The starburst-GRB connection

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***Abstract*. As starburst galaxies show a star formation rate up to several hundred times larger than the one in a typical galaxy, the expected supernova rate is higher than average. This in turn implies a high rate of long gamma ray bursts (GRBs), which are extreme supernova events. We present a catalog of 127 local starburst galaxies with redshifts of $z < 0.03$. Using this catalog we investigate the possibility of detecting neutrinos from Gamma Ray Bursts from nearby starburst galaxies. We show that the rate of long GRBs is correlated to the supernova rate which in turn is correlated to the far infrared output. For the entire catalog, 0.03 GRB per year are expected to occur. The true number can even be higher since only the brightest sources were included in the catalog.**

***Keywords*: Starburst galaxies, GRBs, neutrinos**

I. INTRODUCTION

In our work [1] we present a systematic investigation of radiative emission from starburst galaxies. We explain there the correlation between radio emission and emission in the far infrared and high energy photons and neutrinos. In this contribution we will focus on the possibility to detect secondaries from gamma ray bursts in starburst galaxies. In section II the sample of 127 starburst galaxies used will be presented. Section III explains the connection between starburst galaxies and gamma ray bursts while section IV presents the neutrino spectrum for GRBs. Expected event rates in the IceCube detector for GRBs from nearby starburst galaxies are shown in sub section IV-A.

II. A LOCAL STARBURST SAMPLE

First a sample of 127 nearby starburst galaxies is seleected. For the data of the individual sources see [1] Appendix A. This is a local sample containing only sources with $z < 0.03$. The sources were selected from a larger catalog of starbursts which contained 309 sources. To ensure completeness of the sample, cuts in the radio flux as well as in the FIR flux were applied. To ensure that the selected sources were indeed starbursts, only sources with a high ratio of FIR flux and radio flux, $S_{60\mu}/S_{1.4\,\mathrm{GHz}} > 30$ were selected. $S_{60\mu}$ denotes the FIR flux density at $60\,\mu$m wavelength measured by the IRAS satellite, $S_{1.4\,\mathrm{GHz}}$ denotes the radio flux density at $1.4\,$GHz. This criterium removes possible contamination of the sample by Seyfert galaxies. The ratio is ~ 10 for Seyfert galaxies and ~ 300 for starbursts.

Further, luminosity cuts were applied. It was required that $S_{1.4\,\mathrm{GHz}} > 20\,\mathrm{mJy}$[1] and $S_{60\mu} > 4\,$Jy.

Figure 1a and figure 1b show the luminosity of the starburst galaxies versus their luminosity distance at $60\,\mu$m resp. at $1.4\,$GHz. The crosses represent all 309 starbursts that were selected in the beginning, the triangles show the remaining 127 sources after the cuts $S_{60\mu} > 4\,$Jy and $S_{1.4\,\mathrm{GHz}} > 20\,$mJy and $z < 0.03$. The dotted lines represent the sensitivity for $4\,$Jy and $20\,$mJy, respectively with those cuts applied, a complete, local sample in both wavelengths, FIR and radio is obtained. Since all sources in the sample have a redshift of $z < 0.03$, many of them are located in the super galactic plane. Therefore, the number of sources with a flux density larger than S, $N(> S)$ is expected to follow a powerlaw behavior of $S^{-1} - S^{-1.5}$. For a flat cylinder a pure S^{-1} behavior is expected while a spherical distribution results in an $S^{-1.5}$ behavior. Figure 2 shows the logarithmic number of sources above an FIR flux density $S_{60\mu}$. The data was fitted with the following function:

$$N(> S) = N_0 \cdot (S + S_0)^{-\beta} \tag{1}$$

Here, N_0, S_0 and β are the fit parameters. Using an error of $\sqrt{N}$, the parameters are determined to

$$
\begin{aligned}
N_0 &= 3155 \pm 1297.9 \\
S_0 &= (10.56 \pm 3.78)\,\mathrm{Jy} \\
\beta &= 1.2 \pm 0.2.
\end{aligned}
$$

The behavior $N(> S) \sim S^{-1.2\pm0.2}$ matches the expectation that the function should lie between $S^{-1.0}$ and $S^{-1.5}$.

