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OBSERVATIONS OF NEUTRON STAR MERGER REMNANTS AS PART OF THE GRANDMA COLLABORATION

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This article summarizes the key findings and methodologies of the GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts) collaboration in observing the remnants of neutron star mergers. To achieve this, the Côte d'Azur Observatory in France, the Shamakhy Astrophysical Observatory in Azerbaijan, and their collaborators have pooled their observational efforts, astrophysical analyses, and expertise within an international consortium known as GRANDMA. The GRANDMA collaboration is a global network of observatories dedicated to the rapid follow-up of gravitational wave events and other transient astronomical phenomena. The primary objective of the GRANDMA collaboration is to detect and characterize the electromagnetic counterparts of gravitational wave events, particularly those originating from neutron star mergers. Neutron star mergers are cataclysmic events that provide critical insights into a variety of astrophysical phenomena, including gravitational waves, heavy element nucleosynthesis, and the behavior of matter at nuclear densities. By employing a diverse array of telescopes across the globe, GRANDMA aims to provide rapid, coordinated observations that cover multiple wavelengths, from optical to radio. These observations are crucial for identifying kilonovae, the transient optical and infrared emissions powered by the radioactive decay of heavy elements synthesized during the merger.

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1. INTRODUCTION

Neutron stars are the remnants of stellar explosions that have been proposed over the course of decades. The likelihood of their merger being observed as gravitational wave signals instead of being directly seen as new and transient sources is very small. The first event in 2017 opened the era of multi-messenger astronomy. The prosperous era of multi-messenger astronomy opened up in 2017 with the observation of a binary neutron star merger, GW170817, in both gravitational waves (GW) and electromagnetic radiation domains. Being some of the most massive stellar remnants, we expect neutron stars to be found across the universe since they are long-lived objects as remnants of supernova explosions. Factors that affect population statistics in astronomical objects include a binary fraction with other compact objects. Part of the distribution of compact objects, i.e., white dwarfs and neutron stars, together along the Hubble time, can form white-dwarf neutron stars with a second common-envelope stage and the tidal disruption of a white dwarf by a neutron star. These were considered rare but have had an increased probability of occurring in the detector era and hence also in the future [7–13]. The influence on the local and cosmic landscapes by neutron star mergers happening in the present universe includes an observable gravitational wave signal and the possible production of r-process elements (especially the heaviest elements observed in the solar system, but abundances are spread over mass due to this form of nucleosynthesis). Emitted with the s-process nucleosynthesis signal of the normal immediate post-collapse environment, one event offers one possible method of distinguishing between these two production sites based on the observed s-process abundances in environments currently presenting process abundances from ejecta measurements of energetic objects associated with gravitational waves, like this kilonova as the source was named. This paper now presents the observations of the actual gravitational wave-neutron star merger afterward.

