Detecting neutrino transients with optical follow-up observations

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Abstract

A novel method is presented which will enhance the sensitivity of neutrino telescopes to identify transient sources such as Gamma-Ray Bursts (GRBs) and core-collapse Supernovae (SNe). Triggered by the detection of high energy neutrino events from IceCube or other large scale neutrino telescopes, an optical follow-up program will allow the identification of the transient neutrino source. We show that once the follow-up program is implemented, the achievable sensitivity of IceCube to neutrinos from SNe and GRBs would increase by a factor of 2-3. The program can be realized with a small network of automated 1-2 meter telescopes and has rather modest observing time requirements.

Key words: Neutrinos, Gamma-Ray Bursts, Supernovae, detection methods

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1 Introduction

IceCube, the first instrumented gigaton detector being constructed, will have an unprecedented sensitivity for neutrinos of TeV to PeV energies \cite{1}. The list of astrophysical objects which might be detected is extensive (see \cite{2} for a review) and includes time variable sources such as Active Galactic Nuclei (AGNs) and Micro-quasars as well as transient sources such as Gamma-Ray Bursts (GRBs) and Supernovae (SNe). Because the number of expected events is small, efficient search strategies need to be developed to separate the signal from the background of atmospheric neutrinos. Point sources are identified through the direction of muon-neutrino events which can be reconstructed to within $\sim 1^\circ$ \cite{1}. For time variable sources one can additionally search for a correlation of neutrino arrival times with the activity level of the source.

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observed e.g. in gamma-ray, X-ray [3] or optical [4]. Although promising, this approach is made more complicated by the fact that the correlation features as well as their time-scales and rates are a priori not well known. This is somewhat simpler in case of transient sources. For GRBs, the time constraints from the burst detected by satellites allows one to eliminate essentially all atmospheric neutrino background [5].

A practical problem is that most gamma-ray, X-ray and optical observatories are capable of observing only a small fraction of the sky, while neutrino telescopes monitor essentially a full hemisphere. Hence, unless preparatory steps are taken, only a small subset of data can be used for correlation studies. The solution we discuss in this paper consists of using neutrino detections to trigger other follow-up observations. As we show, such a Target-of-Opportunity (ToO) program can provide the required data to identify transient sources (see [3] for a discussion of this idea in the context of AGNs). As examples we consider two promising source classes, namely GRBs and SNe.

GRBs are among the most spectacular events in the Universe, releasing $\sim 10^{51}$ ergs on time-scales of seconds. These observations, which are best explained by the presence of highly relativistic jets with boost factors $\Gamma \sim 100$, have fueled speculations that GRBs might be the source of the most energetic cosmic rays [6,7]. Protons would be accelerated to high energies, and in the interaction with ambient photons produce pions and kaons, which in their decay produce neutrinos [8,9,10,11].

Furthermore, the recent association of Gamma-Ray Bursts with core-collapse Type Ib/c Supernovae might suggest that certain aspects of the jet phenomenon are present in other, more frequent types of SNe. (The ratio of the local GRB rate, including a jet beaming correction, to the rate of SNe Ib/c was found to be less than $10^{-3}$ [12].) In particular, jets might form with very different ejection velocities, some highly relativistic leading to the GRB phenomenon, while others being only mildly relativistic. A mildly relativistic jet ($\Gamma$ of a few) would stall in the outer layers of the progenitor star resulting in the absorption of all its electromagnetic radiation. However, such a jet would efficiently sweep up matter and accelerate protons. Inevitably, these protons interact with other surrounding nuclei, producing neutrinos. The predicted neutrino yield from the interaction of jets with the outer layers of the progenitor has been calculated by several authors [13,14] and recently shown to be a potentially very strong signal [15,16].

The observational program discussed in this paper consists of a ToO trigger and optical follow-up observations. As we will show, this would improve the perspectives for discovery of neutrinos from transient sources significantly. We quantify the gain in sensitivity for neutrinos from GRBs and SNe and discuss the telescope and observing time requirements.
The difficulty in triggering a ToO follow-up program lies in the fact that the neutrino data stream is dominated by atmospheric neutrinos. We first consider the rate of atmospheric background events in a detector such as IceCube. Near the energy threshold of the detector, a detailed simulation of the detector performance is necessary, resulting in an event rate from atmospheric muon neutrino events of \(9 \times 10^4\) per year (after application of neutrino selection cuts) \([1]\).