The next section will explain the connection between starburst galaxies and gamma ray bursts which will result in a flux estimation for high energy neutrinos from GRBs inside starburst galaxies.

III. GAMMA RAY BURSTS AND STARBURSTS

Starburst galaxies show an enhanced rate of supernova explosions due to their large star formation rate. Thus an increasing rate of long Gamma Ray Bursts (GRBs) directly linked to SN-Ic events [2] is expected. If long GRBs are the dominant sources of UHECRs, the contribution from nearby objects should follow the distribution of starburst galaxies. In the following calculations, it is assumed that every SN-Ic explosion is accompanied by a particle jet along the former star's rotation axis, i.e. by

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[1] 1 Jansky (Jy) $= 10^{-26}\,\frac{\mathrm{W}}{\mathrm{Hz\cdot m}^2}$
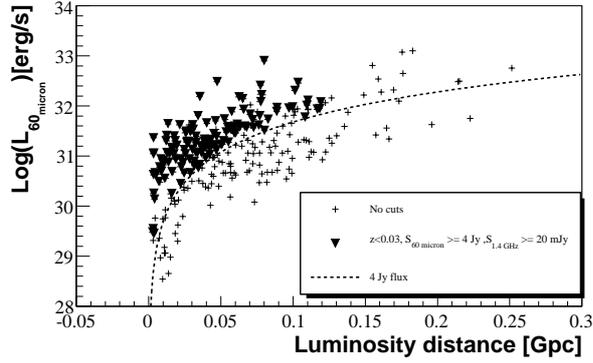
(a) Luminosity at $60\,\mu$m versus the luminosity distance
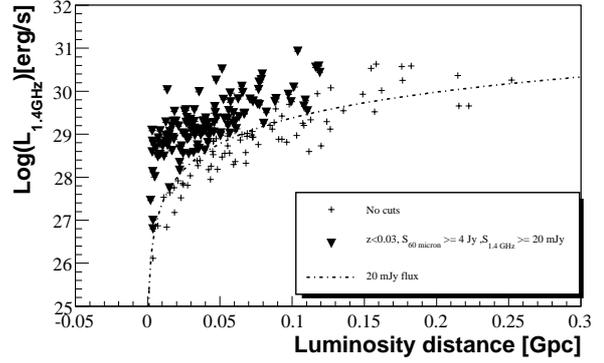
(b) Luminosity at $1.4\,$GHz versus the luminosity distance

Fig. 1.   Luminosity-distance diagrams. Crosses denote all 309 pre-selected starburst galaxies, triangles show the remaining after the cuts $S_{60\mu} > 4\,$Jy and $S_{1.4\,\mathrm{GHz}} > 20\,$mJy and $z < 0.03$. The dashed lines show the sensitivity for $S_{60\mu} = 4\,$Jy and $S_{1.4\,\mathrm{GHz}} = 20\,$mJy respectively.
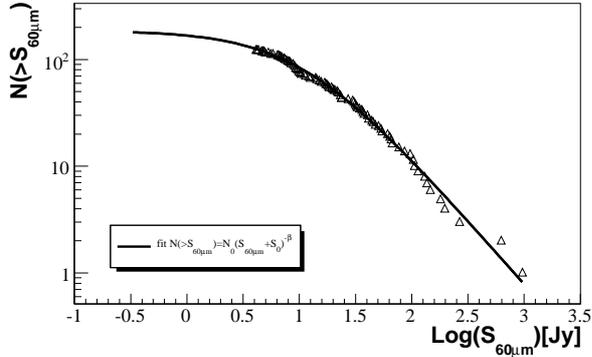

Fig. 2. $log(N) - log(S)$ representation of the catalog. An $S^{-1.2}$-fit matches the data nicely, with a turnover at $S_0 = 10.56\,$Jy.