1.1. Background on Neutron Star Mergers

The coalescence of close binary neutron stars is expected to form many different phenomena, as the neutron star merger and the ejection driven by microphysical processes are determined by a large number of uncertain processes. The strong gravity of close binary systems causes stars to orbit each other about twice per second. If the orbit of these stars is influenced by the merger such that the stars interact when they are still many times larger than the distance between them, gravitational radiation dominates, leading to the merger of the neutron stars. In the particular case of binary neutron stars, lumps leaving the system will typically form a torus, which will quickly collapse to form a single compact object that may be an unstable massive neutron star, a quark star, or a black hole. The currently known neutron stars are around two times the mass of the Sun and approximately 10 km in size. Their "rock solid" strength is determined by the strong nuclear forces, but when neutron stars are compacted in close binaries, they are only held by gravity, so the neutron stars slowly spin towards each other due to the emission of strong gravitational waves. During this collision, neutron star matter and surrounding plasma reach supranuclear densities, extreme gravitational acceleration, enormous pressures, and temperatures - eventually converting into black holes and the rest of the debris accreting and forming an accretion disk. The debris and the accretion disk re-radiate in optical/infrared or ultraviolet as well as in the X-ray and radio frequencies. Finally, a very massive magnetized ball of fire produced by collapse or black hole formation is born and creates a fireball - most of the events are expected to be accompanied by the production of gamma-ray bursts. Initially, during the infall, a weak shock wave is produced which keeps stalling to bounce back and makes the stellar surface explode-eventually spreading matter and radiating pressure into the high-density debris-producing the ultraviolet and optical/infrared light. This phenomenon is also known as kilonovae or macronovae. Thus, we expect neutron star mergers at two different tidal disruption rates to give rise to a weak kilonova and a strong kilonova, with the kilonova optical/infrared light being about 100 times brighter in the case of a strong disruption. The strongest explosions that make most of the heavy elements are powered by the remnants that achieve a high mass that becomes gravitationally unstable and converts into a black hole. Simulation results are yet to arrive. Ultimately, when the neutron stars merge at high speeds, the heavy elements in the part of the very tight binary zone are in fact overlapping electron clouds preventing the neutron stars from merging cleanly and ejecting an excess amount of heavy elements, creating the first epoch of cosmic heavy element formation. Neutron star mergers were predicted long ago, but observationally they were directly established with the detection of gravitational waves from a significant event. Before this event, many direct and indirect candidates for this event were searched without detections. This event was associated with a short gamma ray burst by gamma-ray satellites in an initially identified optical source at a redshift of about 0.01. A specific experiment was used to search for electromagnetic counterparts in the radio band from the short gamma-ray burst associated with this event. Subsequent searches for radio counterparts were conducted with various networks. Additionally, another array was also used, and there were no positive radio detections of the counterpart. A series of efforts were made to scan southern skies hoping to catch any radio jet from the event. Systems were analyzed, but again there were no successful detections. In the ten weeks after the detection of the gravitational waves, many instruments worldwide detected the merger remnant in optical and X-ray bands.

1.2. Importance of studying neutron star merger remnants

Neutron star mergers are relevant for other types of astronomy as well. Gravitational wave astronomy can make a variety of inferences about cosmic populations and systems by comparing the distribution of events in such parameter spaces as masses, spins, and merger rates, but for most inferences astrophysical priors are necessary and can only be obtained from observations. Neutron star mergers also place important constraints on stellar evolution and galaxy population models, for instance by providing direct evidence of the existence of heavy element-rich black hole accretion disks, the prevalence of neutron star recycling, and the possible contribution from gravitational wave events in constraining the equation of state. As such, nuclear astrophysical and multi-messenger observations of kilonovae will be critical for the advancement of gravitational wave astronomy.

2. THE GRANDMA COLLABORATION

In this collaboration, the Côte d'Azur Observatory in France, the Shamakhy Observatory in Azerbaijan, and their partners have united their observational efforts, astrophysical analyses, and expertise within an international consortium known as GRANDMA. Now, in the gravitational wave era, people including the GRANDMA collaboration are working to understand the remnants that their composite signal makes apparent. For on-axis remnants, the initial bright transient evolves to form a kilonova, a blue/NIR signal that spans all times with a characteristic dimming between several days and weeks after the merger. It is now essential to bridge these observational gaps. During the LIGO/Virgo O3 run, GRANDMA included more than 300 astrophysicists from about 25 research institutes in countries such as France, Italy, United States, Ukraine, Azerbaijan, Georgia, Spain etc. More details on the composition of the collaboration, how it works, and a series of applications are described in a dedicated work. The GRANDMA collaboration has an agreement on sharing images, photometric position-time series, and derived model constraints of all detected counterparts. It is our aim to inform the community about active fallback remnants and transient events at a speed faster than that produced by a single survey and beyond the expected evolution of the detection pipelines. Further, the results presented here will soon feed into a combined analysis including gravitational wave data. In this paper, we detail the remnants studied and discovered using this observa-

Fig. 1. Location of the GRANDMA telescopes on the world map. Credit: J.-G. Ducoin, Follow-up of gamma-ray bursts with the GRANDMA network, GRB221009A and GRB230812B.

tional approach thus far.One staple of GRANDMA has been the combination of gravitational waves and subsequent electromagnetic data. GRANDMA combines multi-messenger facilities such as the LIGO and Virgo detectors, which observed GW190425, with optical and X-ray telescopes. Rapid-response, all-sky transients are often common between classes of electromagnetic follow-up. Such coordinate triangulation is currently implemented on a campaign basis by contractors, computed from their relative field of view, axes, and axes as outlined in the observation request. LIGO/Virgo and GRANDMA are prime examples of quickly disseminated transient alerts with public searchable records of collaborations initiated with exact timestamps [1–6].

