Constraining the Fraction of Core-Collapse Supernovae Harboring Choked Jets with High-energy Neutrinos

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ABSTRACT

The joint observation of core-collapse supernovae with gamma-ray bursts shows that jets can be launched in the aftermath of stellar core collapse, likely by a newly formed black hole that accretes matter from the star. Such gamma-ray bursts have only been observed accompanying Type Ibc supernovae, indicating a stellar progenitor that lost its Hydrogen envelope before collapse. It is possible that jets are launched in core-collapse events even in the presence of a Hydrogen envelope, however, such jets are unlikely to be able to burrow through the star and will be stalled before escaping. High-energy neutrinos produced by such choked jets could escape the stellar envelope and could be observed. Here we examine how multi-messenger searches for high-energy neutrinos and core-collapse supernovae can detect or limit the fraction of stellar collapses that produce jets. We find that a high fraction of jet production is already limited by previous observational campaigns. We explore possibilities with future observations using LSST, IceCube and Km3NET.

Keywords: gamma rays: bursts — stars: binaries — stars: neutron — gravitational waves

1. INTRODUCTION

The mechanism driving core-collapse supernova (CCSN) explosions is still unclear. A common explanation is neutrino driven outflows (Colgate & Petschek 1982), however a recent idea is that jets could play an important role in SN explosions (Piran et al. 2019). CCSNe associated with long duration gamma-ray bursts (GRBs), sometimes called Hypernovae, provide a clear evidence for strongly aspherical explosions (Maeda et al. 2008), suggesting a jet-like activity.

Piran et al. (2019) proposed that a similar mechanism might be active also in ”standard” CCSNe types not associated with GRBs. Such a scenario is suggested by observations indicating energy deposition by so called ”choked” jets in a cocoon within the stellar envelope. The cocoon eventually breaks out from the star releasing energetic material at very high, yet sub-relativistic, velocities. It is possible to identify this fast moving material by looking at the very early time supernova spectra, as this component has a unique signature. Recently, a clear evidence has been provided indicating such a deposition by (Izzo et al. 2019), who detected spectroscopic signatures of iron group elements moving at $\sim 120,000\,\text{km}\,\text{s}^{-1}$ originating from the innermost parts of the exploding progenitor star of SN 2017iuk. However, whether or not CCSNe that do not harbor GRBs might be powered by jet/coconos activity is still a matter of active discussion within the community. The most natural interpretation of the energetic fast moving component observed in the early spectra of the supernovae by Piran et al. 2019, is that this is the coconos matter that breaks out from the progenitor. In a few cases such as SN 2008D/GRB 080109 (Mazzali et al. 2008), SN 2006aj/GRB 060218 (Campana et al. 2006) and GRB 171205A/2017iuk (Izzo et al. 2019) we might have even seen the direct thermal emission of this hot cocoon material. In this case Piran’s interpretation implies the existence of powerful jets within these supernovae. These jets have difficult to penetrate the progenitor, therefore these objects are simply observed as energetic supernovae or hypernovae in the optical band and
do not have accompanying gamma-ray emission. The jets that do not succeed to drill the envelope are labelled "choked" jets (CJ).

It may be that a significant fraction of core-collapse SNe, and possibly all those that have lost most (if not all) of their Hydrogen envelope, harbor choked jets. The shocks involved in these hidden jets may be the source of high energy neutrinos observed by IceCube (He et al. 2018).

In choked jets neutrinos and gamma-rays are produced by the decay of pions produced in the interaction of accelerated protons and thermal photons. While these sources are transparent to neutrinos they are opaque to gamma rays photons as these particles are produced inside the stellar envelope. This can justify the lack of association between observed GRBs and IceCube neutrinos. Therefore these sources are dark in GeV-TeV gamma-rays, and do not contribute to the Fermi diffuse gamma-ray background implying that the Waxman-Bahcall bound and the Fermi constrain on the diffuse gamma-ray emission do not apply to these sources (Murase et al. 2016).

These characteristics have been used by Murase et al. 2016(Murase et al. 2016) to show that choked jets so called failed GRBs may be the possible sources for the observed diffuse neutrino flux.

In this paper we investigate the detectability of high-energy neutrinos from choked jets within CCSNe, and the limits set by a non-detection on the fraction of CCSNe that harbor jets. We use the results of Senno et al. (2016) to calculate the expected neutrino emission. In their estimate they include the relevant microphysical processes such as multipion production in pp and p-gamma interactions, as well as the energy losses of mesons and muons.