a GRB. The opening angle of the GRB jet, θ determines, how many SN-Ic can be observed as GRBs, see e.g. [3], [4].

$$\dot{n}_{\mathrm{GRB}} = \epsilon \cdot \dot{n}_{\mathrm{SN-Ic}}. \qquad (2)$$

Here, $\dot{n}_{\mathrm{GRB}}$ is the GRB rate in a galaxy and $\epsilon = (1 - \cos(\theta))$ is the fraction of SN-Ic which can be seen as GRB. The opening angle is expected to be less than $\sim 10°$ for the prompt emission. Afterglow emissions and precursors can have a larger opening angles [5]. Putting the focus on prompt emission, an optimistic opening angle of $\sim 10°$ is used, yielding

$$\epsilon = 0.015. \qquad (3)$$

Further, observational data show that core collapse supernovae of type Ic contribute with 11% to the total supernovarate in starbursts [6]. Using equation 2 the GRB rate in a starburst galaxy is directly correlated to the supernova rate $\dot{n}_{SN}$,

$$\dot{n}_{\mathrm{GRB}} = \epsilon \cdot \xi \cdot \dot{n}_{\mathrm{SN}} \qquad (4)$$

with $\xi \sim 0.11$ as the fraction of heavy SN among all SN. The supernova rate is correlated with the FIR luminosity of the galaxy [7],

$$\dot{n}_{\mathrm{SN}} = (2.4 \pm 0.1) \cdot 10^{-12} \cdot \left(\frac{L_{\mathrm{FIR}}}{L_{\odot}} \right) \, \mathrm{yr}^{-1}. \qquad (5)$$

The FIR luminosity is expressed in terms of the solar luminosity $L_{\odot} = 3.839 \cdot 10^{33}$ergs and is given in the range of $60\,\mu$m and $100\,\mu$m by [8]

$$L_{\mathrm{FIR}} = 4\pi d_l^2 \cdot F_{\mathrm{FIR}}. \qquad (6)$$

Here, d_l is the luminosity distance of the individual source and

$$F_{\mathrm{FIR}} = 1.26 \cdot 10^{-14} \cdot \left(2.58 \cdot S_{60/\mu} + S_{100\mu} \right) \, \mathrm{W\,m}^2 \qquad (7)$$

is the FIR flux density as defined in [9]. $S_{60\mu}$ and $S_{100\mu}$ are the measured flux densities at $60\,\mu$m and $100\,\mu$m, both measured in Jy. Using equation 5 to determine the supernova rate, equation 4 yields a rate of

$$\dot{n}_{\mathrm{GRB}} = 3.8 \cdot 10^{-15} \cdot \left(\frac{L_{\mathrm{FIR}}}{L_{\odot}} \right) \cdot \left(\frac{\epsilon}{0.015} \right) \cdot \left(\frac{\xi}{0.11} \right) \, \mathrm{yr}^{-1} \qquad (8)$$

per starburst. For a $1\,\mathrm{km}^3$ neutrino detector with a lifetime of 10 years (like IceCube or KM3NeT) luminosities of around $3 \cdot 10^{13} \cdot L_{\odot} \sim 10^{47}$ ergs are required for a single event within these 10 years. None of the sources in the catalog provides such a high luminosity. However, if a larger number of starburst is considered for an analysis, the total luminosity increases and so does the probability of observing a GRB. Figure 3 shows the total GRB rate for a number of $N_{\mathrm{starbursts}}$ galaxies,

$$\dot{n}_{\mathrm{GRB}}^{\mathrm{tot}}(N_{\mathrm{starbursts}}) = \sum_{i=1}^{N_{\mathrm{starbursts}}} \dot{n}_{\mathrm{GRB}}(i\text{th starburst}). \qquad (9)$$

