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Multi-messenger astronomy: gravitational waves, neutrinos, photons, and cosmic rays

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Abstract. In the next decade, multi-messenger astronomy will probe the rich physics of transient phenomena in the sky, such as the mergers of neutron stars and/or black holes, gamma-ray bursts, and core-collapse supernovae. The first observations of gravitational waves from the inspiral and merger of a binary black-hole system by the advanced LIGO interferometers marked the onset of gravitational-wave astronomy. The advanced detectors, LIGO and Virgo, observing together with space and ground-based electromagnetic telescopes, and neutrinos and cosmic-ray detectors will offer the great opportunity to explore the Universe through all its messengers. The paper provides a review of the astrophysical sources expected to emit transient multi-messenger signals and the multi-messenger observational strategies and analysis. Challenges and perspectives of the multi-messenger astronomy are presented highlighting gravitational waves as new messenger.

1. Gravitational waves as new messenger to observe the Universe

On September 14, 2015 the two detectors of the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) [1] located at Livingston and Hanford observed for the first time a transient signal of gravitational waves (GW) [2]. The signal provides the first observational evidence of the inspiral and merger of stellar-mass binary black holes (BH) and the existence of black holes with mass larger than 25 solar masses [2, 4]. This detection represents the dawn of the gravitational wave astronomy and adds a new fundamental messenger to explore the Universe and to probe its most energetic events. The two advanced LIGO interferometers operated as a network during the first observational run (September-January) and observed the sky over the 10-1000 Hz band. Advanced Virgo is expected to join the network by the end of 2016 [3], followed by KAGRA (~2019) and LIGO-India. The network sensitivity in terms of the observable Universe and detection rate for the different astrophysical sources and the network capability to localize the gravitational wave signal are the key properties for pinpointing the perspectives and challenges of the multi-messenger astronomy.

The astrophysical sources expected to emit transient gravitational wave signals detectable by the ground-based GW detectors are the inspiral and coalescence of binary systems of compact objects (neutron stars and/or black holes), the core-collapse of massive stars and the isolated neutron stars when sudden and localized energy release due for example to star-quakes excites non-radial oscillation modes. The orbital evolution and the emitted GWs for the binary systems of compact objects are accurately modeled by post-Newtonian approximation, providing precise waveforms for an optimized detection using matched filtering. The energy emitted in GWs is



well known in the detector frequency band, for binary neutron stars it is $10^{-2}M_{\odot}$ (derived from [5]). For core-collapse of massive stars and isolated neutron star (NS) instabilities modeling of the shape and the strength of the GW signals is complicated and thus more uncertain. The search is unmodeled, in order to be sensitive to the widest possible variety of waveforms. The energy emitted in GW might be between about $10^{-8} - 10^{-5}M_{\odot}$ for the core-collapse of massive stars [6, 7] and $10^{-16} - 10^{-6}M_{\odot}$ for isolated NSs [8, 9, 10].

Coalescing binary NSs (NS-BH system) are expected to be detectable by the Advanced LIGO and Virgo network up to a range (location and system-orientation averaged distance) of 200 Mpc (400 Mpc) with corresponding rate of $0.4-400 \text{ yr}^{-1}$ ($0.2-300 \text{ yr}^{-1}$) [11] when the detectors will reach the design sensitivity (expected for 2019, [12]). The rate is poorly constrained due to the fact that only 9 binary neutron star systems have been electromagnetically observed and no NS-BH systems have been observed yet. The results of the first month of observations of the Advanced LIGO constrained the rate of stellar-mass binary BH mergers in the local Universe to $2-400 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [13]. The expected range for a BBH with component masses of $10 M_{\odot}$ will be about 1 Gpc in the detector design sensitivity. The rate of core collapses of massive stars is around 2 per century in a Milky way equivalent galaxy (see, e.g. [14]). These sources are expected to be detectable only within a few Mpc or out to tens of Mpc in more optimistic scenarios (e.g. [15]), which include rotational instabilities in the newly formed proto-neutron stars, nonaxisymmetric instabilities of the accretion disk, or the fragmentation of the collapsing core. The NS instabilities are detectable from the Milky Way or nearby galaxies within a few Mpc.