2. NEUTRINO EMISSION ESTIMATE FROM CHOCKED JETS

We consider the possibility that a fraction of rapidly rotating massive stars at the end of their lives undergo core collapse, form a compact star or a black hole, and produce a jet that it is stalled before it breaks through the star (Meszaros & Waxman 2001; MacFadyen et al. 2001). We take the stellar parameters given in (Meszaros & Waxman 2001).

Following (Senno et al. 2016) we assume that the photons are free to move inside the jet as the plasma is optically thin inside the jet but cannot escape as the envelope or circumstellar medium outside is largely optically thick to Thomson scattering. Since the photons are trapped inside the jet the protons can interact with these thermal photons very efficiently. We can assume that the fraction of protons converted in pions, the so-called $f_\pi$, is almost 1 in this process. The radiation constraints apply to shocks in the envelope material as well as those in the choked jet.

We consider the possibility that electrons and protons are accelerated in the internal shock model and estimate the neutrino flux and spectrum following the model of He et al. (2018). They assume that the jet is choked, protons are accelerated to high energies efficiently, and thermal photons are produced in the jet head and propagate into the internal shock region. Then the accelerated protons interact with the photons from the choked jet head and produce pions. The pions decay into high energy neutrinos. They estimate the neutrino spectra numerically, taking into account micro-physical processes. The parameters that affect most the neutrino flux are the Lorentz factor, the duration of the jet and the luminosity of the jet. We use typical values for these parameters like $\Gamma = 100$, $t = 100$ s and $L = 10^{53} \text{ erg sec}^{-1}$. We should note, however, that thanks to the high neutrino production efficiency, the flux level is insensitive to the GRB jet parameters. The isotropic equivalent energy radiated in neutrinos from a choked jet that we get from this model is $E \sim 10^{53} \text{ erg}$.

3. NEUTRINO DETECTION

High-energy neutrinos interact with nucleons present in the detector producing secondary particles, which travel faster than the speed of light in the sea or ice, therefore induce the emission of Cherenkov light.

Currently operating high-energy neutrino detectors include, IceCube is a cubic-kilometer observatory located at the geographic South Pole (Aartsen et al. 2014); the ANTARES detector deep in the Mediterranean sea (Ageron et al. 2011); and KM3Net (Adrian-Martinez et al. 2016), also in the Mediterranean, currently under construction.

We determine the total number of expected neutrinos by a source by integrating the effective energy of the detector over the energy range 1-100 TeV:

$$N(r) = \int_{E_\nu=1 \text{ TeV}}^{100 \text{ TeV}} dE_\nu \frac{dN_\nu}{dE_\nu} A(E_\nu, \delta) dE_\nu$$

where $r$ is the luminosity distance, $\frac{dN_\nu}{dE_\nu}$ is the neutrino spectral fluence, $A(E_\nu, \delta)$ is the effective area of the neutrino detector, as a function of the neutrino energy $E_\nu$ and of the source declination. We expect $\sim 20$ neutrinos from a source at distance of $\sim 100$ Mpc for the set of model parameters given above.

4. FRACTION OF SUPERNOVA OBSERVATIONS WITH DETECTED NEUTRINO COUNTERPART
We now estimate the fraction $f_\nu$ of CCSNe detected electromagnetically that will also be detected via high-energy neutrinos. We convolve $N(r)$ with the frequency of occurrence of CCSNe as a function of redshift. Due to the shortness of the lifetime of the progenitors of core-collapse supernovae, typically a few million years, we can use star formation history as proxy of the history of the CCSN rate e.g. (Hopkins & Beacom 2011; Madau & Dickinson 2014). We find

$$f_\nu = \frac{f_b \int_0^{r_{\text{max}}} (1 - \text{Pois}(0, N(r))) \rho(r) 4\pi r^2 dr}{\int_0^{r_{\text{max}}} \rho(r) 4\pi r^2 dr} \tag{2}$$

where $f_b$ is the jet beaming factor, defined as the fraction of the sky in which the jet emits high-energy neutrinos, Poiss($k, \lambda$) is the Poisson probability of measuring $k$ for average value $\lambda$, and $r_{\text{max}}$ is the maximum luminosity distance out to which the CCSN can be detected optically.

Here we consider $r_{\text{max}}$ for two representative facilities for ongoing and future observations: the Zwicky Transient Facility (ZTF; Rauch 2019)) and the Large Synoptic Survey Telescope (LSST; https://www.lsst.org/scientists/scibook).