Above a muon energy threshold of 10 (100) TeV, one expects of the order of 2500 (80) events per year from atmospheric muon neutrinos \([17]\) (assuming a muon energy resolution of \(\sigma(\log E_\mu) = 0.4\)). In the case of GRBs, the expected neutrino spectrum is significantly harder than that of atmospheric neutrinos, hence one can introduce an energy cut to efficiently reduce the background.

When searching for transient events such as SNe or GRBs, one obvious signature to look for are neutrino-bursts: a multiplet of neutrino events from the same direction and within a short time window. Let’s consider the background rate from \(n\) coincident, uncorrelated, upwards traveling atmospheric neutrinos:

\[
R_{\text{atmo} - \nu}^n \approx n! \left[ \frac{\Delta\Omega}{2\pi \Delta t} \right]^{n-1} (R_{1 - \nu}^\text{atmo})^n. \tag{1}
\]

Inserting the corresponding values for IceCube, an angular accuracy of \(\Delta\Omega = 2^\circ \times 2^\circ\) and a rate, \(R_{1 - \nu}^\text{atmo}\), of \(9 \times 10^4\) atmospheric neutrino events per year as well as a duration of the neutrino-burst \(\Delta t\) of 100 seconds, one can estimate the background rate for higher order multiplets. A doublet \((n = 2)\) is expected at a rate\([1]\) of 10 year\(^{-1}\). Hence, the detection of a doublet would by itself not be significant. As will be discussed below, this changes once an optical transient event such as a GRB or a SN is detected in coincidence. If the neutrino multiplet consists of more than two events, it becomes significant. The \(2 \times 10^{-3}\) year\(^{-1}\) rate of triple coincidence background atmospheric neutrino events poses little threat of false trigger.

### 3 Follow-up observations

Searches performed with optical telescopes have been shown to be by far the most efficient in detecting supernovae. Depending on the supernova type, the rate of background multiplets is very sensitive to the rate of atmospheric neutrinos and the angular bin-size. While it is possible to exactly compute the rate for any experimental setup, it will generally differ somewhat from the quoted value.
the light-curve brightens for about 10-20 days after explosion before reaching its maximum. If the rising part of the light-curve is measured well enough, one can extrapolate to the explosion time $t_0$. For GRBs, one would rely on detection of the afterglow, which has been observed for about 50% of the well localized GRBs [18]. The measurement of the afterglow can be extrapolated to obtain an estimate for $t_0$. We show that for both SNe and GRBs, a resolution $\Delta t_0 \lesssim 1$ day can be achieved with a rather modest optical follow-up program.

**Gamma-Ray Bursts:** The afterglow decays initially as a power-law $f(t) = a(t - t_0)^{-\gamma}$, with an average index of $\gamma \sim 1.2$ [18]. One day after the burst, a typical brightness of the afterglow is 19-20 magnitudes. Such afterglows therefore represent a promising target for a neutrino triggered optical follow-up. To determine with which precision one can obtain the explosion date $t_0$, we simulate the afterglow with a power-law index $\gamma = 1.2$ and fit for the parameters of the light-curve model: $a, \gamma$ and $t_0$. With three observations of the afterglow at 8, 16 and 24 hours after the burst, and the first being a 20 sigma detection (i.e. an error on the flux of 5%), we obtain an average time resolution $\delta t_0 \sim 0.3$ days (see Fig. 1).

**Supernovae:** The explosion time can be obtained by extrapolating the supernova light-curve. A simple model for the initial, rising part of the light-curve is
We consider the lightcurve of Type Ia supernovae. We assume that, in analogy to Type Ia supernovae, the lightcurve can be approximated by

\[ F \propto (t - t_0)^2 \]  

(19) (This behavior can be understood by assuming that in the initial phase after the explosion, the supernova photo-sphere is represented by a black body of constant temperature, which expands with velocity \( v \). The area of the photo-sphere, which is directly proportional to the photon flux, then increases \( \propto v(t - t_0)^2 \).) The time after which the light-curve evolution begins to slow down, and start to deviate from the \( t^2 \)-parameterization, will be called \( T_{\text{parabola}} \). For Type Ia Supernova, one finds \( T_{\text{parabola}} \sim 10 \) days. We will assume that a similar relation holds for core-collapse supernovae, however with different \( T_{\text{parabola}} \). Generally, Type II supernovae have a very fast rise-time corresponding to a short \( T_{\text{parabola}} \) of a few days while Type Ib/c have a slower rise-time. We will make the general ansatz for the early time flux evolution:

\[ F(t) = a(t - t_0)^2 \]  

for \( 0 < (t - t_0) < T_{\text{parabola}} \). This defines a template for times before \( T_{\text{parabola}} \) which, in combination with the observed lightcurve, can be used to constrain the parameters \( a \) and \( t_0 \). An observational program with daily observations of the same field is assumed. The exposure time is chosen such that for the range of target supernovae, the flux error at the time \( T_{\text{parabola}} \) is \( \sim 5\% \) (see Fig. 1). One can then estimate the achievable measurement errors from the light-curve up to times \( T_{\text{parabola}} \) using simulation. We find that the achievable statistical error on \( \Delta t_0 \) is about half a day, and largely independent of \( T_{\text{parabola}} \) (and hence the rise-time). Even if we neglect the information of the first three days (which might be showing the shock breakout), the expected error increases only to \( \Delta t_0 \approx 0.8 \) days.

