The role of eXTP in the multi-messenger astronomy era

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The first detection of gravitational waves on 2015 with the Advanced LIGO and Advanced Virgo interferometers has opened a new observational window in the Universe. The last decade has also welcomed decisive discoveries in neutrino astronomy. Expected advances of gravitational wave and neutrino detectors by the end of the 2020s will mark the start of a golden era of multi-messenger astrophysics. The most promising multi-messenger sources in the high-energy sky, e.g. GRBs, AGNs, magnetars, are among the main targets for the enhanced X-ray Timing and Polarimetry (eXTP). In this proceeding, we describe the possible role of eXTP in the context of multi-messenger astronomy and in particular on the synergies with gravitational wave interferometers at the sensitivity expected by the end of the twenties.

Keywords: X-ray sources; gravitational waves; neutrinos; multi-messenger astrophysics.

1. Introduction

In the quickly evolving framework of multi-messenger astronomy, two breakthrough results have been achieved in the last few years that magnificently show the power of combining different "messengers" from the same source as well as the crucial role of high-energy observatories.

On 17 August 2017 a binary neutron star merger (GW170817) has been detected with the network of Advanced LIGO (aLIGO,[1]) and Advanced Virgo (AdV,[2]) gravitational wave interferometers. The source was found to be spatially and temporally coincident with a short Gamma Ray Burst GRB170817.[3,4] This association marked the first direct evidence that at least a fraction of short GRB progenitors are NS-NS mergers. Short GRB progenitor nature so far was based on indirect evidence collected in the last 15 years that goes from the lack of any core collapse supernova associated with a short GRB to the explosion site within the host galaxy, typically far from star forming regions (see[5] for a review). Both the burst and afterglow properties of GRB 170817 were found to be consistent with a significant inclination angle of the binary system. In particular, the afterglow properties provided the first empirical evidence of a narrowly collimated jet and allowed to define its energy angular distribution.[6,7] Another emission component distinguished from the afterglow was also detected as a fading opt-NIR source (AT2017gfo)[8] and identified with the theoretically predicted thermal emission (kilonova) powered by the intense radioactive decay from instable heavy nuclei freshly-formed during the neutron star merger.[8,9] Past kilonova observations where claimed in few short GRBs and their identification relied on few data points (e.g.[10]). The exceptional high-quality temporal and spectral data of AT2017gfo allowed us to study in great details the kilonova properties for the first time.[11,12]

The other breakthrough discovery was achieved on 22 September 2017 when a high-energy neutrino event was detected with IceCube[13] and found to be spatially consistent with a gamma-ray emitting blazar at z=0.34 (TXS0506+056). The association has a confidence level lower than the case of GW/GRB170817 (i.e. $\sim 3\sigma$) but is an important finding that provide crucial hints on the origin of the identified diffuse flux of astrophysical very-high-energy neutrinos (10 TeV-10 PeV) detected by IceCube[14] and the possible role of blazars within most extreme particle accelerators in the Universe.

In the next few years, gravitational wave and neutrino detectors will undergo significant upgrades reaching unprecedented sensitivities. A new gravitational wave detector located in India (LIGO-India[a]) will join the current network of second generation (2G) interferometers formed by the two aLIGO in the USA, AdV in Italy and KAGRA in Japan.[15,16] Both aLIGO and AdV will reach a sensitivity larger than the nominal one with the upgraded configurations "A+" and "Virgo+"[17] during the fifth observation run (the start of which is currently scheduled for mid 2025). The completed network will be able to detect neutron star binary mergers (the most promising source for an associated electromagnetic counterpart) up to 330 Mpc, with an expected rate of few tens of detections per year (updated to the third observation run results).[17] By the end of the twenties, major upgrades are under consideration for aLIGO in the "Voyager" configuration[18] that will test some of the key technologies need for the third generation (3G) interferometers as the Cosmic Explorer (CE,[18,19]) and Einstein Telescope (ET,[20–22]) expected to be operational by mid-thirties. The "Voyager" configuration will possibly place the GW detection rate mid-way between the 2G and 3G detectors by the end of the twenties. The 3G detectors will have about one order of magnitude better sensitivity than current ones, with an expected rate of compact binary coalescences (CBCs) per year of the order of $O(10^5)$, up to distances that will cover the peak of star formation epoch and far beyond.[22]