Individual GW detectors do not have good directional sensitivity. The source localization requires a network of detectors, which allows to reconstruct the sky position of a GW transient mainly measuring the differences in signal arrival times between the different network detector sites. The sky localization uncertainties for the LIGO and Virgo network are expected to be tens to hundreds of square degrees [12].

2. Multi-messenger emission from transient GW sources

2.1. Electromagnetic emission

Promising astrophysical sources of gravitational-wave transient signals have been observed or are expected to emit photons and neutrinos. The merger of binary systems containing a NS is expected to give origin to the engine (BH or magnetar and accretion plus an accretion disk), which power the short GRBs. These are brief ($< 2 \text{ sec}$), sudden and powerful flashes of keV-MeV radiation that release a huge amount of energy (isotropic-equivalent energy in the range $10^{49}-10^{51} \text{ erg}$) (see, e.g. [16, 17]). During the merger, as result of tidal disruption, NS material is ejected and becomes unbound providing a promising site to form heavy elements (r-process nuclei), whose decay is expected to power macronovae (see, e.g. [18, 19]). The ejected sub-relativistic material interacting with the interstellar medium might power radio remnants [20, 21]. The core-collapse of massive stars is associated with supernovae and long GRBs (2-100 seconds flashes with isotropic-equivalent energy up to 10^{54} erg) [22]. NS instabilities are expected to be associated with the soft-gamma ray repeaters and anomalous X-ray pulsars, sources that emit hard X-ray/gamma-ray repetitive 0.1 sec flares (10^{42} erg/s) and occasionally giant flares (10^{47} erg/s) [23]. They are also associated with the pulsar glitches, sudden increases in the neutron star rotational phase, frequency, or frequency derivatives observed in radio and gamma-ray bands.

The electromagnetic emission from the above sources covers all the electromagnetic bands from the high-energy to radio. It is beamed in jets or isotropic and spans different time scales from seconds to months, years. The broad emission band and the different timescales require a global network of ground-base telescopes and satellites able to catch the electromagnetic signatures of the GW sources, and the appropriate multi-messenger observational strategies and data analysis (as described in section 5).

2.2. Neutrino emission

Shock-accelerated particles (protons and nuclei) interacting with matter and radiation in and around astrophysical sources produce neutrinos. GRBs and SGRs are sources expected to emit high energy cosmic neutrinos (HEN) from MeV to PeV (see, e.g. [24]). In the GRBs TeV-PeV HENs are expected to be produced in the baryon-loaded jets during the prompt gamma-ray emission, which last for seconds, and PeV-EeV HENs during the afterglow phase when X-ray and optical photons are emitted. In the SGRs the sudden magnetic reconfiguration is expected to accelerate protons and other nuclei, leading to the production of HEN. The observatories of HEN currently in operation include IceCube [25] located at the South Pole and Antares [26] in the Mediterranean Sea. The searches for HEN are based on analysis of diffuse flux capable to find significant neutrino excess with respect to the atmospheric neutrino background, searches for anisotropies on the sky to identify point sources and multi-messenger searches in coincidence with other messenger signals (GRBs, GWs, and ultra-high energy cosmic rays). The first type of search gave a breakthrough result with the discovery of a diffuse flux of astrophysical neutrinos by the IceCube detector [27, 28, 29]. Core-collapse supernovae emit low-energy neutrinos, as confirmed on February 23, 1987, when neutrinos with energies of a few tens of MeV emitted by the supernova SN1987A, exploded in the nearby Large Magellanic Cloud, were recorded simultaneously by the Kamiokande-II [30, 31], IMB [32] and Baksan [33] detectors a few hours before its optical counterpart was discovered.

2.3. Ultra-high energy cosmic rays

The GRBs are astrophysical sources also expected to produce Ultra-High Energy Cosmic Rays (UHECR). In the case of UHECR the astrophysical source identification is complicated by UHECRs deflection in magnetic fields inside and outside our Galaxy and the time delay between arrival of cosmic rays and photons/neutrinos imparted by extra-galactic magnetic fields which is larger than 10^4 yr. An indirect way to identify potential UHECR sources is based on the detection of gamma-ray fluxes and neutrinos resulting from the interaction of UHECRs with matter or photons in the vicinity of the cosmic accelerators [34, 35]. This multi-messenger approach would require gamma-ray detection by observatories like HESS, MAGIC, VERITAS, Fermi, CTA associated with neutrino detections by the same source [36].