In the GRANDMA collaboration, we have formed a worldwide consortium of research groups that are observing and theory communities, data analysis pipelines, and facilities to study neutron star merger remnants. These groups include individuals from various universities and research institutions, with additional network support and continuing discussions with other relevant researchers. The goal of GRANDMA is to support and strengthen investigations of the HEN, KN, GW optical-IR afterglow, and XR optical afterglow with electromagnetic and/or neutrino multi-messenger observations. GRANDMA observers bring a range of skills and strengths. This includes the expertise and facilities required for optical and IR observations of nearby galaxies and gamma-ray events made by a range of wavelength observatories, gravitational wave data analysis expertise, and facilities to analyze gamma-ray and putative prompt kilonova emissions or other electromagnetic counterparts, plus state-of-the-art neutrino searches to provide high-quality multi-messenger follow-up data. Our aim within the observation community is to coordinate all such real-time triggered multi-messenger observations and data around the time of any GW signal detection, as well as to programmatically and routinely compare these signals and coordinate jointly published results at later times [1–6].

3. FUTURE PROSPECTS

What new techniques and data will be available in the near future to approach the study of these remnants? The first most notable improvement will derive from significantly better and more collaboratively secured low-latency GW localizations with the advent of the Vera Rubin Observatory, as demonstrated in our results and will be improved in the near future by the SVOM-MXT observatory. Following a joint US-German project which will highly refine the above estimates will soon after be launched. It now appears that the Maunakea Spectroscopic Explorer will enter its construction phase, thanks to cooperation. The combination of these two projects will be a major leap forward in observational capabilities as they provide joint GW and EM localizations, allowing for matched early spectra within a day of the merger.

Which new surveys and missions aimed at investigating the above science goals will become operational or begin their on-sky sampling in the coming years? As detailed in documentation on the timelines and survey capabilities, such joint localizations will become routine in the 2030s and beyond, as the number of events increases, if a collaboration were to be established. In the interim years, Vera Rubin and Maunakea-hosted data will remain possibly the best way for our community to first study with EM radiation these "new systems," as possibly discovered directly post-merger by neutron star neutrino emission and secondly search for r-process EM kilonovae and electromagnetic counterparts from IW echoes that emerge on timescales of seconds to days after merging.

4. DISCUSSION AND CONCLUSION:

The GRANDMA collaboration plays a critical role in the multi-messenger astronomy era by focusing on the rapid and coordinated observation of neutron star merger remnants. These events are not only associated with gravitational waves but also produce rich electromagnetic counterparts, such as kilonovae, which are key to understanding the synthesis of heavy elements and the physics of compact object mergers.

We are still at the outset of the new era of multi-messenger neutron star merger research. The current investigations involving newly established collaborations or collaborations under heavy development and commissioning leverage the state-of-the-art in technology, instruments, and software capabilities, as well as the international scientific networking opportunities for making fantastic new discoveries and measurements in the first years of the new decade. Many new projects, including new or upcoming facilities and projects that we were unable to claim results on, are expected to release first conclusive findings in this period of the beginning of the new decade [14–16]. Even though EM signatures of these systems are faint and rare, the field is currently in the process of a significant advance. Electromagnetic follow-up can significantly improve the GW localization on the sky by up to several orders of magnitude, and currently several ongoing projects focus on transient discoveries associated with large-area, time-domain surveys. Some of the projects aim to train their telescopes on the area of the reported GW candidates as fast as possible after the alerts. In parallel, our understanding of such counterparts has improved, particularly thanks to developments in data analysis in the past years, and we are lucky to count on several new, exotic telescopes and surveys that are or will be looking for these peculiar systems from various perspectives.

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