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KILONOVA-CATCHER: A NEW CITIZEN SCIENCE PROJECT TO EXPLORE THE MULTI-MESSENGER TRANSIENT SKY

D. Turpin[1] and the GRANDMA collaboration

Abstract. On 17^{th} August 2017, the detection of electromagnetic (EM) radiations associated to the gravitational wave (GW) event GW170817 has greatly revived the interest of the scientific community for the multi-messenger astronomy. A new window is now opened to study in detail the compact objects such as black holes (BH) and neutron stars (NS) as well as the physical processes occurring when they are in close binary systems and eventually merge. Several multi-wavelength radiation components are expected from NS-BH and NS-NS mergers like Gamma-ray Bursts and kilonovae. Those two bring complementary information to the GW data about the post-merger physics and the nature of the surrounding environment. Capturing the global picture of these astrophysical events is a real observational challenge as it requires to quickly identify and characterise the EM sources hidden in the very large and atypically shaped GW localisation regions. To reach this goal, coordinated efforts between several observatories are crucial. Since 2018, the GRANDMA Collaboration is operating more than 30 telescopes around the world to perform fast and coordinated follow-up of GW sources detected by the LIGO and Virgo detectors. To complement its future EM/GW follow-up observations and popularise the multi-messenger astronomy towards the amateur astronomer community, GRANDMA has created the *Kilonova-Catcher* (KNC) citizen science program in 2019. This program will be largely involved in the scientific exploitation of the upcoming O4 GW data acquisition run.

Keywords: Gravitational waves, Kilonova, Gamma-ray burst: general, Methods: observational

1 Introduction

The Universe is continuously the scene of cataclysmic astrophysical phenomena which release tremendous amount of energy in short time scales, typically from few milliseconds to several months, through different forms: electromagnetic (EM) and gravitational waves (GW) as well as high energy particles. Among those transient events, the coalescence of compact objects involving at least one neutron star are one of the most fascinating ones. During the merger process, they produce gravitational waves signals that are first detected by the LIGO and Virgo (and now Kagra, LVK) detectors then sometimes followed by intense bursts of EM radiations observable at all wavelengths such as Gamma-ray bursts (GRBs) (Abbott et al. 2017a). Since the first studies of these violent phenomena in 2015 (Abbott et al. 2016a,b,c), new scientific perspectives are now foreseen to better understand the physical processes at work during these cataclysmic events (see for example Abbott et al. 2016d, 2020a,b). Many other scientific domains related to the cosmology (Abbott et al. 2017b), to the study of the fundamental physics of the supra dense matter (Abbott et al. 2018) or to the understanding of the heaviest elements nucleosynthesis and their dissemination in the Universe (Abbott et al. 2017c, and reference therein) are also covered. However, for both physical and technical reasons, catching the electromagnetic counterparts of such events is still one of the greatest observational challenge of the modern astronomy.
Since 2018, the GRANDMA scientific collaboration has built a worldwide optical telescope network in order to quickly identify the visible and infrared counterparts of the gravitational wave sources by following them up during several days (Antier et al. 2020a,b). This network now groups together more than 20 observatories and will be fully deployed during the upcoming LVK O4 acquisition run (Agayeva et al. 2022). To complement its professional telescope network, GRANDMA has initiated an innovative citizen science program in 2019 called *Kilonova-Catcher* which invites amateur astronomers to actively participate to the searches for these

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optical/GW counterparts and make breakthrough discoveries in this young field of research. So far, more than a hundred of astronomers distributed all around the world have joined us in this scientific adventure.
In section 2, we will remind the main scientific challenges of the EM follow-up of GW sources. Then, in section 3, we will show how the *Kilonova-Catcher* project is built to unify together both the professional and the amateur telescope networks towards the same scientific objectives. Finally, in section 4, we will give our conclusions.