Gravitational wave source sky localisation from the interferometer network is based on the triangulation method. By the end of the twenties, the completed GW detector network will have improved sky localisation capabilities, with average

[a]https://dcc.ligo.org/LIGO-M1100296/public

uncertainty regions of the order of few tens of square degrees for CBCs.[17] At distances larger than $\sim$ 100 Mpc, this scenario challenges the identification of the electromagnetic counterparts at optical wavelengths due to the large number of transient sources expected in such large areas and the incompleteness of galaxy catalogs above 100 Mpc. On the contrary, the high-energy transient sky is much less populated and gamma-ray or X-ray counterparts detected with all sky monitors might represent the most suitable way to pinpoint the GW source in the sky.

The GW source localisation uncertainties strongly depends on the presence of a network. This is still uncertain for the 3G interferometers during the thirties. A single GW detector such as ET, thanks to its sensitivity at low frequency, is able to localize about 100 binary neutron star merger per years within a few tens of square degrees up to a redshift of 0.3. These sources are detected before the mergers (some of them also few hours before the merger). For a network of detectors including ET and CE, the number of well localized events increases of an order of magnitude. However, going to large distances the sky-localization becomes of hundreds of square degrees for a large majority of events (e.g.,[22,23]). Early warnings from GW detectors allows ground and space-based telescopes to slew onto the identified sky region before the advent of the expected electromagnetic transient emission. Early warning alerts of the order of few minutes for the most nearby sources (i.e. NS-NS mergers at few tens of Mpc) are planned also for the 2G next observation runs[b].

For neutrino detectors, the Km3NeT[24] in the Mediterrean Sea will provide IceCube comparable sensitivites in the Northern Emisphere on the second half of the twenties and it will work in synergies with the Gigaton Volume Baikal late neutrino detector. In the Southern Emisphere, IceCube-gen2 will gradually increase the current IceCube sensitivity up to one order of magnitude,[25] boosting the current astrophysical neutrino detection rate to values that will significantly increase the chances to find the electromagnetic counterparts. The neutrino sky localization accuracy depends on neutrino flavour, where long tracks topology (for ν_μ) provide angular resolution down to 0.1-0.2 deg and a 2π sr sky coverage, while cascade topology (for ν_e and most ν_τ) angular resolution are typically 3-5 deg for the whole 4π sky, thus still requiring an electromagnetic counterpart and detectors with sky localization capabilities better than few arcmin to pinpoint the host galaxy and/or identify the source.

The launch of the enhanced X-ray Timing and Polarimetry mission eXTP,[26] currently scheduled by 2027[c], coincides with the middle/final stages of the above described major upgrades of neutrino and gravitational wave detectors. The recent breakthrough results described above, point to the gamma-ray bursts and active galactic nuclei among the most promising classes of multi-messenger sources that will be observed in the next years. Further promising candidates are represented by

[b] $https://emfollow.docs.ligo.org/userguide/early_warning.html$
[c] https://www.isdc.unige.ch/extp/

magnetars and core collapsing supernovae. All these sources are among the main targets for eXTP and a number of white papers describe all the science we will be able to do with eXTP.[27–30] The onboard wide field monitor (WFM, 2-50 keV, 3.7 sr field of view), with few arcmin-scale sky localization capabilities, and two sets of focusing telescope arrays with spectroscopic and polarimetric capabilities (SFA and PFA), will allow eXTP to play a crucial role in finding and characterizing the electromagnetic counterparts of the gravitational wave and neutrino sources by the end of the twenties.

In the following sections we focus on the capabilities of eXTP to observe two specific classes of multi-messenger sources: the compact binary coalescences (CBC) formed by two neutron stars (NS-NS) or a neutron star and a stellar-mass black hole (NS-BH), and core collapsing massive stars (ccSNe). For NS-NS mergers and ccSNe, a metastable or stable neutron star remnant may form after the main event. Both NS-N/NS-BH and ccSNe, as well as the possible NS remnant, have a number of theoretically expected emission components in the electromagnetic spectrum and in particular at high energies.

