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Multi-messenger emission from astrophysical sources hidden in γ-rays

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Abstract. Over the last decade, choked jets have attracted particular attention as potential sources of high-energy cosmic neutrinos. Testing this hypothesis is challenging because of the missing gamma-ray counterpart; hence the identification of other electromagnetic signatures is crucial. Extended H envelopes surrounding collapsing massive stars might choke launched jets. In addition, the same progenitors are expected to produce a shock breakout signal in the ultraviolet (UV) and optical lasting several days. Early UV radiation, in particular, will carry important information about the presence and nature of choked jets. While UV observations of core-collapse supernovae have so far been limited, the full potential of observations in this spectral band will soon be transformed by the ULTRASAT satellite mission with its unprecedented field of view. Here, we investigate the detection prospects of choked jet progenitors by ULTRASAT, in relation to their visibility in the optical band by the currently operating telescope ZTF. We find that ULTRASAT will double the volume of sky currently visible by ZTF for the same emitting sources, enlarging the sample of observed Type II supernovae by $\sim 60\%$. For optimised multi-messenger detections, the delay between neutrinos produced at the shock breakout (during the jet propagation inside the stellar envelope) and ULTRASAT observations should be of $\sim$4(5) days, with subsequent follow-up by instruments like ZTF about one week after.

1 Introduction

At the end of its life, a massive star (initial mass $\gtrsim$ 8 Solar mass) will typically undergo core collapse, resulting in the formation of a compact object – a black hole or a neutron star. Accretion of some stellar matter by this compact object can drive an energetic relativistic outflow, or jet. The core collapse of massive stars that are stripped of their outer layers of Hydrogen (H) and Helium (He) by strong winds produces Type Ib/c supernovae (SNe). If these outer layers are not lost, core collapse results in a Type II SN.

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H-rich SNe II come from the explosion of extended massive stars. Because of the wide variety of observational properties in their light curves and spectra, these can be further divided into several categories (refer to [1] for a recent review about the diversity of SNe II). 60% of the total amount of SNe II are core-collapse SNe (CCSNe). Detections in pre-SN images have allowed the community to firmly associate them with red supergiants (RSGs). Among the possible progenitors of CCSNe, it is also worth considering blue supergiants (BSGs) [2]. The large radial extension of both RSGs and BSGs constitutes a challenge for the emergence of the jet [3] as the preservation of their large stellar envelope (a few tens of solar radii, or $R_\odot$) might lead to choked jets if the central engine activity stops early enough before the jet reaches the outer edge of the star. If so, γ-ray emission would not emerge, as the remaining envelope is opaque to γ rays.

Before stalling, the jet crosses a large fraction of the stellar envelope, a cocoon can be formed that can be energetic enough to break out of the star by itself and produce an observable electromagnetic signature: first, a bright X-ray/UV flash, lasting from few seconds to a fraction of an hour, followed by a long-lasting (day timescale) UV/optical emission related to the expanding cocoon envelope. In any scenario, however, the electromagnetic signal requires that the shock reaches the stellar surface. The interested reader can refer to, e.g., [4] for details on shock breakout (SBO) theory. The UV emission will be possibly detected by the Ultraviolet Transient Astronomy Satellite (ULTRASAT) [5].

Prior to the electromagnetic emission, high-energy neutrinos may also be produced by the hidden jet: hadronic acceleration and subsequent interaction with the intense radiation field produced in the SN explosion lead to neutrinos at TeV-PeV energy scale that are immediately released [6]. On the contrary, γ rays emitted in the jet are likely absorbed in pair production processes because of the presence of intense radiation fields intrinsic to the source. Neutrinos from choked jets are characterised by higher energies, are described by a non-thermal spectrum, and are emitted at later times. The TeV-PeV neutrino signal from choked jets has been considered recently by several authors [7–12]. In the presence of a sufficiently dense medium, pp collisions can also occur, generating further neutrinos via meson and muon decay.

In review, we focus on SN types coming from stellar envelopes. In particular, we consider BSG and RSG progenitors, assuming that both of them embed choked relativistic jets in their stellar envelopes [13]. We quantify the improvement that the scientific community will gather once ULTRASAT will be operational, by combining its results with those of other existing facilities, as the Zwicky Transient Facility (ZTF) for the optical band [14, 15].