2 Electromagnetic follow-up of gravitational waves sources

While several astrophysical scenarios are thought to produce detectable signals of gravitational waves, mergers of two compact objects (either Black Holes -BH or Neutrons Stars -NS or a mix of these two sources) bounded in close binary systems are so far the only GW sources detected during the successive acquisition runs lead by the LIGO and Virgo collaborations (Abbott et al. 2019, 2021; The LIGO Scientific Collaboration et al. 2021). Binary systems involving at least one neutron star (NS+BH -NSBH or NS+NS - BNS) are expected to be the most favourable cases for the emission of EM signals right after the merger.

2.1 EM counterparts from NSBH/BNS systems

In 1989, Eichler et al. (1989) express the idea that the multi-wavelength emission of the so-called short Gamma-ray bursts (sGRB) could arise from the merger of two compact objects once an remnant accretion disk is rapidly formed around the newly born BH or NS. A joint EM/GW detection would then give new insightful information about the nature of the sGRB progenitor systems. Furthermore, it would help to better understand the formation and the geometry of the relativistic plasmas (supposed to be highly collimated) that are ejected after the merger as well as their internal kinetic energy dissipation processes that lead to bright GRBs.
In addition to the sGRBs, more isotropic ejecta have been also thought to be ejected from these merger events (Lattimer & Schramm 1974; Li & Paczyński 1998). According to these scenarios, they would originate from neutron-rich matter extracted from the merging NS and then ejected either into a dynamical quasi isotropic plasma flow or in a spherical ejecta created via an accretion disk bounded to the BH or NS remnant. Inside these ejecta, heavy radioactive elements (lanthanides) would then be produced through rapid neutron captures (r-process) heating up the surrounding matter. This hot plasma would radiate back a thermal emission at optical and infrared wavelengths called *kilonova* (for a complete and recent review, see Metzger 2019). Hence, kilonovae are the smoking gun signatures of the r-processed chemical elements production in the Universe. Among them, the lanthanides elements produce high opacities at short optical wavelengths (in the UV and B-band) and therefore, depending on their mass fraction in the different ejecta, the kilonovae would look like "redder" (maximum brightness reached several days post merger mostly in the near infrared) or "bluer" (maximum brightness reached about a day post merger mostly in the UV and blue bands). The detailed study of the kilonovae color evolutions is therefore crucial to identify the nature of the different ejecta and to quantify the efficiency of the r-process in such post merger environments. NSBH and overall BNS mergers are the unique laboratories from which we can study all of these radiative processes in great detail as they are usually detected by GW detectors in the nearby Universe ($D_{BNS} < 200$ Mpc). So far, this has been done only once on 2017 August, 17^{th} with the discovery of GW170817/GRB170817A(Abbott et al. 2017d,a) and the AT2017gfo kilonova(Abbott et al. 2017c) during the O2 GW run. To better understand this physics, more EM/GW joint detections are required during the future GW acquisition runs starting by the O4 run in the beginning of 2023.

2.2 Observational challenges

Detecting the optical counterparts of the GW sources is still a real observational challenge. Currently, it is primarily connected to the status of the GW detectors network and the methods used to localise the events. Indeed, the respective sensitivities of the individual GW detectors and their sparse distribution on Earth largely explain why the localisation of the GW events is sometimes poorly constrained by combining the individual GW datasets. As an example, during the O3 run, the two LIGO detectors could detect BNS merger inspiral signal within a typical distance range of ∼ 110 (Handford) and ∼ 130 (Livingston) Mpc while Virgo reached $d_{BNS} \lesssim 60$ Mpc (The LIGO Scientific Collaboration et al. 2021). Due to these sensitivity heterogeneities, the localisation of the BNS mergers were poorly constrained for D_{BNS} >100 Mpc (see Appendix 1 in Antier et al. 2020a).While each GW detector have been upgraded these last two years in preparation of the O4 run, EM observers might still encounter these localisation constraints. The first challenge is therefore to pave the maximum area of the GW localisation regions. It usually requires a coordinated network of telescopes to efficiently perform this task.