2. NS-NS/NS-BH mergers

Several electromagnetic components are expected in the soft/hard X-ray bands after the merger phase of coalescing NS-NS/NS-BH systems. A short GRB, possibly accompanied by a soft extended emission (see below), is expected soon after[d] the coalescence if the observer line of sight lies along the jet axis or within a certain angle range that depends on the combination of the source distance, the jet energetic angular distribution and the detector sensitivity. The collimated nature of gamma-ray emission implies that only a fraction of GW-detected NS-NS/NS-BH can be observed as short GRBs. To make a rough estimate, by assuming that all NS-NS/NS-BH produce a GRB, the number of GW+GRB detection is $f_b = (1 - cos\theta_{jet})$ times lower, where f_b can be as low as 0.001 for $\theta_{jet} \sim 2-3$ deg. Interestingly, recent results on the jet structure based on the observation of GRB170817,[31] shows that at large viewing angles gamma-ray emission get fainter but also softer, thus allowing sensitive wide field monitors to cover energies down to a few keV, as eXTP/WFM, best suited for detecting the electromagnetic counterpart of most nearby NS-NS/NS-BH events that are more likely off-axis. Simultaneous detection of GRB+GW can provide a wealth of information on jet launching mechanisms exploiting for instance the temporal delay between the GRB trigger and the GW detection. Also a non-detection of a GRB counterpart can provide useful insights on jet formation efficiencies in NS-NS/NS-BH.

The impact of the jet with the circumburst environment gives rise to an afterglow emission that, depending on the viewing angle from the jet axis, it can show an initial steep decay followed by a plateau and then a typical $t^{-\alpha}$ decay (with $\alpha \sim 1-2$), or an

[d] For GW170817, the short burst was observed 1.7 seconds after the merger epoch.[4]

initial slow rising behaviour followed by a late time power law decay in case of large viewing angles. At very late time, e.g. months up to years after the NS-NS/NS-BH merger, the impact of the nearly isotropic ejecta of neutron-rich matter released during the merger, may eventually produce a mildy-relativistic blast wave from which synchrotron radiation could be observed in X-rays (e.g.,[32] see also §2.1.3). For NS-NS mergers, if a NS remnant is formed, nearly isotropic X-ray emission produced from the pulsar nebula might escape if successfully ionizes the surrounding ejecta of matter released during the merger. Such non-thermal X-ray emission is expected on timescales of the order of days for certain values of the pulsar magnetic field and ejecta mass and with luminosities up to $\sim 5 \times 10^{44}$ erg s^{-1}.[33,34]

We will see in the next sections how eXTP will play an important role in detecting these high-energy components, significantly contributing to multi-messenger observational campaigns by the end of the twenties.

2.1. *eXTP and GRB 170817-like sources*

In this section we present preliminary results from data simulations of X-ray emission from a GRB170817-like source observed with eXTP. For these simulations we used calibration files released by March 2021 and the data analysis software package XSPECv12.10.[35]

2.1.1. *Prompt emission*

GRB 170817 is so far the only short GRB that has been associated with a NS-NS merger system detected through GW emission (see §1). Despite a high-energy signal rather typical for short GRBs, with duration of $\sim$ 2s and peak photon flux of 3.7 ± 0.9 ph cm^{-2} s^{-1} in the 10-1000 keV band,[36] given the very small distance of the source ($\sim$ 40 Mpc,[3]), the isotropic equivalent luminosity $L_{iso} = 1.6 \times 10^{47}$ erg s^{-1}[37] is several orders of magnitude lower than the average value for short GRBs ($\sim 10^{52}$ erg s^{-1}, see e.g.[38]). According to Goldstein et al.,[36] the burst spectrum is best fitted by a power-law model with exponential cut-off $f(E) = A(E/E_0)^{\alpha} e^{-E(2+\alpha)/E_p}$ in the first 0.6 s, with $\alpha = -0.62 \pm 0.40$, peak energy[e] $E_p = 185 \pm 62$ keV, 10-1000 keV flux $(3.1 \pm 0.7) \times 10^{-7}$ erg cm^{-2} s^{-1} and fluence $(1.8 \pm 0.4) \times 10^{-7}$ erg cm^{-2}. During the tail of the burst, the spectrum is best fitted by a black-body with KT=(10.3 ± 1.5) keV, flux $(0.5 \pm 0.1) \times 10^{-7}$ erg cm^{-2} s^{-1} and fluence $(0.61 \pm 0.12) \times 10^{-7}$ erg cm^{-2} in the 10-1000 keV. By using these best-fit models, and introducing photoelectric absorption with equivalent hydrogen column density[f] $N_H = 7.5 \times 10^{20}$ cm^{-2},[36] we perform simulations of eXTP/WFM observations of the main burst in the 2-50 keV energy band and find that a GRB 170817-like burst at the same distance could be