2 UV/optical emission in shock breakout flares from Hydrogen-dominated stellar envelopes

The first electromagnetic emission escaping an exploding star emerges as a fast shock-breakout flare, with a spectrum peaking in the UV and X-ray bands. After the breakout, the stellar envelope expands and cools. As the photosphere penetrates into the outer shells of the envelope, the adiabatically cooled radiation stored within the envelope escapes, leading to early UV/optical emission over a timescale of days. In this review we consider the UV/optical cooling after the explosion following [16] for RSGs and BSGs, both characterised by H-dominated envelopes. Following the methodology described in detail in [13] we have estimated the rate of events per year $\dot{N}$ expected to be detected into the ULTRASAT FoV as a function of the time t after the SBO occurrence, as below

$$\forall\, t \rightarrow \dot{N} = \int d\Omega \int_0^{z_{\lim}} \frac{dN(z)}{dz} dz = \int d\Omega \int_0^{z_{\lim}} \frac{R(z)}{1+z} \frac{dV(z)}{dz} dz, \quad (1)$$

where $z_{\rm lim}$ is the maximum z at which the model expected $f_\lambda > f_\lambda^{\rm lim}$ at given t. In the previous equation, $dV(z)/dz$ is the differential comoving volume, $R(z)$ is the comoving rate of sources, and $1 + z$ comes from the cosmological time dilation of the observed rate. The redshift dependence follows the star formation rate from [17] and we considered the normalization given in [13].

As a result, Figure 1 (Left) shows the maximum redshift as a function of the elapsed time since the SBO from which the signal can be revealed by ULTRASAT and ZTF. The trend shows a growing horizon for a few days after the SBO (depending on the observing instrument), later decreasing, which reflects the presence of a peak of visibility in the emission : at later times, only closer sources can be still accessible. We also note that ULTRASAT will exploit larger volumes of the Universe for these explosions, being able to catch observations from further redshifts. Figure 1 (Right) shows the corresponding number of SNe II per year detectable by ULTRASAT and ZTF (following Equation (1)) under the present assumptions.

3 Results and multi-messenger implications

In this Section, we discuss our results within the context of multi-messenger observations, focusing at first on UV and optical electromagnetic signals visible by ULTRASAT and ZTF and later on neutrino associations.

Ultraviolet and optical follow-ups- Figure 1 (Left) enables us to derive the following conclusions, namely: For RSG progenitors, UV (optical) signal from SBOs by ULTRASAT(ZTF) can be detected out to $z \sim 0.08(0.06)$, corresponding to luminosity distances of $\sim 360(270)$ Mpc, if the SBO occurred $\sim 4(10)$ days before detections. Later emissions, as well as signals from times closer to the SBO, can still exceed the sensitivity of the detectors only for closer SNe II. For BSG progenitors, the probability of detecting an analogous signal is smaller than RSGs and the results can be found in [13] The results found in [13] are expected to help the scientific community in constraining the progenitor of SNe II observed in both UV and optical wavelengths via ULTRASAT and ZTF-like instruments, as well as in identifying possible choked jets taking advantage of a multi-wavelength strategy. In fact, if the UV/optical emission lasts more than ten days, this may indicate that the progenitor was a RSG star. Moreover, the lack of a γ-ray counterpart (i.e., the associated GRB) points towards the observed emission to come from a choked jet, given that successful GRBs exploded at the distances here discussed are typically detected by current instruments. Figure 1 (Right) shows the expected rate of detectable SNe II as a function of time after the SBO event. It is visible that, once ULTRASAT will be operational, the multi-messenger and multi-wavelength community can profit from at least as many observations as in the optical field, or even more. Under the present assumptions, ULTRASAT will be able to reveal up to $\sim$40(2) SNe II per year from RSGs(BSGs) if the detection is performed within $\sim$4(1) day(s) after the SBO. About 60% of SNe II from RSGs can be accompanied also by an optical detection by ZTF, in case it will be able to catch optical emission within $\sim$10 days after the SBO (namely, around one week after the UV one). ZTF cannot perform sky observations as deep as ULTRASAT. As regards to the signals produced by BSG progenitors, one source out of the three detectable by ULTRASAT per year might be associated with optical measurements by ZTF. Within the multi-messenger context, neutrinos can also play a crucial role. Indeed, interaction of accelerated protons and thermal photons and/or hadronic collisions in choked jets can lead to the production of νs, able to escape from the thick stellar envelope of the system. This scenario has attracted much attention recently because of the possibility of explaining the astrophysical IceCube diffuse flux (TeV-PeV neutrino energies) without incurring into inconsistencies with isotropic diffuse γ-ray background observed by Fermi (e.g., [18]). In the next Section we discuss how neutrino observations can be combined in association with electromagnetic signals from SBO events.

