world.

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1. Introduction

High-energy physics has long had a close connection with astronomy. Indeed, since particle states other than the ordinary components of atoms (protons, neutrons, electrons) were first discovered and studied using the products of cosmic ray interactions with the atmosphere [1, 2], one can say that high-energy physics owes its origin to astrophysical processes. Nevertheless, astronomy, through most of its history, has relied primary on electromagnetic radiation to inform us about stars, galaxies, and cosmic processes. Besides employing telescopes of ever-increasing size and quality, electromagnetic (EM) astronomy has expanded to utilize a very wide swath of the EM spectrum, from radio waves (with wavelengths up to many meters) to gamma rays (with energies up to $\sim$100 GeV detected directly [3], and up to $\sim$100 TeV detected indirectly, e.g. [4]). Different instrumentation, such as spectroscopy in the visible and infrared bands, also has greatly expanded our ability to make detailed inferences about distant objects from the light we receive.

Of course, since all EM waves have a dual nature as photons, EM astronomy has an intrinsic particle nature, but this is normally only evident at X-ray and higher energies where the discreteness of light becomes more obvious and detectors routinely sense individual photons and measure their energies. In any case, the timing, intensity and spectra of light and other EM emissions received from a distant astrophysical object can tell us about particle acceleration, interactions and decay processes that transfer energy and material in the universe and largely determine the evolution of stars and galaxies.

In recent decades, new types of detectors have been built and applied to the study of astronomical objects and events using particles other than photons and using gravitational waves. These different "messengers" all carry different kinds of information because they are produced, and detected, using different physical processes. Neutrinos, being particles which interact with matter only through the weak force, require massive detectors to be sensed but travel a straight path[1] and thus reliably point back to the source location on the sky. Cosmic rays, being charged particles, are subject to being deflected by magnetic fields so only very-high-energy cosmics rays, for which the deflection is minimized, travel straight enough to be useful for localizing a specific source. (Lower-energy cosmic rays carry information in their energy spectum, composition, and variations in flux over time, which allow inferences to be made about relatively nearby sources and magnetic fields and the properties of the interstellar medium.) Gravitational waves are generated by rapid motion of mass and energy, and will be discussed in more detail below.

As illustrated in Figure 1, it is not just the existence of these four "messengers" but also their connections which are valuable. Generically, we may define multi-messenger astronomy to be correlated observations using two or more of these messengers, and multi-messenger *astrophysics* to be inferences about the properties of sources and the astrophyical processes at work in them. However, these two terms tend to be used interchangeably, and MMA is a convenient abbreviation which can refer to either.

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[1] Note that neutrinos, light, and gravitational waves are are all subject to gravitational deflection and lensing. That is, they travel undisturbed along "straight" paths—geodesics—in spacetime which may itself be curved relative to a nominal flat-geometry universe.

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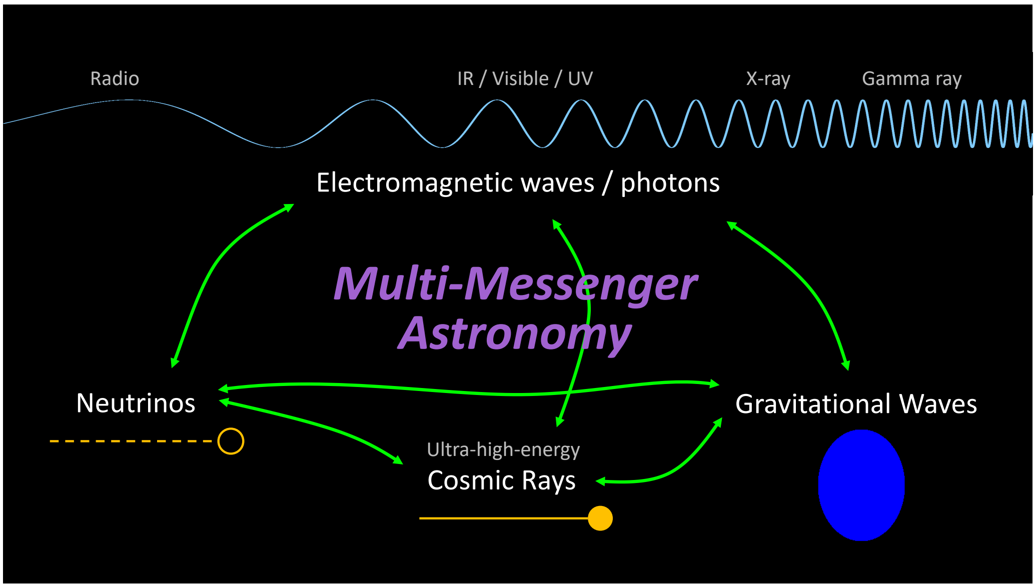

