Prospectives IN2P3 - GT04 astroparticules

Multi-messenger astroparticle physics

Auteur principal
Nicolas Leroy
Laboratoire de l'accélérateur linéaire d'Orsay
0164468373 - leroy@lal.in2p3.fr

co-auteurs:

- les **groupes Virgo** de l'APC, d'ARTEMIS, de l'ILM, de l'IPHC, de l'IP2I, du LAL, du LAPP et du LKB
- J. **Peloton** LAL, CNRS/IN2P3
- D. **Horan**, S. **Fegan** LLR, CNRS/IN2P3
- J. **Biteau** IPNO, CNRS/IN2P3
- C. **Lachaud**, A. **Coleiro** APC, CNRS/IN2P3
- J.-P. **Lenain** LPNHE, CNRS/IN2P3
- J. **Bregeon** LPSC, CNRS/IN2P3
- F. **Piron** LUPM, CNRS/IN2P3
- F. **Schüssler**, E. **Le Floc'h**, D. **Götz**, J. **Guilet**, S. **Chaty** CEA/AIM, IRFU/DAp
- S. **Vergani** GEPI CNRS/INSU
- F. **Daigne** IAP CNRS/INSU

Introduction:

The first joint detection of gravitational waves (GW) from the binary neutron star (BNS) merger GW170817, of its electromagnetic counterpart in form of the short γ-ray burst GRB170817A, and of the subsequent kilonova signified the dawn of a new GW multi-messenger (MM) era. Gamma-ray bursts (GRBs) have also been detected recently in the TeV range, which was expected for a long time, but was only possible with the improved sensitivity of the current generation of observatories. Future MM observations of GWs, electromagnetic radiation, neutrinos, and cosmic rays will provide the most complete understanding of the physical processes at work at the heart of the most-violent phenomena in the Universe. Having access to different messengers provide information on the different steps happening in cataclysmic events : central engine (with GW), acceleration mechanisms (with neutrinos) and ejecta (with electromagnetic observation). Complementary information could also have impact in cosmology (H0 measurement) and fundamental physics (difference of speed between messengers).

Our understanding of the transient astrophysical sky is changing rapidly and the pace of change will accelerate with the ever increasing sensitivity of the GW observatories LIGO-Virgo and the start of new major observatories including the Cherenkov Telescope Array (CTA), the SVOM mission, KM3NET and the Large Synoptic Survey Telescope (LSST), in which our laboratories are deeply involved. These new facilities will reinforce instruments already in place such as the *Fermi* and INTEGRAL satellites, the H.E.S.S. observatory (γ-rays), as well as the Pierre Auger Observatory (ultra-high energy cosmic rays, UHECR). Over the past several years these large facilities have been aided by networks of follow-up robotic telescopes such as the TAROT within the GRANDMA Collaboration. These telescopes are also useful for performing scans of the large error boxes often associated with MM alerts. Such follow-ups are then reinforced with deep spectrometry using the 8m class telescopes at ESO that are accessible through the ENGRAVE Collaboration.

Such studies will be only possible in close relationship with our INSU and CEA colleagues

Overview

Over the past few years, gravitational waves (GW) and neutrinos have changed the way we observe the Universe. When combined with the conventional electromagnetic (EM) observations, those new ‘cosmic messengers’ provide new insights about the astrophysical sources and the related physics.

This has been particularly evident in the case of the binary neutron star merger GW170817. This source, first detected in GW by LIGO and Virgo, has then been observed by a myriad of EM observatories over the entire range of wavelengths from radio to TeV energies. GW provided an unambiguous indication of the nature of the source and an 'epoch' (time of the merger) that defines the time scales for all subsequent phenomena. In the first seconds and hours after the merger, gamma-rays and optical (near-IR to UV) observations evidenced the launch of an ultrarelativistic jet and the ejection of material in the surroundings of the source. At later times X-rays and radio (including VLBI) observations were essential to understand the interaction of the jet with the surrounding material thus forming a hot cocoon, and to demonstrate that the jet eventually broke out and emerged from the cocoon.

GW and multi-wavelength EM observations have been instrumental to extract the science of GW170817 and led to a remarkably comprehensive description of the main physical processes at play before and after the merger. Fourteen laboratories of IN2P3 have been involved in the science associated with this landmark event, through their work within the major involved experiments (Virgo, Fermi, Pierre Auger Observatory, ANTARES, H.E.S.S., Integral) or through collaborations with other groups.

Having an EM counterpart (from radio to TeV energies) to these new messengers will allow to improve our knowledge on the mechanisms involved in the central part of these most powerful objects ever observed. Populations studies will also be possible thanks to the improved sensitivity of the new generation instruments that will come online in the next two decades and that are already in discussion/preparation in the institute.