[e] The peak energy is the cut-off energy multiplied by $(\alpha + 2)$

[f] based on the host galaxy NGC4993 dust extinction $A_V = 0.338$

confidently detected ($\sim 7\sigma$) during the first 0.6 s, if spectral parameters were at the 1σ soft side of the error margins, confirming past results.[27] We estimate that a GRB170817-like source could be detectable with eXTP/WFM under this spectral assumption up to about 70 Mpc.

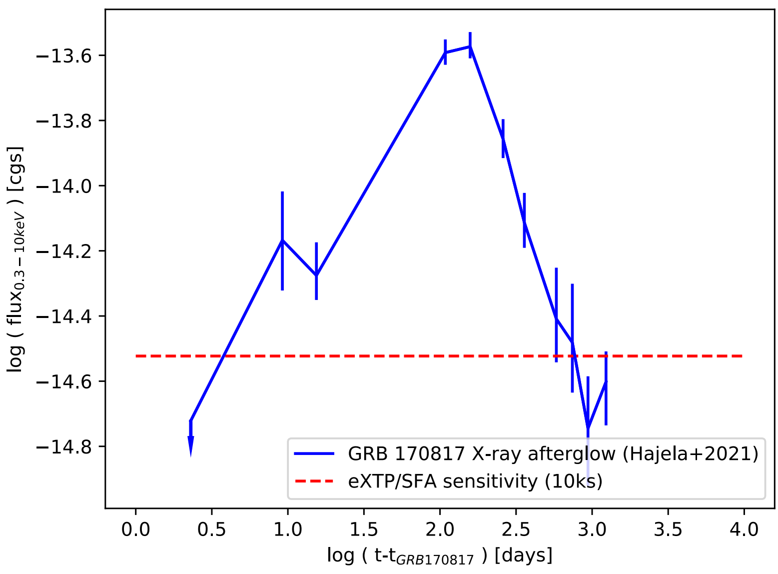

Fig. 1. X-ray (0.3-10 keV) flux of the short GRB 170817 afterglow that was associated with a NS-NS merger progenitor. Data are from Hajela et al. 2021 and references therein. The eXTP/SFA sensitivity will allow us to monitor a similar source from the very first phases up to the late ones, providing accurate sky localization. Horizontal line indicates the eXTP/SFA sensitivity for 10 ks of exposure from Zhang et al. 2016 and[26] computed in the 0.3-10 keV by assuming an absorbed power law model with phton index $\Gamma = 1.7$ and $N_H = 5 \times 10^{20}$ cm^{-2}.

2.1.2. *Afterglow emission*

The X-ray afterglow emission of GRB 170817 was detected with Chandra only 9 days after the merger as a faint source spatially coincident with the optical counterpart AT2017gfo and with flux $\sim 5 \times 10^{-15}$ erg cm^{-2} s^{-1} (0.3-10 keV,[39]). GRB170817 X-ray afterglow showed a slow rising behaviour that reached a peak of the emission after 100 days, with X-ray peak flux of a few 10^{-14} erg cm^{-2} s^{-1} (see Fig. 1). The overall properties of GRB170817 are in good agreement with the predictions for a GRB observed with a large inclination angle ($\sim 20-40$ deg) with respect to the jet axis. Given the eXTP/SFA sensitivities by assuming 10 ks of exposure ($\sim 2\times10^{-15}$ in the 2-10 keV energy band and $\sim 5\times10^{-16}$ in the 0.5-2 keV energy band, see Zhang et al. 2016), an X-ray afterglow of a GRB 170817-like source could be observed at almost all epochs, if accurate source sky localization is provided. The light curve long monitoring provided by eXTP/SFA is crucial to disentangle among different jet structure modellings that in turn encode the physics of jet formation and launching mechanisms in GRBs.