In cases where the shock breakout can be detected directly, the supernova is seen as an initially bright object, with a rapidly cooling and declining light-curve. A well observed Type Ib/c supernova showing a shock breakout is SN 1999ex [20]. The determination of \( t_0 \) can be done in a manner similar to the case of GRB afterglows.

4 Neutrino-Optical Coincidences

After introducing all the necessary ingredients in the previous sections, we now turn to the strategy for a combined neutrino/optical detection. The basic scheme is that the detection of neutrino-induced muons triggers the optical observations. Since supernovae and GRBs differ in their rate and in their expected neutrino spectra, they need slightly different strategies.

**Supernovae:** Three trigger scenarios are considered.

1) **Neutrino-triplets and higher order multiplets:** From Eq. (1) follows that three or more neutrinos detected within a small angular and temporal window constitute a statistically significant neutrino-burst. Optical follow-up would then
serve the purpose of identifying the source of the neutrino-burst.

2) Neutrino-doublet: A neutrino-doublet in IceCube is expected several times a year from the background of atmospheric neutrinos. A doublet detection by itself is hence not significant. However, this changes if a coincident supernova is detected. The rate of core-collapse supernovae is about one per year within a 10 Mpc sphere \cite{21}. Thus, within a time-window of one day, an angular window of $\Delta \Omega = 2^\circ \times 2^\circ$ and within a distance $d_{\text{max}}$, we expect to observe a supernova with a probability $P_{\text{SN}}^{\text{bg}} \approx 3 \times 10^{-7} \times (d_{\text{max}}/10 \text{ Mpc})^3$. For $d_{\text{max}} = 200 \text{ Mpc}$, the expectation to observe a background doublet in coincidence with a random supernova is $P_{\text{atmo}^\nu \nu}^{\text{bg}} P_{\text{SN}}^{\text{bg}}(d < 200 \text{ Mpc}) \approx 2 \times 10^{-2}$. If in addition one would require that the supernova is of Type Ib/c, the background expectation rate would reduce by another factor of 6 \cite{22} to $3 \times 10^{-3}$ per year. With such a small background expectation, a neutrino-optical coincidence would become a very interesting detection. Finding supernovae with $d_{\text{max}} \gg 200 \text{ Mpc}$ can only be associated with small confidence (unless they have some features making them exceptional supernova, as for example a Gamma-Ray Burst afterglow).
3) *Neutrino-singlet:* Because of their large rate, single neutrinos are rather
difficult to associate with a supernova. The maximal distance allowed has to be
restricted accordingly. For example, for a rate $R_{\text{atmo}}^{1-\nu}$ of $9 \times 10^4$
neutrino events per year and $d_{\text{max}} = 20$ Mpc, one obtains a rate of accidental coincidences of
$R_{\text{atmo}}^{1-\nu} P_{\text{SN}}^{\text{bg}} \approx 0.2$ per year. At least three or four such coincidences have to be
detected to make it meaningful (i.e. $\gtrsim 3\sigma$). Because the number of galaxies
within 20 Mpc is still reasonably small, a nightly scan of a catalog of galaxies
would still be feasible (see [23] for an ongoing program to monitor the largest
galaxies within 10 Mpc).

We can now compute the sensitivities of the three observing scenarios
described above. We assume a model with two parameters. The first parameter
is the rate of supernovae producing internal jets and the second parameter
is the kinetic energy released into the jet. We scale the expectation from the
model of [15], 30 events above a muon energy of 100 GeV for a detector of
km$^2$ area, with the factor $(E_{\text{jet}}/3 \cdot 10^{51}$ erg). We distribute the supernovae ac-
paring the continuum distribution of [21], and weight their contribut ion with
the distant dependent probability to produce one, two, three or more neutrino
events in the detector. The inclusion of Poisson-fluctuations in the number of
expected events leads to a large increase in the number of detectable super-
novae, as one samples from a larger volume. For example, the median distance
of doublet producing supernovae is 120 Mpc, compared to 40 Mpc without
Poisson fluctuations.