EM follow-up of binary NS mergers will be critical in pinning down host galaxies and will help to reveal their formation mechanism and localization of such events to less than galactic scales is then needed. Having the host galaxy of the GW event, it will then be possible to have the redshift measurement (Link to cosmology standard sirens). Without an EM counterpart, the vast majority of GW events will have error boxes that greatly exceed the typical radii of potential host galaxies. Being able to follow accurately both in timing and photometry such types of events is also important to understand better the nucleosynthesis of heavy elements through the study of the kilonova process. In addition to discovering BNS and NSBH mergers beyond the peak of star formation, 3G detectors, because of their wide band sensitivity, will track the full inspiral, merger and ringdown signal. This could enable exquisite measurements of the intrinsic masses prior to coalescence, and determine companion spins and the nature of the remnant, key parameters to fully determine the dynamics of the merger, the nature of the relic star, and the type of debris responsible for panchromatic emission of radiation.

The study of GW170817 revealed that there was both a wide-angle mildly relativistic cocoon (Nakar et al 2018) as well as a narrow ultra-relativistic jet (Ghirlanda et al 2019). This was not seen in previous studies of cosmological short-hard gamma-ray bursts. Combining the EM and GW allowed to directly constrain system parameters with unprecedented precision. GW170817 opened up many questions for future events to answer. Specifically, what is the connection to the class of cosmological short hard gamma-ray bursts? Does a wide-angle mildly relativistic cocoon always accompany a BNS merger? Does the jet always successfully escape the cocoon or is it sometimes choked? How do the observed jet properties vary as a function of viewing angle, mass ratio, hypermassive neutron star lifetime, remnant spin, and ejecta mass? Do mergers produce prompt EM signals? What is the distribution of the time delays between the EM and GW signal arrival times? What are the characteristics of a jet from a NSBH merger? With the first census of BNS and NSBH coalescences, and full GW and EM coverage of the signals, joint multi-messenger Bayesian parameter inference will be key in understudying the physical origin of jets, ubiquitous around relativistic sources (Coughlin et al 2019). For the first time, a direct measurement of the BH spin in a source emitting a collimated jet, will provide the ability to establish the close correlations between the jet power, the spin and the inflow rate from the debris disk, which determines the conditions for launching the jet. The 3G GW network combined with new, powerful EM facilities can further revolutionize our understanding of the physics of jets. 3G GW network will enable the detection of neutron-star mergers out to redshifts of z ~ 10. Even with the planned upgrades, we are limited by the sensitivity of gamma-ray, X-ray and radio telescopes to study jet physics to only out to 500 Mpc. To build a sample large enough to map the full parameter space, we would need ~ thousand events localized to better than few sq deg. This is a realistic goal with the proposed 3G GW network.

A close follow-up is also needed in case of extraordinary events like the recent reports of TeV emission by H.E.S.S. and MAGIC in long GRBs (GRB180720B, GRB 190114C and GRB 190829A). Such emissions will bring new information on the energy budget and on the timescale of the particles' flow, see contribution "Extragalactic gamma-ray astronomy". If possible detection could also be done in the next years including the new messengers we will then be able to have a complete view of such powerful astrophysical events.

Recent years have seen great advances in time-domain astrophysics, which, continuing into the future should bring us much closer to a more complete understanding of explosive phenomena such as supernovae or GRBs. However in the next decade the number of transients found will increase by several orders of magnitude as even more powerful facilities come on-line, in particular the Large Synoptic Survey Telescope (LSST) and the Square Kilometre Array (SKA). The sheer grasp of the new facilities, which will produce thousands of alerts per day from variable or transient sources, means we will require super-computers to process the data in real-time and smart algorithms to broker which transients to focus on with follow-up facilities.

Thanks to the involvement of its teams in experiments such as SVOM, CTA, LSST and Virgo, IN2P3 is in a very good position to make important contributions to the future discoveries of multi-messenger astronomy. To maximize the scientific outcome, it is essential to establish better connections and strong partnerships with the teams of INSU and Irfu. At the French national level, the PNHE program and the "Transient Sky 2020" network will help to strengthen collaborative projects across scientific consortia, see contribution "Le ciel transitoire et le réseau TS2020".

Work in the next decade

Access to a variety of EM observatories :

The sky error region of MM alerts can span over hundreds of square degrees in the case of GW candidate, see contribution "Real time gravitational waves astronomy". To be able to find a counterpart to such an event it is then important to have a large diversity of instruments. Present configurations include networks of robotic or fast reaction telescopes to span the whole error region and find the first candidates and then get follow-up of such events with larger instruments with spectroscopic capabilities (to obtain the spectrum of the sources to classify the nature of the EM transient and its redshift measurement).