For ZTF, we assume a magnitude limit of $R \sim 19$ for a typical 30 s exposure (Bellm & Kulkarni 2017; Rauch 2019). For LSST we assume a magnitude limit of $R \sim 24$ for a typical exposure of $2 \times 15$ s (Abell et al. 2009). After assuming an absolute magnitude at maximum for CCSNe of is $M = -17.5$ (Patat et al. 1994), we find that they can be detected out to $r \sim 200$ Mpc with ZTF, and out to $r \sim 1.5$ Gpc with LSST.

With these observational limits, using Eq. 2 we find that a fraction $f_{\nu}^{\text{ZTF}} \approx 0.5 f_b$ of CCSNe detected by ZTF might produce neutrinos detectable with IceCube or Km3NET. For LSST, this fraction becomes $f_{\nu}^{\text{LSST}} \approx 10^{-2} f_b$. The same estimate can be performed for SNe-Ibc which are a fraction of CC, about 30% (Botticella et al. 2017) but, on average, slightly brighter (up to $M \approx -18$) so detectable with LSST up to 2.3 Gpc and with ZTF to 280 Mpc.

We find that a fraction $f_{\nu}^{\text{ZTF}} \approx 0.2 f_b$ of SNe-Ibc detected by ZTF might have IceCube or Km3NET neutrinos detections. For SNe-Ibc detected by LSST, this fraction is $f_{\nu}^{\text{LSST}} \approx 4 \times 10^{-3} f_b$.

Finally we consider the Hypernovae (without GRBs) which are about 7% of SNe-Ibc (Guetta & Della Valle 2007). These sources are of particular interest because possibly they are the most suitable candidates to harbor choked jets. HNe are as bright as $-19$, so detectable up to 3 Gpc (to 400 Mpc with ZTF).

We find that a fraction $f_{\nu}^{\text{ZTF}} \approx 0.02 f_b$ of Hypernovae detected by ZTF will may produce neutrinos detectable by IceCube or Km3NET. For Hypernovae detected by LSST, this fraction is $f_{\nu}^{\text{LSST}} \approx 7 \times 10^{-4} f_b$.

All these factors are smaller by a factor about 10 for ANTARES.

The fractions of CCSNe producing neutrinos detectable with IceCube or Km3NET, decrease from ZTF to LSST because the latter telescope will be able to discover an increasing number of supernovae out to very large distances therefore hardly recognizable by neutrinos detectors.

5. NEUTRINO BACKGROUND RATE

The main component for the background is the flux of atmospheric neutrinos, which is caused by the interaction of cosmic rays, high energy protons and nuclei, with the Earth’s atmosphere. Decay of charged pions and kaons produced in cosmic ray interactions generates the flux of atmospheric neutrinos and muons. Their energy spectrum is about one power steeper than the spectrum of the parent cosmic rays at Earth, due to the energy dependent competition between meson decay and interaction in the atmosphere.

Supernovae have evolutionary time scale of the order of dozens of days. However, we expect that a jet will be driven and neutrinos will be emitted from SNe only for a time frame comparable to the duration of long GRBs, i.e. about a minute. The time of core collapse is much more uncertain than this time frame, with characteristic uncertainties of hours-days. This means that the relevant time frame for background accumulation is hours-days. Here, we consider 1 day as a characteristic uncertainty. Given that IceCube detects about 100,000 neutrino candidates per year (Aartsen et al. 2019), and assuming 1 deg$^2$ directional uncertainty, the expected number of background neutrino candidates coincident with a given CCSN is $N_{\text{atm}} \sim 10^{-2}$.

6. HOW MANY SUPERNOVA FOLLOW-UPS WILL LEAD TO A MULTI-MESSENGER DETECTION?

We first consider a search for neutrinos coincident with a population of $N_{\text{sn}}$ detected CCSNe. We want to know how many supernovae will lead to a 3$\sigma$ detection of neutrinos, assuming that a fraction $f_{\text{jet}}$ of the supernovae produce jets and therefore high-energy neutrinos with luminosities estimated above.

The expected number of background neutrinos candidates detected in coincidence with the $N_{\text{sn}}$ supernovae is $10^{-2} N_{\text{sn}}$. The expected number of signal neutrinos from these supernovae is $N_{\text{sn}} f_{\nu}$. Taking a beaming factor $f_b \approx 0.1$ (Liang et al. 2007) and assuming that the number of background neutrino candidates follows a Poisson
distribution, we find that a 3\(\sigma\) detection requires about 40 CCSN detections by ZTF or \(10^5\) detections by LSST.