Neutrino follow-ups- During stellar collapse, neutrinos can escape the thickest envelopes, such that their detection would constitute an early warning for the multi-messenger astronomical community, advertising that the light from the explosion is coming. This would trigger the search for the SBO electromagnetic signals following core collapse. Therefore, the combination of multi-messenger signals from UV, optical, and neutrino emissions provides an unprecedented opportunity to probe the existence of choked jets, and shed light on their progenitors. High-energy neutrino telescopes, such as IceCube [19] and KM3NeT [20], being this latter under construction at the bottom of the Mediterranean Sea and taking data in a partial detector configuration, may be able to reveal a flux of neutrinos from SNe II with choked jets, depending on their distance and energetics. Real-time analysis systems in these instruments allow for a prompt reaction, resulting into a distribution to the multi-messenger community within a few seconds. The high duty cycles of these instruments, combined with the all-sky field of view, make them ideal partners in multi-messenger strategies. Note that IceCube has been sending neutrino alerts to external communities for triggering subsequent follow-ups since 2016 [21], while for KM3NeT the plan is to automatically start sending alerts within the end of this year (see [22] for the description about the current status of the KM3NeT online system). The idea of performing optical follow-up of single high-energy neutrinos to find SNe dates back to several years ago [23]. We here now provide further indications for defining a proper strategy, focused on Type II CCSNe. We encourage UV, optical, and neutrino telescopes to optimise both their alert sending and external follow-up programmes based on the results presented in this manuscript. We believe that, if the observational strategy that we propose is combined with photometric and spectroscopic studies, it would be crucial to unveil choked jets. By considering the maximal probability to detect SNe II, we can argue that, if an interesting neutrino alert is released, ULTRASAT(ZTF) could point to the suggested direction of the sky within around 4(10) days to search for possible electromagnetic counterparts, thus maximising the reachable sky volume and hence the number of detectable sources. IceCube and KM3NeT are collecting several dozen neutrino events every day, it is fundamental to develope a strategy to optimize "alerts" (i.e. localization of the source in a short time period). This would maximize the capacity of multi-messenger research.

However, note that this time window leads to the time of the SBO occurrence. To also consider the production of neutrinos during the shock propagation time inside the stellar envelope, we need to enlarge this time window up to $\sim$ 1 day. In particular, we expect the shock wave to take $\lesssim$ 1 day to propagate in the radiative envelopes of BSGs and around 1 day in the convective envelopes of RSGs, for values of the explosion energy considered in this work [24]. It is worth stressing that neutrino and electromagnetic follow-ups are extremely important nowadays. Although, over the last years, the IceCube Collaboration has reported some observational indications of sources contributing to the diffuse neutrino flux, the majority of the diffuse flux is still unexplained. There is evidence that most of observed neutrino emission remains unexplained and many other astrophysical sources are needed to account for the remaining part. Recently, CCSNe have been tested as potential sources of the diffuse neutrino flux in the energy range of about $10^3 - 10^5$ GeV, assuming that the neutrino energy spectrum follows a power-law with an index of -2.5 [25]. Correlations between seven years of IceCube neutrino data and a catalogue containing more than 1000 CCSNe of types IIn and IIP, and a sample of stripped-envelope SNe, have been looked for, via either individual source studies and stacking analysis for combined emission from the whole sample. Despite no significant spatial and temporal correlation between CCSNe and neutrinos has been found, this study ruled out CCSNe of type IIn and stripped envelope SNe as the dominant source of the diffuse neutrino flux. Current limits indicate that type IIP SNe might at most contribute to the production of high-energy neutrinos for ∼ 60% of the diffuse flux (under the aforementioned assumptions). This strongly motivates the follow-ups that we propose in the present work, as we focus on the search of high-energy neutrinos from H-rich type II CCSNe, to which the RSG class belongs. Following [13] we find that, among the ∼40(20) RSGs per year detectable in the UV (UV+optical) band by ULTRASAT(ULTRASAT+ZTF) within 360 Mpc, high-energy neutrino emissions from about 2 per decade of these hosting choked jets would allow us to explain the origin of the cosmic diffuse neutrino flux. This evaluation shows the primary necessary to run such multi-messenger analyses for several years. It is worth pointing out that the approach presented in this review can be extended to combined searches between any existent electromagnetic facility and neutrino telescopes. If a SN is detected somewhere in the Universe in UV and/or optical wavelength band, by knowing its host galaxy (hence, its distance and the characteristic extinction) and by combining the information about the expected flux by the model and the limit flux detectable by the electromagnetic instrument reporting the detection, it is possible to define a reasonable time window when looking for neutrinos coincident with different emission phases of that SN. Finally, our results can also be used to more accurately tune the neutrino search time window of offline analyses performed in correlation with observed SNe [10, 11]. In fact, offline comprehensive studies might provide higher significance than real-time analyses via stacking sources from catalogues of optical and UV emitters.