Figure 1: Four types of astronomical "messengers" which travel along more-or-less straight paths and, when detected at Earth, can provide complementary information about an astrophysical source.

1.1 Gravitational waves

Because gravitational waves are less familiar to high-energy physicists, this subsection provides a brief introduction.

It is tempting to associate the four messengers in Figure 1 with the "four fundamental forces" which govern their dominant emission mechanisms and interactions (with detectors, water or earth): the electromagnetic force for EM waves/photons, the weak force for neutrinos, the strong force for high-energy cosmic rays (since the majority are hadrons), and the force of gravity for gravitational waves. However, Albert Einstein's general theory of relativity (GR) says that gravity is really just a consequence of "curvature" in the geometry of space, not a force. The appearance of gravitational acceleration, then, is simply a view of objects naturally moving along locally straight paths in curved spacetime. The Einstein field equations of GR have static solutions which describe the regular gravitational field, but they also have wave solutions, in which *perturbations* of the spacetime metric (relative to a locally flat spacetime) propagate at the speed of light. Because the spacetime metric determines the effective distance between points in space and time, the physical effect of a gravitational wave (viewed as a function of time) is to stretch and squeeze space—and anything in it. Thus, remarkably, the geometry of spacetime has its own dynamics.

GR allows gravitational waves to have two polarization states. In the usual basis, these are described as the "plus" and "cross" states, and each manifests as a stretching along one direction together with a squeezing along a perpendicular direction, both transverse to the direction of travel. The metric describes a fractional stretching/squeezing, i.e. a *strain*, so that larger objects are deformed more in absolute terms.

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2. Science enabled by multi-messenger astronomy

The goal of multi-messenger astronomy is to detect and compare different emissions from the same sources, either individually or as as population. For example:

- The collapse of a massive star may produce a supernova, which is normally defined by its light curve (brightness as a function of time) in visible, infrared (IR) and ultraviolet (UV) light. That light comes from the envelope of expanding material blown off by the conversion of gravitational potential energy from the collapsing stellar core, although the mechanism which transfers that energy to the envelope is still a subject of debate. Gravitational waves and neutrinos, on the other hand, emanate from the core itself and carry information about the axisymmetry of the core collapse and nuclear reactions induced by the rapid increase in density, respectively. The remanant of a supernova can also produce cosmic rays via shock acceleration.
- The flux of high-energy cosmic rays should be directly related to the flux of high-energy neutrinos, because the latter are produced when cosmic rays interact with ambient photons [5].
- Relativistic jets of accelerated particles can be generated by accretion around a black hole, which could be a supermassive black hole in a galaxy (in which case this is an active galactic nucleus, AGN) or a smaller black hole from a stellar collapse or merger (which may produce a gamma-ray burst, GRB). These result in EM emissions at a wide range of wavelengths from shocked material, synchrotron emission from particles in turbulent magnetic fields, and inverse Compton scattering.
- A neutron star binary system in a close orbit will gradually spiral inward and finally merge, releasing gravitational waves. Accretion around the remnant object can produce relativistic jets (see above) as well as UV/visible/IR light from heated, expanding ejecta. This will be discussed further in section 5.