Inside the GW error boxes, many optical transients can be found with different brightness and flux evolution time scales. The second challenge is then to be able to quickly distinguish promising transients, i.e. fast transients evolving at daily timescale as expected for GRB afterglows and kilonovae, from the large number of unrelated ones (typically supernovae, CVs, flaring stars, etc.). Finally, kilonova transients are relatively faint sources as they peak at a typical absolute magnitude $M_v \sim -16$ within a day or so with a fast color evolution (Cowperthwaite et al. 2017; Villar et al. 2017; Arcavi 2018) depending on the kilonova models. As a consequence, it implies that small robotic telescopes (D<1m) that are usually the first to perform these searches are strongly limited in time to find the kilonovae associated to the GW mergers before they fade away. All of these observational and physical constraints for the EM observers can be finally summarised with the following saying rules : *Be fast in observing wide portions of the sky and do it with multiple photometric bands at deep limiting magnitudes.* Because all these requirements are rarely satisfied by a single telescope, the GRANDMA collaboration and the Kilonova-Catcher project have been created.

3 GRANDMA and the Kilonova-Catcher project

The GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts) collaboration[*] is formed by more than 80 astrophysicists distributed over 42 international institutes. GRANDMA has access to more than 30 telescopes located in 23 observatories. These individual telescopes are combined into a coordinated network using a common scheduler to perform quick and optimised follow-up observations of GW sources. More details about GRANDMA can be found here (Antier et al. 2020a,b; Agayeva et al. 2022). In parallel, GRANDMA has developed an innovative citizen science program to complement its observations of the GW sources. Called *Kilonova-Catcher (KNC)*, this program propose to the amateur astronomer community to actively participate to the optical follow-up campaigns of GW sources.

3.1 Connecting the amateurs to the GRANDMA network

The KNC users are directly connected to the GRANDMA alert streams which broadcast only the most promising GW merger events such as BNS or nearby NSBH ($D_{BNS} \lesssim 150$ Mpc). As soon as a GW alert is sent to the KNC astronomers, each of them will receive an observation plan customised to their own instrumental settings (mainly the telescope field-of-view and its location). They will be able to visualise the alert information and their observation plans by logging into the KNC web portal[†]. From this web portal, they will be also able to send and modify their telescope and user information. On their personal dashboard, each KNC user can subscribe to any follow-up campaign he/she wants to be part in. For a given alert, a skymap visualisation is provided from which we display the GW localisation region, the list of pointings to be observed and the Moon/Sun constraints. This skymap can be visualised at different periods of time (within a 24h time window after the GW trigger time) so that each astronomer can easily decide when he/she can start his/her observations. A working procedure is being released soon by GRANDMA to guide the KNC astronomers regarding the best observation strategy to employ (response latency, filters, limiting magnitude to reach, number of revisits, image calibration, data quality, etc.). Once the astronomers have taken images, they have to save them into the standard FITS format[‡] and transfer them into the KNC image server via the web portal. An automatic check of the image headers is performed and the image is then either considered as valid for a scientific analysis or the user is invited to manually fill in the missing information. Once all the images have been transferred, a KNC astronomer has made is part of the work. Live discussion between the KNC astronomers and GRANDMA scientists are organised via dedicated Slack channels in order to help them following the working procedure or answer to any inquiry they might have. Finally, GRANDMA proposes regular meetings to collect the feedback of the web portal users and give the latest news about the project and the upcoming GW follow-up campaigns.