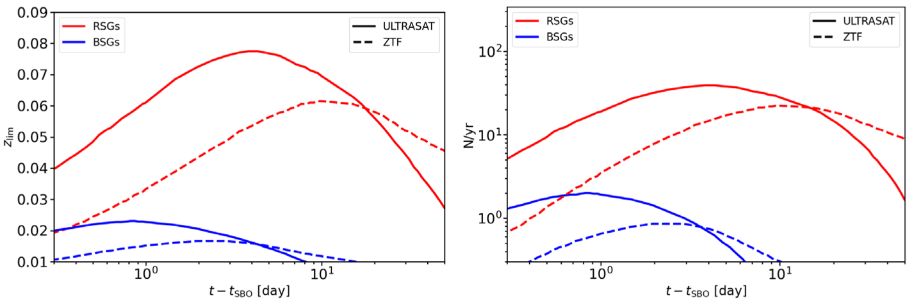

Figure 1. (Left) Maximum redshift from which RSGs and BSGs would have UV/optical emissions detectable by ULTRASAT and ZTF as a function of the emission time t. (Right) Rate of SNe II per year from RSGs and BSGs detectable with ULTRASAT and ZTF and a function of the emission time t. In both panels, the following fiducial parameters are adopted: for RSGs $R_* = 722\ R_\odot$, $E = 10^{51}$ erg, $M_{\rm ej} = 2.8\ M_\odot$, and $f_\rho = 1.455$; for BSGs $R_* = 50\ R_\odot$, $M_{\rm ej} = 10\ M_\odot$, $f_\rho = 0.0465$, and $E = 10^{51}$ erg. The emission time corresponds to the time elapsed since the SBO. Results for RSGs and BSGs are shown in red and blue, respectively. Solid and dashed lines are used for ULTRASAT and ZTF, respectively.

4 Summary and Conclusions

In this work, we investigated the radiative emission from core-collapse SNe with extended H envelopes (SNe II), specifically RSGs and BSGs. These sources are particularly interesting, as their lack of GRB counterparts indicates that these SN types can potentially harbour jets that are choked within the stellar envelopes. In the last decade, a few indications of the presence of jets in SNe have arisen. From the neutrino point of view, choked jets are fascinating, as they are considered to be possible contributors to the astrophysical diffuse flux detected by IceCube.