The different messengers give complementary information about an astrophysical event due to the different emission mechanisms and detection technologies which are used in Earth-based facilities or orbiting instruments. Broadly, observational strengths include:

- **Gamma ray:** timing, spectrum, particle acceleration signature
- **X-ray:** timing, good localization, low background
- **Visible/IR:** precise localization, spectroscopy (and redshift), thermal signature
- **Radio:** late-time synchrotron afterglow, precise localization
- **Neutrino:** timing, particle acceleration signature
- **Gravitational waves:** timing, distance, mass parameters

And different messengers reveal different parts of the event:

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- **Core engine:** low-energy neutrinos, gravitational waves
- **Outflows:** high-energy neutrinos, gamma rays, X-rays, visible/IR, radio
- **Environment:** X-ray and radio afterglow

For instance, the first multi-messenger astrophysics event to be observed using two messengers was supernova 1987A [6]. A total of 24 or 25 (depending on selection criteria) low-energy neutrinos were recorded by three detectors a few hours before the supernova became known from its rising light curve, located in the Large Magellanic Cloud.

High-energy neutrinos, on the other hand, are produced in relativistic jets or by shocks. The IceCube neutrino detector embedded in South Pole ice introduced us to this new messenger in the form of a diffuse flux of astrophysical neutrinos [7, 8] above the background of atmospheric neutrinos. IceCube has also measured the flavor ratio [9], but the source(s) of this diffuse flux is currently unclear. Candidate sources include AGN, GRBs, supernovae, and tidal disruption events; see, for instance, [10].

However, multi-messenger astronomy faces challenges. First, there is the issue of whether a particular event is simultaneously detectable using more than one messenger, given the emission mechanisms and the sensitivities of available detectors. Next, even if comparably sensitive detectors are available, they much be observing the transient source at the same time, or at compatible times if the emissions peak at different times (as for a supernova). Gravitational-wave detectors monitor the entire sky and store all useful data, while neutrino detectors and some gamma-ray instruments monitor a large fraction of the sky, but most other EM instruments need to be pointed. Wide-field EM instruments are more likely to have the source in view, but the most sensitive optical and X-ray telescopes are narrow-field and must be pointed in the right direction. This fact motivates real-time analysis to identify and assess candidate events as quickly as possible. It also motivates rapid sharing of information (i.e., cross-facility triggering) to allow further follow-up of interesting events, such as additional photometric observations and/or spectroscopy to fully characterize the event before it fades completely. Finally, even when multi-messenger data is obtained, interpreting the combined signatures may require sophisticated and challenging modeling of astrophysical processes.

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3. Highlights from relevant ICHEP2018 presentations

A number of presentations given in the parallel sessions illustrate some of the range of current multi-messenger activities. Only brief summaries are given here; see the articles elsewhere in this Proceedings volume for details.

In **Astrophysical Neutrinos at Hyper-Kamiokande**, I. Shimizu described the prospects for detecting neutrinos from supernovae using the Hyper-K detector, an upgrade to the well-known Super-Kamiokande detector which will expand the water volume to 260 kiloton (187 kiloton fiducial). For a supernova in the Milky Way at a typical distance of $\sim$10 kpc, Hyper-K should detect about 50,000 neutrinos and provide precise directional information. For comparison, the IceCube detector should detect about 300,000 neutrinos, but will not provide directional or energy information. The DUNE and JUNO detectors should detect about 3000 and 5000 neutrinos, respectively.

Hyper-K will also be able to study low-energy neutrinos from the Sun and the "relic" neutrinos which arrive individually from distant supernovae.

In **Physics Potentials of the Hyper-K 2nd Detector in Korea**, S. Seo described plans for constructing a second Hyper-K detector in Korea; several candidate sites are under consideration which align with the J-PARC neutrino beam and therefore would greatly enhance the T2HKK neutrino oscillation experiment, increasing the statistics and giving additional leverage on the parameter space due to adding the second, longer baseline. Naturally, the second detector would also increase the statistics for multi-messenger studies of supernovae.