2.1.3. *Very late time X-ray emission*

Currently, the X-ray emission of GRB 170817 is still detectable and shows an intriguing possible rebrightening phase 4 years after the merger epoch.[40] Among the possible interpretations, this rebrightening could be the evidence of the theoretically predicted non-thermal emission produced by the impact of the kilonova ejecta into the circumburst medium,[32,41] though other interpretations are under investigations.[42] Measured spectrum during this phase assuming a power-law model, has photon index $\Gamma = 1.6$ and an integrated flux of 2.5×10^{-14} erg cm^{-2} s^{-1} in the 0.3-10 keV energy range.[32] We find that by assuming the spectral parameters provided by,[32] such late time X-ray emission could be detected with eXTP/SFA at more than 5σ level with 20 ks of exposure.

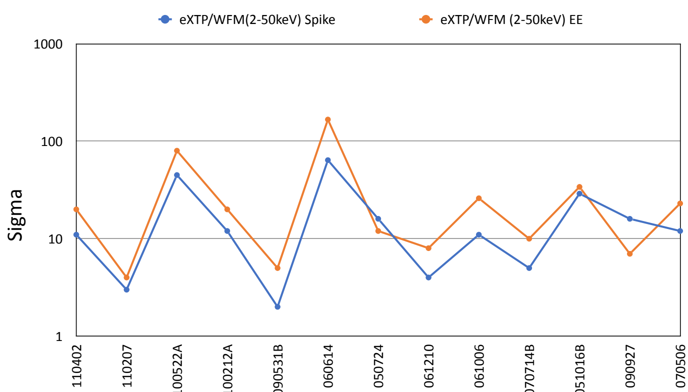

Fig. 2. Detection significance of a sample of short GRB spikes (blue) with Extended Emission (EE, orange). The x-axis shows the short GRB names, where the last 8 has measured redshift and cover a range from z=0.125 for GRB060614 to z=2.31 for GRB070506.

2.2. ***Short GRB with Extended Emission***

An interesting perspective that potentially can increase the simultaneous GRB+GW detection is represented by the subclass of short GRBs that, following the main spike with hard spectral properties, show a prolongued softer and fainter Extended Emission (EE) that lasts after few tens of seconds.[43–46] The fraction of short GRBs with EE is still very uncertain and from high-energy detector catalogues range from $\sim 2 - 20\%$. However, recent studies over a large sample of short GRBs detected with the coded mask telescope onboard the Neil Gehrels Swift Observatory (Swift, hereafter,[47]) and for which the X-ray telescope (XRT) observations could start during the EE, showed that providing a spectral coverage down to sof X-rays (i.e. $\sim$ few keV), the fraction of short GRBs with EE can be as high as 50% or more.[48] Among the possible hypothesis on the origin of the extended emission there is the presence of a magnetar formed soon after the merger of two neutron stars.[49,50] The important consequence in this case is that the extended emission component is expected to have a much lower degree of collimation with respect to the main spike that characterizes the short GRB.[33,50] If so, the EE detection rate can be in principle higher than short GRBs, making wide field monitors sensitive to the X-ray band as eXTP/WFM best suited to detect the electromagnetic counterparts of a potentially large fraction of NS-NS mergers.

We simulate 5 short GRB with EE with measured spectral parameters from Fermi/GBM and Swift/BAT joint analysis plus 8 short GRB with EE observed with Swift/BAT with known redshift. We take best fit parameters from Kaneko et al.[44] For these simulations we used calibration files released by March 2021 and the data analysis software package XSPECv12.10.[35] We find that EE component is always detected with eXTP/WFM and in most cases with better significance than the hard spike (see Figure 2).