Following the SBO occurrence, the stellar envelope expands and cools nearly adiabatically. As the photosphere penetrates into the outer shells of the envelope, radiation is produced in the UV and optical band. We focussed on this radiative signal, investigating future multi-messenger prospects for combined UV/optical/neutrino observations between the future UV satellite ULTRASAT, the currently operating optical telescope ZTF, and high-energy neutrino telescopes such as IceCube and KM3NeT. We estimate the expected photon flux, by considering fiducial values for stellar progenitor parameters: $R_* = 722\ R_\odot$, $E = 10^{51}$ erg, $M_{\rm ej} = 2.8\ M_\odot$, and $f_\rho = 1.455$ for RSGs, and $R_* = 50\ R_\odot$, $E = 10^{51}$ erg, $M_{\rm ej} = 10\ M_\odot$, and $f_\rho = 0.0465$ for BSGs. We then evaluated the possibility of detecting the extinction-corrected signals, taking advantage of ULTRASAT for the UV band at (230-290) nm and the optical instrument ZTF. In this way, we characterised the future detection prospects of these sources, that we summarise as follows:

- The furthest distance out to which UV (optical) signal produced by the cooling emission after SBO in RSGs can be detected by ULTRASAT (ZTF) **is** $z \sim 0.08$ (0.06), or ~ 360 (270) Mpc, if the SBO occurred ~ 4 (10) days before detections. Lower-redshift SNe can still produce signals exceeding the limiting magnitude flux of the detectors, even from later emission times or at times closer to the SBO.
- The probability of detecting a similar signal from BSGs is less than in the case of RSGs because of the different characteristics among the two progenitors and subsequent less pronounced emission resulting from SBO in BSGs. In particular, ULTRASAT (ZTF) can detect signals coming from a SBO that occurred in BSGs located up to $z \sim 0.023$ (0.017), or ~ 100 (75) Mpc.
- ULTRASAT will be able to reveal up to 40 (2) SNe II per year from RSGs (BSGs) if the detection is performed within ~ 4 (1) days after the SBO.
- Around 60% of SNe II from RSGs can be accompanied also by an optical detection by ZTF, if it catches optical emission within ~10 days after the SBO (namely, around one week after the UV detection).
- One source out of the three detectable by ULTRASAT in one year in the case of SNe II from BSGs may be associated with optical measurement by ZTF.

As these sources can also produce neutrinos via interactions between protons and thermal photons in the choked jets, neutrino observations by existing Cherenkov high-energy neutrino telescopes (such as IceCube and KM3NeT) can be used in association with electromagnetic signals coming from SBO events. Indeed, both IceCube and KM3NeT have leading roles into the multi-messenger community, working in synergy with several partners, in both offline and online analyses. In particular, much effort has been devoted to reconstructing and classifying their own data in real-time as to alert external communities about interesting neutrino events, as well as to follow-up interesting astrophysical transients revealed by other facilities. We find that:

- By considering the maximal probability to detect SNe II, if an interesting neutrino alert is released, under the hypothesis that it comes from the SBO emission phase, ULTRASAT (ZTF) could point to the provided direction of the sky within ~ 4 (10) days to search for possible electromagnetic counterparts. This way, the reachable sky volume, and hence the number of detectable sources, is maximised.
- To consider the possibility that neutrinos are produced during the shock propagation time inside the stellar envelope, electromagnetic observations can wait up to a day more with respect to times indicated above.

We find that UV, optical and neutrino follow-ups adopting the strategy that we present here, combined with photometric and spectroscopic studies, would be crucial to unveil choked jets. By considering the recent constraints to the local rate of choked jets from RSGs computed in [12] to reproduce the IceCube diffuse flux, and restricting their contribution to at most 60% of the rate there derived, as indicated by the upper limit set by IceCube Collaboration in CCSN searches [25] as compared to the estimated local rate of RSGs, we find that at most ~1% of CCSNe from RSGs can host a choked jet producing high-energy (>TeV) neutrinos. Because of the ~ 40 (20) RSGs detectable per year in the UV (UV+optical) band by ULTRASAT (ULTRASAT+ZTF) within 360 Mpc, it will be necessary to perform UV, optical and neutrino follow-ups for several years to possibly catch just a few RSGs as choked neutrino sources. This would allow us to explain the origin of the high-energy diffuse neutrino flux, identifying choked jets as sources of multi-TeV neutrinos.

Note that, besides fast follow-ups on single serendipitous sources, the considerations presented here can also be used for offline analyses based on the comparison between SN catalogues and neutrino data. In fact, in these studies, the proper definition of the time window where searching for neutrinos is fundamental. Thanks to the results discussed here, the connection between choked-jet from SNe and high-energy cosmic neutrinos can be more tightly constrained in the near future with respect to existing studies in the literature (e.g., [10]).

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