In **Latest results of the ANTARES detector and perspectives for KM3NeT/ARCA**, A. Creusot spoke about the ANTARES high-energy neutrino detector which is currently operating in the Mediterranean sea, as well as the in-progress upgrade to produce KM3NeT. Multi-messenger searches are a key component of the ANTARES science mission and the team is actively coordinating with many other projects. ANTARES issues real-time alerts when certain trigger conditions are satisfied, to enable concidence tests with other facilities (including IceCube), and has placed limits on neutrino flux associated with certain GRBs and with gravitational-wave merger events detected by the LIGO and Virgo gravitational-wave observatories.

In **IceCube's astrophysical neutrino spectrum from CPT violation**, D. Marfatia discussed tests of the hypothesis that high-energy neutrinos have the same origin as ultra-high-energy cosmic rays and/or gamma-ray bursts, using spectrum comparisons. These test the possibility that GRBs or AGN are the source(s) of the diffuse high-energy neutrino flux which IceCube has observed.

4. Multi-messenger observations of the blazar TXS 0506+056

Although it was not presented at ICHEP2018, a hot topic in high-energy astrophysics at the time of the conference was the origin of an extremely-high-energy muon track reported by IceCube with the identifier IC-170922A [11]. The incident neutrino that produced this track in the detector pointed back just 14 arcminutes away from a known blazar, TXS 0506+056. Since a blazar is an AGN oriented such that the relativistic jet, produced by accretion around the supermassive black hole, is pointed toward Earth, high-energy neutrinos could also be produced with time variability following what is seen in EM emissions across the spectrum. Adding evidence to this hypothesis, the *Fermi* Large Area Telescope (LAT) instrument detected a significant increase in gamma-ray flux from this blazar at around the same time at GeV energies [12], and the MAGIC atmospheric air shower Cerenkov imaging telescopes detected very-high-energy ($>$ 100 GeV) gamma-ray emission from the blazar in the following couple of weeks [13].

A full understanding of these apparent connections was not available at the time of ICHEP2018, but futher analysis (reported later) of IceCube data and EM observations has put the significance of the association at 3σ [14] and also has found, in 9.5 years of IceCube data, a 3.5σ excess of neutrino candidates consistent with the position of the blazar [15]. This makes a compelling case for being the first detection of a known source with high-energy neutrinos. This was one of the two great multi-messenger breakthroughs of 2017.

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5. Multi-messenger observations of the binary neutron star merger GW170817

The other multi-messenger breakthrough of 2017 occurred on August 17: the detection of a binary neutron star merger in gravitational waves and EM.

In **In between the Observation Runs 2 and 3, a status report on the Advanced LIGO and Advanced Virgo GW detectors**, N. Arnaud reported on the detection of the strong gravitational-wave signal from this event in both LIGO detectors [16], immediately recognizable as a merging binary with component masses consistent with other known neutron stars [17]. The *Fermi* Gamma-ray Burst Monitor (GBM) recorded a short GRB about 2 seconds after the merger time, suggesting very strongly that it originated from the merger [18], confirming a long-standing hypothesis that neutron star binary mergers are the progenitors of most short GRBs (see, for example, [19]).

The Virgo detector [20] was operating but no significant signal was seen. The Virgo data, however, helped to localize the source to a region of about 30 square degrees near a minimum of the Virgo antenna pattern, and consistent with the larger *Fermi* GBM localization region. Normally a sky map would be produced from the gravitational-wave data within minutes, but in this instance a glitch in the LIGO Livingston detector had to be worked around, and the resulting ∼5-hour delay in sending the sky map to partner astronomer groups slowed the ability of the astronomers to search for a counterpart. Nevertheless, a bright optical counterpart with a consistent sky location and distance was found in the galaxy NGC 4993 first by the Swope Supernova Survey team [21], a little under 11 hours after the merger, and also by five other teams within the space of 45 minutes. That led to an extremely extensive campaign of follow-up observations [22].