2.3. *Polarisation of GRB jets*

2.3.1. *The prompt emission*

Despite the fact that GRBs have been observed more than forty years, the basic properties of the GRB jets are not yet constrained. We still can not discriminate baryonic jets[51,52] from ones dominated by the Poynting flux[53,54] by only analysing the spectral and temporal properties of short lasting prompt emission pulses ($\sim$0.1 s) at the keV-MeV energy range (see[55] and[56] for a review). We also do not have a clear understanding of the dissipation processes that lead to the GRB production. Our knowledge is limited by the lack of an interpretation of the GRB spectra which are typically modelled by the two broken power laws smoothly connected at $\sim$ 200 keV for LGRBs and at higher energies for SGRBs.[57] The observed spectra are too narrow to fit the fast cooling synchrotron radiation model and they are too broad compared with the simple thermal emission.[57,58] The absence of a single and straightforward emission mechanism to explain the typical GRB spectra has left us with big number of diverse physical models that correspond to very different GRB jet models. We can roughly classify the GRB production models by their dissipation side. The "standard" model assumes that the prompt emission is produced above the jet photosphere by the synchrotron emission of the non-thermal electrons that are produced by the internal shocks.[59,60] The "expected" parameters of the internal shocks model return fast cooling regime of the synchrotron radiation to dominate in the prompt phase, however it contradicts the observed values of the photon indices at the low energies.[58] Other class of models assume that the dissipation of the jet takes the place below the jet photosphere via the radiation dominated shocks.[61,62] The complex nature of the formation of the final spectrum via many Compton scatterings allows to produce spectra much broader than a simple thermal ones, thus close to the observed GRB spectra. However, it remains quite challenging to explain the observed variability, the power law structure of the high energy tail of the GRB spectra and the long lasting X-ray tails of the GRB pulses in these models.[63] There are numerous effects that can modify the spectral expectations from internal shocks model or any other optically thin synchrotron sources (e.g. non-thermal particles from magnetic re-connection), including the anisotropy of electron's pitch angles or presence of an external source of photons (see[64] for a brief review). While all these models could explain some of the observed GRB spectra, or at least partially (at the low or the high energy part), their prediction on the level of polarisation and the evolution of the polarisation angle is quite different, also depending on the structure of the local magnetic field (see[65] for a review). Therefore, the polarisation measure of the prompt phase is crucial for discriminating among GRB jet models including the acceleration processes (the magnetic field orientation).

So far the attempts to measure the GRB polarisation over short time-scales in the soft γ-rays returned inconclusive results due to contradictions between instruments and methods of data reduction performed by the Gamma-Ray Burst Polarimeter (GAP) (Yonetoku et al. 2011), POLAR,[66] and the Astrosat CZTI[67] instruments. The future γ-ray polarimeters, such as POLAR-2, LEAP and SPHiNX, have the capabilities to improve the polarisation measure accuracy of the prompt emission phase. However, measuring the polarization in the X-rays is equally interesting and has its own advantages. While the prompt emission pulses are very short in the soft γ-rays, we do observe regularly their tails (X-ray steep decay phase) for much longer time (100-1000 s) in 0.3-10 keV thanks to Swift/XRT. The X-ray steep decay is quite bright and starts at $\sim 10^{-7}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ at the peak of the prompt pulse and drops in two orders of magnitude in 100-1000 s. This phase is modelled as remnant of the prompt emission, i.e. the emission we observe when the GRB pulse is diminished at the jet co-moving frame.[68] Recently, it was demonstrated that X-ray steep decay is the lower energy prompt emission originated by the adiabatically cooling jet after its heat source is switched off.[69] Measuring X-ray polarization in the steep decay phase by the Polarimetry Focusing array (PFA) onboard eXTP would be a direct probe of the prompt emission polarisation (see[70]). The sensitivity of PFA is enough to constrain the linear polarisation degree for exposures of 100-1000 s given the extraordinary brightness of the X-ray steep decay phase. It requires a precise sky localisation of each detected GRB by the wide field γ or X-ray instruments, comparable with the extremely narrow FoV of PFA. The localisation level of arcminutes are expected to be provided by the eXTP/WFM and also by the next generation nano-satellite detectors such as HERMES.[71] Therefore, the prompt communication between eXTP instruments and advanced networks of γ-ray telescopes could provide a unique tool to study early X-ray polarisation. The presence of precursors and the quiescent periods in the temporal structure of LGRBs could be useful to send early trigger to detect bright X-ray counterparts of GRBs by PFA.

While *Swift*/XRT has been able to detect the steep decay phase of LGRBs, it is still technically challenging to promptly slew in the case of SGRBs. Given the spectral differences between long and short GRBs, one would expect physical differences between their jets and the dissipation processes. Therefore, the early detection of the X-ray emission from SGRBs and the measurement of its polarisation is of a great interest. The early warning and localisation of GWs prior to the BNS merger by the next generation GW detectors, such as the Einstein Telescope,[72] could be a unique trigger for the detection of the early X-ray polarisation of the the tail of the prompt emission from SGRBs.