3. Advantages from multi-messenger astronomy

The discovery of the EM/neutrino/cosmic rays counterparts of a GW event will be a key ingredient for maximizing the science return of each GW observation. It represents the only way to obtain a complete knowledge of the astrophysical sources and their emission engines, providing complementary insight into the physics of the progenitors and their environment. GWs and neutrinos carry information from the inner regions of the astrophysical engines, from which photons and charged cosmic rays cannot reach us. They can reveal the existence of new sources opaque to hadrons and photons. Photons can give a precise (arcsecond) localization, to identify host galaxy and study the source environment. Fixing location, distance, possibly system orientation through photons and neutrinos allows us to gain sensitivity on intrinsic parameters like spin and source mass. The presence or absence of EM emission together with intrinsic parameter estimation could be a powerful tool to constrain the NS equation of state (see e.g [37, 38]). The first GW detection and the proved capabilities of the ground-based detectors to detect GWs open the scenario of many future detections. In the multi-messenger context these will be extremely useful for statistical studies, where the knowledge of the astrophysical sources and their environment will be crucial to shed light on how NS and BH are born and evolve, testing scenarios of isolated binary or dense environment (globular and young star cluster) dynamical evolutions [4].

4. Multi-messenger observational strategies and analysis

The multi-messenger searches can be summarized in three main approaches: (1) the use of information of one messenger detection or candidate in the data analysis of another messenger to improve its search, (2) the search for coincidence or correlation among separate lists of candidate events from different messengers to increase their significance or to identify common astrophysical sources, and (3) the use of GW/neutrino candidates to set up observational strategies to point EM observatories and search for the EM signatures of the astrophysical sources. All these approaches need to take into account the timescale of the different messengers and spatial localization capabilities of their detectors. Some examples of these searches are reported below.

The prompt gamma-ray emission of long and short GRB (lasting seconds) have been used to search for GWs for statistical studies and for single events. The time and sky position of the GRB are used to analyze the GW data around the GRB time and considering GWs incident from its sky position. In this way the parameter space of the GW search is reduced gaining in sensitivity with respect to all-sky GW searches [39]. This search has been performed with hundreds of GRBs found by the gamma-ray satellites during the Initial LIGO and Virgo observing runs [40, 41]. The non-detection results set lower limits on the progenitor distances. The Initial LIGO and Virgo capabilities were not able to set limits consistent with the astrophysical distances typical of GRBs, but the expected improved sensitivity of the advanced detectors will make GRB and GWs joint detections quite possible or vice versa the non-detection results will place relevant constraints on GRB population models and energy emitted in GWs. The non-GW detection for two particular events, the short GRB070201 and GRB051103 observed overlapping with two close galaxies, were used to exclude these galaxies as the host of the binary system progenitor, and interpret these events as SGR giant flares or coalescence in more distant galaxies [42, 43]. A coincident short GRB and GWs would be the strongest observational evidence that compact binary mergers are the progenitor of this class of GRBs. Other searches for GWs triggered by photons can use the flares of SGRs and anomalous X-ray pulsars [9], the pulsar glitches [10] detected in radio and gamma-ray pulsars, the optical [44] and/or the X-ray/UV shock breakout emissions [45] of core-collapse supernovae in local galaxies.