3.2 From KNC images to scientific outputs

Each time an image is transfered into the KNC image server, an automatic routine using the STDPipe pipeline (Karpov 2021) is triggered via the scientific plateform of the GRANDMA collaboration[§] to analyse it and

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[*] `https://grandma.ijclab.in2p3.fr/`

[†] `http://kilonovacatcher.in2p3.fr/`

[‡] `https://fits.gsfc.nasa.gov/fits_documentation.html`

[§] `https://skyportal-icare.ijclab.in2p3.fr` search for optical transients (OTs). The results (image residuals, limiting magnitude, OT magnitudes, etc.) are manually checked by data specialists on duty and reported onto the GRANDMA scientific database. At this stage, the observations and results obtained by the KNC astronomers are available to the whole GRANDMA collaboration. If an interesting OT is discovered, further follow-ups will be engaged to characterise in detail its optical emission. Inside GRANDMA, it will be done by emitting both an internal alert to the GRANDMA and KNC facilities. If the OT is confirmed as a very promising EM/GW counterpart, then public GCN Circulars[¶] will be emitted as soon as possible. Finally, if some KNC data are used to make GRANDMA scientific publications, the associated amateur astronomers will be included as co-authors sharing the same rights and duties than the professional scientists.

3.3 First results from the Kilonova-Catcher program

Since 2019, the Kilonova-Catcher has participated to several follow-up campaigns including the GW O3 run (Antier et al. 2020b), the identification of kilonovae candidates found by the Zwicky Transient Facility[‖] (Aivazyan et al. 2022) and selected by the Fink brokerMöller et al. (2021) and Swift GRB afterglow follow-ups (see for example Yan et al. 2022; Klotz et al. 2022). The most recent results from the *Kilonova-Catcher* campaigns are summarised below:

1. From June to September 2021, we organized a campaign to perform fast follow-ups of kilonova candidates issued every fridays by the Fink broker from the Zwicky Transient Facility (ZTF) public alert stream. The goal was to encourage amateur astronomers to follow-up kilonovae candidates during the weekend and train them in following a working procedure close to what they will do during the O4 run. This also allows us to test our photometric pipeline on very diverse data and to revise our observation strategies for kilonovae. Among the 12 events sent, we observed 4 Supernovae Ia, 3 Supernovae II, Ip and IIb, one CV and 4 asteroids. We demonstrated that GRANDMA could robustly classify events by its own, i.e without waiting for additional images from ZTF, but also provided sufficient light curve sampling for studying fast transient sources. Finally, the campaign also demonstrated the ability of amateur astronomers to achieve the sensitivity needed to detect kilonovae in the local Universe ($D_{KN} \lesssim 150$ Mpc).

2. GRANDMA organised a GRB follow-up campaign from March to May 2022. The aim of this campaign was to measure the capacity of the GRANDMA network to detect and characterise the GRB afterglow emissions to foresee possible monitoring of the future GRB events detected by SVOM (Wei et al. 2016). With GRANDMA, we observed 11 gamma-ray bursts with more than 20 professional telescopes. Eight of them were observed by the KNC atronomers showing how responsive the amateurs can be. As an example, the first GRANDMA image taken for GRB220408A was made by a KNC astronomer less than 1 hour after the GRB trigger time during the early GRB emission phase. The analysis of the data taken during this GRB campaign is in progress and the results will be soonly communicated in a dedicated publication.

4 Conclusions

We have presented the *Kilonova-Catcher* citizen science program managed by the GRANDMA collaboration. For the first time, this project will allow amateur astronomers located all around the world to actively search for the optical and infrared counterparts of the future detections of BNS and NSBH mergers. A complete system based on communication tools and a web portal has been developed by GRANDMA in order to connect the amateur telescope network to the professional one. All the observations collected by the KNC astronomers will be analysed on real-time by the GRANDMA data analysis group and the results will be made publicly available to the scientific community as soon as possible. The *Kilonova-Catcher* project has been designed to make the amateur community an important actor of the multi-messenger astronomy starting as soon as 2023 with the LVK O4 acquisition run.

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[¶] `https://gcn.nasa.gov/`

[‖] `https://www.ztf.caltech.edu/`

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