2.3.2. *The afterglow emission*

Although we have very little knowledge on the physics of the prompt emission production, GRB afterglow emission (lasting for days) has a quite convincing interpretation. It is widely accepted that the dissipation of the GRB jet in the circumburst medium via shocks produces afterglow emission.[73–75] There have been several indications of detection of the linear polarisation in the late afterglow emission at the level of few percent[76] and a detection of circular polarisation in the afterglow of GRB 121024A.[77] The linear polarisation of level of few percent has been found at very early times,[78] when the emission is dominated by the reverse shock propagating into the GRB jet ejecta. Thus these measurements result to be essential for probing the shock physics by constraining the orientation of the magnetic field relative to the bulk motion, as well as for understanding the nature of the GRB jet by itself (reverse shock). Furthermore, nearby GRB sources can be detected off-axis, as the multi-messenger event of GW 170817/GRB 170817A. An upper limit of 12 percent in the linear polarisation at 2.8 GHz was obtained 244 days after the binary neutron star merger.[79] This upper limit allowed us to establish that the magnetic field has a finite parallel component, calling for turbulence amplified magnetic field in the external shock.[80]

X-ray domain in the physics of the GRB afterglow has a special importance for the following reasons. While the radio, optical and Very High Energy emissions in the afterglow phase are typically consistent with the standard external shocks model, *Swift* has discovered, that roughly half of the X-ray afterglow emission deviated from the standard forward shock emission, showing a long lasting (up to $\sim 10^4$ s) plateau phase, which is characterised by nearly constant flux. The X-ray plateau emission is can be produced by the additional energy input from the GRB central engine (e.g. newborn magnetar)[68] or it can be caused by the viewing angle effects[81] or by the delayed prompt emission from the jet wings.[82,83] In either case, the measure of the polarisation would be essential for constraining the physics of this mysterious GRB phase, simply because the polarisation would probe the structure of the magnetic field of the emission surface. From the observational perspective, the plateau phase has some advantages; it appears later compared to the steep decay phase giving more time to slew on, lasts longer ($\sim 10^4$ s), it is relatively bright ($\sim 10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ comparable with the PFA sensitivity) and with absence of significant spectral evolution, which could remove polarisation. In the era of the Einstein Telescope, it would be also possible to constrain the BNS postmerger signal for relatively nearby sources. Combining the information from the BNS postmerger signals together with the X-ray polarisation from the plateau phase will be extremely powerful to shed light on our understanding of the origin of the central engine powering SGRBs.

Another intriguing possibility to probe the prompt emission is to measure the polarisation of the late-time X-ray flares. *Swift* has discovered numerous X-ray flares superimposed to the afterglow emission.[84] These flares appear up to 10^5 s after the GRB detection and their variability suggests their internal nature, i.e. they could be hardly produced by the external shocks. Therefore, they are often interpreted as late-time prompt emission. Their late-time appearance and relative brightness increases the chances for PFA to measure their linear polarisation,[85] thus providing complementary observations to the the next generation γ-ray polarimeters. From one side, the X-ray flares polarisation measurements would probe the prompt emission zone, and on the other side, the comparison between the polarisation measurements at early times in γ-rays and at late times in X-rays would finally help us to establish the nature of the late time X-ray activity.

3. Core collapse supernovae and magnetars

Core collapse supernovae (ccSNe) have been claimed as another potential class of high-frequency gravitational wave sources,[86–88] as well as neutrino sources,[89] that current and/or future ground-based GW detectors and neutrino detectors may reveal in the next years. The ccSNe energy output transferred with GWs however is still very uncertain depending on the rather unnown explosion mechanism. Recent modelling contraints on possible GW energy values, obtained from a search of GW transients associated with optically detected ccSNe within ~ 20 Mpc during the first two observational runs of aLIGO and AdV (between 2015 and 2017), suggest that ccSNe GW detection may happen in the next years for sources up to few tens of Mpc in a few, very optimistic scenarios.[90] The GW signal detection from ccSNe, possibly combined with neutrinos detection, represents a unique opportunity to probe the inner dynamics inaccessible to electromagnetic observations. The electromagnetic counterpart of ccSNe plays a key role in allowing to confirm or discard the likely very faint GW signal by providing a precise sky localization and an estimate of the epoch of the explosion.