We have taken into account that about 20% of supernovae (and GRBs) cannot
be followed optically because they occur to close too the sun. We do not
include the impact of dust extinction, which will hide a fraction of SNe in
starburst galaxies from their detection with optical follow-up [21,24]. This
fraction will depend on the wavelength range of observations and could be
somewhat reduced by observing in the near infrared or by more powerful
telescopes.

Figure 2 shows the achievable constraints on the jet energy as a function of the
rate of supernovae with jets. As can be seen, neutrino-doublets, if combined
with an optical follow-up can improve the sensitivity by a factor of a few,
either by lowering the accessible supernova rate or by lowering the energy of
jets, which can still be detected. The constraints from neutrino-singlets show a
cut-off around a fraction of $\sim 0.1$ which is a consequence of having to restrict
the distance of the supernova to be within 20 Mpc. Hence, rare supernovae
jet configuration can not be efficiently probed with neutrino singlets.

*Gamma-Ray Burst:* In order to compute the reach of a neutrino-optical co-
incidence search, we first estimate the rate of accidental afterglow detections
consistent with the timing and direction of a neutrino event. Assuming 500
GRBs per year and hemisphere, of which 50 % produce detectable afterglows
[18], a coincidence time window $\delta t_0 \sim 0.3$ days and an angular resolution of $1^\circ$, the probability for an accidental coincidence is $\sim 3 \cdot 10^{-5}$ for each detected neutrino event. Hence, in order to make a meaningful detection, the rate of neutrino triggers should not exceed several hundred. The neutrino energy spectra expected from GRBs are significantly harder than that of atmospheric neutrinos. By demanding that the reconstructed muon energy is higher than a certain threshold energy, the number of atmospheric neutrino events can be reduced significantly. We have extended the simulation of [17] to include the GRB neutrino flux prediction of [9]. Assuming a muon energy resolution of $\sigma(\log E_\mu) = 0.4$, we find that about 50% (16%) of neutrino events would have a reconstructed energy larger than $10$ (100) TeV. Hence, taking into account the afterglow and neutrino detection probability, as well the fact that about 20% of the sky can not be observed due to the sun, every 5th (16th) GRB neutrino event could be identified as such, with about 93% (99.98%) confidence. With an expectation of about 10 events from GRB per year and hemisphere [9], this would lead to up to 2 GRB detections per year.

Note that for GRBs, unlike SNe, the rate is so low and the luminosity so high, that one samples through cosmological distances. The variations due to GRB distances have less dramatic consequences and as a result, the ratio of doublets to singlet neutrino detections will be smaller for GRBs. We will consider one specific calculation as an example. In [11], individual neutrino event rates where modeled for 579 long duration GRBs. For Model I, they obtain about 6 muon neutrino events per 1000 bursts for a cubic kilometer array. The expected rate of doublets for this sample is 0.3. Hence, taking into account the efficiencies discussed above, the rate of identifiable doublets will be observed at a rate a few times lower than singlets.

5 Discussions and Conclusions

As illustrated here, an optical follow-up of interesting events, either neutrinos of very high energy or neutrino multiplets ($n \geq 2$), would improve the perspective for neutrino detection from SNe and GRBs significantly.

The follow-up can be achieved with a rather modest observing program. Depending on the neutrino-trigger settings, a ToO would be issued several times a year (multiplet detections) up to several times a day (events with $E_\mu \geq 10$ TeV). In case of a detection of a transient object, lightcurves are constructed from repeated observations every few hours during the first night (to measure the afterglow) and then once a night for the next 10 days. Optical telescope with 1-2 meter apertures can acquire the needed signal-to-noise (5% flux error for a 20th magnitude point-source) within about one minute exposure time.
To reduce the number of pointings, the field of view (FoV) of the follow-up telescope should ideally match the resolution of the neutrino telescopes (∼ 1° for IceCube [1] and less than half that for large-scale water cherenkov detectors [25]). Such optical telescopes/instruments already exist and many more are being planned or constructed. For example, the ROTSE III network consists of four 0.45 meter robotic telescopes with a 1.85° × 1.85° FoV, which has been successfully operated since 2003. The MegaCAM camera on the CFHT 3.6 meter telescope, which is also in operation since 2003, has a FoV of 1° × 1°. With these telescopes, searches for orphan afterglows have already been performed and it was shown that the astrophysical background, e.g. due to variable stars, can be fully controlled [26,27].