The EM radiation of MM transients (e.g. short GRBs, kilonovae, etc.) is generally characterized by several phases. The prompt phase lasting only seconds is followed by an afterglow phase during which the flux decays rapidly. The shortest accessible timescales for follow-up observations are on the order of minutes. To benefit from rapid reactions, follow-up scheduling of EM observatories has to be fully automatized. Different developments have been made in different collaboration and possible joint work is proposed to be undertaken in the next few years to improve the scheduling either for single instruments or networks of telescopes.

Different teams of the IN2P3 are involved in this effort and will continue in the next years, it includes the GRANDMA collaboration (with the French TAROT instruments), ENGRAVE collaboration with observation time on the largest ESO telescopes, SVOM from visible light to MeV range, INTEGRAL in the MeV range, Fermi GBM/LAT and H.E.S.S./CTA in the TeV energy range, see contribution to "The Science of SVOM at IN2P3".

Galaxy catalogs :

Detections of MM transient events such as GW, GRBs and neutrinos are notoriously affected by considerable position uncertainties on the sky (e.g., up to 1000 square degrees for LIGO/Virgo detections). This challenges our ability to pinpoint their true location and to associate them with

other known astrophysical sources. In the context of GW follow-up, the technique of “galaxy targeting” has become increasingly popular and consists in searching MM counterparts by targeting galaxies localized within the 3D error box associated with the GW. This approach thus relies heavily on the use of catalogs that depict the population of galaxies in the nearby Universe (up to a few 100s Mpc, Dalya et al. 2018, Cook et al. 2018).
Completeness of such catalogs with accurate parameters is then important to find the possible EM counterpart. In particular, the public GLADE catalog (“Galaxy List for the Advanced Detector Era”, Dalya et al. 2018) has become a standard reference in the field: it includes ~3.2 million sources with a full-sky coverage and is now extensively used throughout the MM community.
Such catalogs only provide very limited information on both the observed and physical properties of the galaxies themselves. It is then needed to improve such tools with other information and improve the photometric redshift with techniques based on Machine Learning and convolutional neural networks. This will possibly also be linked with work already on-going on LSST.

Such catalogs will also have an impact on ultra high energy cosmic rays (UHECR). The detection of a dipolar anisotropy beyond the ankle of ~6% amplitude pointing 120° away from the Galactic center, and consistent with the distribution of galaxies in the 2MASS redshift survey up to ~300 Mpc, provides the first observational evidence for an extragalactic origin of the most energetic particles known to date (Pierre Auger Collaboration, 2017). The analysis of the flux pattern of UHECR at the highest energies (> 40 EeV) revealed a closer match to that expected from star-forming than from active galaxies (Pierre Auger Collaboration, 2018), each pattern being now favored against isotropy at the 4.5σ and 3.1σ level, respectively (Caccianiga, for the Pierre Auger Collaboration, 2019). Galaxies with high SFR being surprisingly favored, it is possible to investigate a transient UHECR origin, effectively smeared out in time and angle throughout propagation, see contribution "Towards uncovering the origin of UHECRs at the Pierre Auger Observatory".

Millions of alerts:

The future observatories LSST and SKA will completely change the paradigm in the studies of the transient sky. For example LSST will release more than 1,000,000 alerts per night and present techniques used in brokers will not be able to deal efficiently with this new data flux, and specific projects are ongoing to develop and apply novel techniques from the big data and machine learning ecosystems. The LSST will also able to find the best candidates of orphan GRB optical afterglows: counterparts could then be searched for in existing observatories, and some could deserve a target of opportunity or search in archival data. Part of the multi-messenger astronomy community gathered recently around Fink, a collaboration led by LSST-France to propose a broker system to digest LSST alerts, and redistribute the information worldwide. To tackle the challenges, the broker uses cluster computing to work at scale, and the alert classification relies on state-of-the-art adaptive machine learning techniques. The latter allows to update the classification capability with new information as soon as they are made available by e.g. follow-up observations, leading to more reliable scientific class estimates and lower incidence of false positives that are usually high with static data bases or pre-trained machine learning algorithms, see contribution "Listening to the transient sky at the LSST era".

Preparation of next generations of instruments:

The new generation of instruments (LSST, CTA, SVOM, KM3NET) will become online in the next few years and will have several months to years of installation and commissioning. The GW network will interleave installation/commissioning periods with data taking. However the preparation of the 3G instrument is done in parallel and will need involvement from the interested teams in the next decade.

See contribution to Einstein Telescope

See contributions to "GWHEN, the next multi-messenger connection", "Low energy transients in KM3NeT", "Multi-messenger neutrino analyses".

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