The number of detections required for SNe-Ibc are 200 for ZTF and \(6 \times 10^5\) for LSST while for Hypernovae are \(2 \times 10^4\) for ZTF and \(2 \times 10^7\) for LSST. The results show that these numbers are much higher for these two other categories, showing that it is suboptimal to include very distant events in the estimates.

With CCSN rate density \(7 \times 10^{-5}\) Mpc\(^{-1}\) yr\(^{-1}\), the required number of CCSN detections can be achieved in less than a year by either ZTF or LSST.

7. HOW MANY NEUTRINO FOLLOW-UPS WILL LEAD TO A MULTI-MESSENGER DETECTION?

It is not known what fraction of the astrophysical neutrinos observed by IceCube come from CCSNe. Also accounting for the fact that some of the high energy neutrinos are not astrophysical, let the fraction of detected high-energy neutrinos of CCSN origin be \(f_{\text{SN}}\). Given that the density of CCSNe follows the cosmic star formation rate, we can calculate the fraction of neutrinos from CCSNe that come from within a distance threshold. For ZTF’s 200 Mpc this fraction is 2\%, while for LSST’s 1500 Mpc it is 15\% (Bartos et al. 2017). Therefore, the fraction of detected neutrinos that originate from CCSNe detectable by ZTF is 0.02\(f_{\text{SN}}\), while for LSST it is 0.15\(f_{\text{SN}}\). Assuming optimistically that a significant fraction of astrophysical neutrinos come from CCSN jets, i.e. \(f_{\text{SN}} \sim 1\), we find that about 50 (6) neutrinos need to be followed up to find a coincident CCSN with ZTF (LSST). This number is proportionally higher if not all neutrinos originate from CCSNe.

8. DETECTION WITH NEUTRINO MULTIPLETS

Detecting a single neutrino in coincidence with a supernova is not by itself sufficient for discovery. However, two coincident neutrinos with a single supernova would strongly indicate an astrophysical origin. For one supernova the probability of observing two coincident background neutrinos is \(10^{-4}\). Using Eq. 2 with a slightly modified Poisson term, we find that the probability of detecting two astrophysical neutrinos from a supernova detectable by ZTF is \(\sim 0.02\) for IceCube and Km3NET, and \(10^{-5}\) for ANTARES. Here we accounted for \(f_{\nu} = 0.1\). This means that, while a neutrino multiplet in coincidence with a supernova would be a detection at the 3\(\sigma\) level, a search specifically for neutrino multiplets is not expected to yield a detection sooner than the single neutrino search.

9. CONCLUSION

We investigated the prospects of probing jet production by a large fraction of core-collapse supernovae below the stellar envelope, as proposed by Piran et al. (2019). We calculated the expected high-energy neutrino flux from choked jets below the stellar envelope and calculated their detectability with IceCube, Km3NET and ANTARES. We computed the number of follow-ups that need to be carried out in order to find coincident supernovae+neutrinos and obtain the fraction of supernovae that produce jets. Our conclusions are the following:

- If all CCSNe produce jets with a beaming factor of 0.1 then we need about 40 CCSNe detected by a ZTF-like telescope, or \(10^5\) CCSNe detected by LSST, to be able to establish neutrino emission and therefore jets from CCSNe. This can be achieved within 1 year of observations with either ZTF or LSST. If not all CCSNe produce jets then these numbers are proportionally higher.

- Considering the electromagnetic follow-up of astrophysical neutrinos, about 50 astrophysical neutrinos need to be followed up by a ZTF-like telescope in order to find a corresponding CCSNe according to our neutrino emission model. LSST only needs to follow up 6 astrophysical neutrinos to find a counterpart. The required number of follow-ups is greater due to the fraction of high-energy neutrinos that are not astrophysical, and if not all CCSNe drive jets.

- Searching for neutrino doublets coincident with CCSNe can lead to discovery even with a single such association. We find that the search for such doublets will lead to discovery on a similar time frame as the accumulation of singlets.

- The results show that the search for distant Hypernovae will add a lot of noise and few neutrinos, therefore if we include Hypernovae it will take many years to make a detection. We recommend a search strategy that does not look beyond CCSN distances in order to optimize signal to noise ratio.

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