While no neutrino counterpart to GW170817 was found by IceCube, ANTARES, or the Pierre Auger Observatory [23], the EM emission from this event was remarkably rich and well-studied. It was initially visible in ultraviolet and blue light [24], but those faded quickly. The fading was slower at longer wavelengths, with infrared emission peaking after a few days and remaining visible for weeks (see, for instance, [25, 26]). The spectrum was quite similar to a blackbody with a temperature of ∼10000 K when initially observed and cooled steadily to ∼2500 K eight days later. This rapid fading and reddening was unlike any known supernova.

In fact, the UV/visible/IR light curves observed from this event closely matched the “kilonova” model that had been predicted for neutron star binary mergers [27, 28]. Tidal disruption of the neutron stars just before they merge ejects a few percent of their mass, which remains around the merger remnant (initially a hypermassive neutron star, soon collapsing to a black hole) as a combination of unbound and accreting material. The extremely neutron-rich material forms heavy elements via the r process, such as gold, platinum, and uranium. Decays of unstable isotopes heat the ejected material as it continues to expand and become less optically thick, producing the thermal emission signature observed.

X-ray and radio emissions were not initially detected from this event, but continued monitoring found counterparts of both types which appeared ∼9 and ∼16 days after the merger, respectively, and brightened over a period of ∼4 months before ultimately fading [29].

The GRB observed by *Fermi*-GBM had typical short GRB characteristics but was exceptionally faint considering the distance to the galaxy, suggesting that the jet which produced it was viewed off-axis and that a “structured jet” or a “cocoon” produced some gamma-ray emission at larger angles. Indeed, this hypothesis was ultimately confirmed using very-long-baseline interfer-

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ometry [30]: the observed position of the radio counterpart shifted by $\sim$2.7 milliarcsec from 75 to 230 days after the merger, representing "superluminal" motion that confirmed the presence of a relativistic jet at an angle of 20 ± 5 degrees away from the line of sight.

One more bonus from the multi-messenger observation of this event was the opportunity to measure the Hubble constant using the distance estimated from the gravitational-wave data (since a binary merger with measured masses is a "standard siren") and the well-measured redshift of the host galaxy. This analysis yielded $H_0 = 70^{+12}_{-8}\,\mathrm{km/s/Mpc}$ [31], fully consistent within errors with the best available H_0 measurements from the cosmic microwave background and type Ia supernovae. A refined analysis using the VLBI-determined viewing angle to improve the distance determination from the gravitational-wave signal amplitude yields an estimate with smaller errors: $H_0 = 68.9^{+4.7}_{-4.6}\,\mathrm{km/s/Mpc}$ [32].

6. Summary and outlook

We have entered a new era for multi-messenger astronomy and astrophysics. Neutrino and gravitational-wave observatories are fulfilling their promises, as evidenced by the detection of GW170817 and TXS 0506+056. However, those are just the start, and more events will be needed to fully understand the astrophysics of those types of transients as well as other multi-messenger sources. The time-domain astronomy community has highly capable instruments and observing techniques to contribute on the EM side. Some major upgrades are on the horizon, including the Large Synoptic Survey Telescope (LSST), the Square Kilometer Array (SKA), and bigger neutrino detectors. The astronomy community also needs to keep excellent gamma-ray and X-ray instruments in orbit to catch GRBs and other high-energy astrophysical events. Complementary observations enable tests of astrophysical models and fundamental physics, including theories of gravity, nucleosynthesis, and properties of matter at extreme densities (in neutron stars), which could be influenced by exotic particles and fields.

Many projects are continuing or enhancing their efforts to find corresponding signals in other messengers through direct collaboration and/or open sharing of information. For example, N. Arnaud described the plans of the LIGO and Virgo collaborations to begin issuing public alerts for all event candidates (compact binary coalescence and unmodeled bursts) below a false alarm rate chosen to achieve a certain "purity" of the event sample. While information will be provided as quickly as possible, automated and manual checks of detector status, data quality and environmental factors will also be undertaken, and event candidates which fail checks will be retracted. Communication both ways between the gravitational-wave projects (LIGO, Virgo, and soon the KAGRA detector in Japan) and astronomers is envisioned, and we can expect many interesting results from multi-messenger observations in the future.

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