Similar searches for GW signals have been performed using the arrival time and sky localization of the HEN candidates identified by ANTARES [46]. The non-detection results were used to place limits on the density of the possible sources of HEN and GW emission in the local Universe. Taking as fiducial sources the merger of two compact objects (short GRB-like) and the collapse of a massive object (long GRB-like) the density was evaluated to be smaller than 10^{-2} and 10^{-3} $\text{Mpc}^{-3} \text{ yr}^{-1}$, respectively. These values can be compared with the rate expected for the NS-NS mergers of 10^{-8} - 10^{-5} $\text{Mpc}^{-3} \text{ yr}^{-1}$ and the rate of Type Ibc supernovae of $1.5 \cdot 10^{-4}$ $\text{Mpc}^{-3} \text{ yr}^{-1}$, respectively. Similar upper limits were obtained using the IceCube HEN candidates [47]. In this case a joint analysis has been performed searching for spatial and temporal coincidence between independent lists of HEN and GW candidates and using the nearby galaxy distribution to reduce the large localization uncertainties of the GW signals. One year of observations with the advanced detectors is expected to reduce these upper limits by about two orders of magnitude. For a complete review on the multimessenger astronomy with gravitational waves and high-energy neutrinos see [24]. Alerts on low energy (MeV) neutrinos from the supernovae will be sent out with low latency by the SuperNova Early Warning System (SNEWS, <http://snews.bnl.gov/>) and used for GW triggered searches.

For these examples of searches, the knowledge of the time delay between the messengers and the sky localization accuracy are extremely important to define the time-spatial window where to analyze the data. Smaller time-spatial windows increase the search sensitivity gain. The sky localization capabilities of the EM observatories spans arcsec to degrees and the neutrino detectors degrees to a few tens of degrees.

Multi-messenger searches have been done to find correlation between the arrival direction of 2190 ANTARES neutrino candidates and 69 Pierre Auger Observatory observed UHECRs [36]. The existence of a correlation would indicate regions of the sky where sources could lie and exclude as dominant source the single-shot transients (for these, time delays between the messengers are expected to be much larger than the observations time). The stacking analysis using an angular search region around the UHECR of 4.9 degree, based on the most optimistic assumption on magnetic field deflection of protons (larger region destroys benefit from the stacking), found no significant correlation. Similar joint searches between UHECR and GWs would be complicated by the poor sky localization of the GW signal and not be appropriate for the transient sources described above.

The real identification of GW or neutrino candidate events can trigger prompt EM observations to catch the transient EM signature of the sources. This search is typically called EM follow-up. Low-latency data analysis pipelines run over the data, identify statistically significant candidates with respect to the background, and send alerts containing the sky localization of the candidates to the EM observatories within a few tens of minutes [48, 49]. The first campaign of electromagnetic follow-up of GW candidates (2009-2010) involved a dozen of observatories covering the X-ray, optical and radio bands [50, 51]. No EM counterparts were found and off-line analysis showed that GW candidates were consistent with the noise. However, this first pioneering campaign showed the main challenges of this type of search. The large sky localization of the GW signal requires to cover tens to hundreds of square degrees region of the sky, to repeat observations, to detect transient events and to deal with many transient contaminants, which need to be removed to identify the EM counterpart of the GW event. The EM search proceeds in stages: first wide-field ($> 1 \text{ deg}^2$) telescopes covering the GW sky localization, then efficient image analysis run over huge amount of data to promptly identify a contained sample of candidate counterparts, and as last step more sensitive (with narrow field of view) telescopes are used to characterize the candidate counterpart nature and to identify univocally the EM counterpart. The distribution of the galaxies in the local Universe can help in the EM follow-up campaign to cover smaller regions of the sky and to reduce the number of contaminants [52, 48, 53, 50].

5. Conclusion

The multi-messenger astronomy requires to coordinate a global network of multi-messenger instruments, to develop multi-messenger observational strategies and data analysis and an interdisciplinary effort to interpret observations and constrain models. All this requires tight collaborations between the different GW/EM/neutrino/cosmic-rays communities. The weak interaction with matter of GWs and neutrinos, which make them precious messengers to probe regions opaque to photons, makes their detection challenging. The current GW detectors demonstrated their detection capabilities. And the first GW detection by the advanced LIGO interferometers demonstrated that the community is ready for the multi-messenger astronomy including GWs. Even if binary BH mergers are neither expected to emit detectable electromagnetic emission nor neutrinos, the GW detection was followed by an impressive multi-messenger observational campaign, which represents a milestone in the exploration of this new exciting frontier of observational astronomy [54, 55].

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