For supernovae, the detection rate of neutrino transients would improve by a factor of ∼ 3 compared to the case without follow-up. For GRBs, which are sampled over large cosmological distance, the advantage might be even larger. In particular, the afterglow follow-up observations proposed here could become an important counterpart to the search for a correlation between a neutrino signal and gamma-ray bursts. Dedicated satellites, such as SWIFT [28], are very efficient in finding GRBs and allow for a reduction of the coincidence search time-window to the duration of the gamma-ray burst. However, limited sky coverage results in a reduced detection rate. With a FoV of 1.4 sr, the SWIFT satellite triggers on only every 9th GRB, while the neutrino-triggered optical follow-up, with the right trigger-settings, allows the detection of about every 5th neutrino producing GRB. Finally, there is the possibility of neutrino production in GRB afterglow flares [10]. Due to the effect of jet broadening, such GRBs might be more efficiently detected through their afterglow observations.

Perhaps as important as the gain in sensitivity is the acquired ability to identify the transient source of a neutrino burst, once it is detected with neutrinos. In this work we were guided by the phenomenology of GRBs and SNe. Yet, the optical lightcurves obtained from the follow-up observations of neutrino events might equally well lead to the discovery of other transient or variable sources of high-energy neutrinos.

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**References**

[1] J. Ahrens et al., Astropart. Phys. 20 (2004) 507.

[2] F. Halzen and D. Hooper, Rept. Prog. Phys. 65 (2002) 1025.
[3] E. Bernardini et al. 2005, Proc. of Workshop *Towards a Network of Atmospheric Cherenkov Detectors*, Palaiseau, France (2005), arXiv:astro-ph/0509396. E. Resconi, Proc. of *TeV Particle Astrophysics*, Madison, USA (2006).

[4] M. Bayer et al., Proc. of *TeV Particle Astrophysics*, Madison, USA (2006).

[5] K. Kuehn et al., in Proc 29th *Int. Cosmic Ray Conf.* (2005); M. Štamatikos ibid; B. Hughey, ibid; (see astro-ph/0509330).

[6] E. Waxman, Phys. Rev. Lett. 75 (1995) 386.

[7] M. Vietri, Astrophys. J., 883 (1995).

[8] E. Waxman and J. N. Bahcall, Phys. Rev. Lett. 78 (1997) 2292.

[9] E. Waxman and J. N. Bahcall, Phys. Rev. D 59 (1999) 023002.

[10] K. Murase and S. Nagataki, Phys. Rev. Lett. 97 (2006) 051101.

[11] D. Guetta, D. Hooper, J. Alvarez-Muniz, F. Halzen and E. Reuveni, Astropart. Phys. 20, (2004) 429; http://www.arcetri.astro.it/~dafne/grb/

[12] T. Le, & C.D. Dermer (2006), arXiv:astro-ph/0610043

[13] P. Meszaros and E. Waxman, Phys. Rev. Lett. 87 (2001) 171102.

[14] S. Razzaque, P. Meszaros and E. Waxman, Phys. Rev. Lett. 93 (2004) 181101. [Erratum-ibid. 94 (2005) 109903]; S. Razzaque, P. Meszaros and E. Waxman, Phys. Rev. D 68 (2003) 083001.

[15] S. Ando and J. F. Beacom, Phys. Rev. Lett. 95 (2005) 061103.

[16] S. Razzaque, P. Meszaros and E. Waxman, Mod. Phys. Lett. A 20 (2005) 2351.

[17] M. Kowalski, JCAP 0505 (2005) 010.

[18] T. Piran, Rev. Mod. Phys. 76 (2004) 1143.

[19] A. Conley, et al., Astrophys.J., 132 (2006) 1707.

[20] M. Stritzinger et al., Astrophys.J., 124 (2002) 2100.

[21] S. Ando, J. F. Beacom and H. Yuksel, Phys. Rev. Lett. 95 (2005) 171101.

[22] E. Cappellaro, R. Evans and M. Turatto, Astron. Astrophys. 351 (1999) 459.

[23] A. Gal-Yam et al., http://www.astro.caltech.edu/~avishay/nosweat.html

[24] F. Mannucci et al. Astron. Astrophys. 401 (2003) 519.

[25] Y. Becherini et al., Nucl. Instrum. Meth. A 567 (2006) 477; U. F. Katz, Nucl. Instrum. Meth. A 567 (2006) 457.

[26] E. S. Rykoff et al., Astrophys. J. 631 (2005) 1032.

[27] F. Malacrino et al. (2007), astro-ph/0701722

[28] S. D. Barthelmy, et al. Space Science Reviews 120 (2005) 143.