At high-energies, the best GW-detected ccSNe electromagnetic counterparts would be the typical long GRBs due to their brightness and the expected temporal proximity to the epoch of the GW burst originating from the core collapse. The rate of typical long GRBs, however, is expected to be extremely low due to the small fraction of ccSNe known to be associated with such energetic events (only about few %, e.g.[91]), and to the combination of the GRB collimated nature and the short distances that GW detectors may reach for this type of burst signals. However, a subclass of anomalously faint and soft long GRBs, named Low Luminosity GRBs (LLGRBs), have been suggested to represent a distincted class of long GRBs that populate the local Universe at a much higher rate (up to 10^3 times the typical long GRBs). The redshift distribution of LLGRBs detected so far is well below 1, where the most nearby was detected at z=0.0085 (37 Mpc).[92] These properties make LLGRBs an interesting class of sources that may enhance the chances of simultaneous detection with GWs with high-energy wide field monitors. LLGRBs are also softer than typical long GRBs and this highlight the role of wide field monitors with peak sensitivity between few to few tens of keV as eXTP/WFM. We simulated how eXTP/WFM would detect GRB 060218, a typical LLGRB observed with Swift/BAT. This was a close GRB at 139 Mpc showing an unusual long and soft burst, with duration 2740s.[93] The burst was best fitted by a simple power law spectrum in the 15-150 keV with photon index $\Gamma = 2.5 \pm 0.1$, fluence of 5.8×10^{-6} erg cm^{-2} and peak flux 2×10^{-8} erg cm^{-2} s^{-1}. By simulating with XSPECv12.0 the eXTP/WFM observations using the most recent calibration files we find that with 1ks of exposure this burst could have been clearly detected with significance of $\sim 40\ \sigma$.

Another electromagnetic counterpart at high-energy is represented by the X-ray emission from the ccSNe shock breakout (SBO). The advantage of such component with respect to LLGRBs is that it is thought to be not collimated. However, the SBO phenomenology lack of statistics so far, with only one event observed (XRO 080109/SN2008D,[94]). The 0.3-10 keV spectrum of XRO080109 was consistent with a power law with photon index $\Gamma = 2.3 \pm 0.3$, equivalent hydrogen column density $N_H = 6.8^{+1.8}_{-1.5} \times 10^{21}$ cm^{-2} and peak flux of 7×10^{-10} erg s^{-1} cm^{-2}.[94] Such low fluxes could not had been detected by the majority of current wide field monitors. Indeed, its discovery happened serendipitously by falling within the Swift/XRT field of view while performing a follow-up campaign of another source in the very same galaxy. By assuming the best fit spectral model of XRO080109, very preliminary simulations with eXTP/WFM with 400 s of exposure show that this source would not be detected, confining the SBO detection with eXTP/WFM within our Galaxy.

4. Conclusions

The eXTP expected launch date and lifetime are timely for a full synergy with upgraded second generation GW detectors and with next generation neutrino detectors. Among the most promising multimessenger sources there are the compact binary mergers from which the high-energy electromagnetic counterpart is expected in the form of short GRBs and their afterglows and possibly additional X-ray emission, yet to be confirmed, as from the impact of the kilonova with the circumburst medium. We have shown how eXTP/WFM can observe short GRBs, including the "Extended emission" observed in a fraction of short GRBs. The eXTP/SFA could have monitored almost all the evolution of the associated X-ray afterglow of GRB 170817 up to very late times and the eXTP/WFM detect the soft component of the prompt emission up to 70 Mpc. Both neutrino and GW are expected from cc-SNe, a subclass of which is the progenitor of long GRBs and in particular of the much more numerous low luminosity GRBs that are populating the nearby Universe. eXTP/WFM can play a crucial role in detecting the associated GRB and providing accurate burst timing and sky localization that will help in refining GW/neutrino event detection confidence and parameter estimation. In particular, the eXTP/WFM sky localization will allow us to trigger follow-up campaigns by next generation facilities as ELT, SKA, CTA, etc. to characterize GW sources with unprecedented sensitivities. eXTP/SPA is capable to detect the GRB prompt and afterglow emission polarisation to disentangle among different jet launching mechanisms as well as to shed light on the nature of the late time activity observed in the X-ray afterglow of several events.

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