In the figure the GRB rates achieved in the single starbursts are summed up, starting with the most luminous source, adding sources in descending luminosity order. The points show the GRB rate summing up over all starbursts in the sample, starting with the strongest one
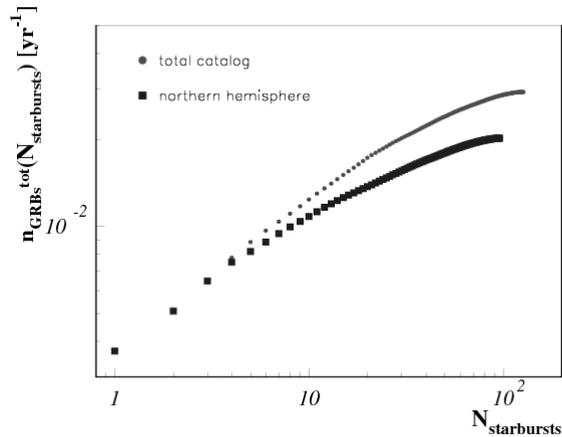
Fig. 3. Number of GRBs per year in the starburst catalog, including $N_{starbursts}$ sources, starting with the strongest one. The total GRB rate in the sample, including all 127 sources is $0.03\,\mathrm{yr}^{-1}$, this means that a GRB could be observed every 30 years on average. The total GRB rate just in the northern hemisphere is $0.02\,\mathrm{yr}^{-1}$ or an occurrence every 50 years, the data shown in squares. These source lie in IceCube's FoV.

and adding the next strongest sources subsequently. On total, 0.03 GRBs per year are expected to be observable in the sample. The squares display the total GRB rate, summing up sources in the northern hemisphere, which corresponds to IceCube's Field of View (FoV). Here, 0.02 GRBs per year are expected. This number can be enhanced significantly when taking weaker sources into account which were not included in the sample in order to ensure completeness, see section II.

IV. ENHANCED NEUTRINO FLUX FROM GRBs IN STARBURSTS

Due to the high atmospheric background seen by high-energy neutrino telescopes, the detection of a diffuse neutrino signal from GRBs in nearby starbursts will not be possible. However, with a timing analysis one might be able to identify Gamma Ray Bursts in neutrinos. In such an analysis, the location of a nearby starburst can be chosen as a potential neutrino hot-spot. By selecting a time window of the typical duration of a long GRB ($\sim 100\,\mathrm{s}$) the atmospheric background can then be reduced to close to zero. In this context the general neutrino intensity and in particular the possibility of neutrino detection with IceCube are discussed.

For the first time the neutrino energy spectrum during the prompt photon emission phase in a GRB was determined by Waxman&Bahcall [10], [11] and can be expressed as

$$\frac{dN_\nu}{dE_\nu} = A_\nu \cdot E_\nu^{-2} \cdot \begin{cases} E_\nu^{-\alpha_\nu+2} \cdot \epsilon_\nu^{b\,\alpha_\nu-\beta_\nu} & , E_\nu < \epsilon_\nu^b \\ E_\nu^{-\beta_\nu+2} & , \epsilon_\nu^b < E_\nu \le \epsilon_\nu^S \\ \epsilon_\nu^S \cdot E_\nu^{-\beta_\nu+1} & , E_\nu > \epsilon_\nu^S \end{cases}$$

(10)

The spectrum includes two spectral íodices, α_ν and β_ν, two break energies, ϵ_ν^b and ϵ_ν^S and a normalization factor A_ν. For the GRBs in starbursts, these parameters were

discussed in detail in [1]. Their numerical values were determined to

$$\begin{aligned} \alpha_\nu &= 1 \\ \beta_\nu &= 2 \\ \epsilon_\nu^b &\approx 3 \cdot 10^6\,\mathrm{GeV} \\ \epsilon_\nu^S &\approx 3 \cdot 10^7\,\mathrm{GeV} \\ A_\nu &\propto d_l^{-2} \end{aligned}$$

The normalization constant A_ν is calculated for each individual source. It depends on d_l^{-2} as well as on the fraction of energy transferred into electrons and the fraction of energy transferred into charged pions. In addition, the normalization of the neutrino spectrum scales with the luminosity of the burst. This released energy varies from burst to burst. In addition to this burst-to-burst fluctuation, regular GRBs are distinguished from low-luminosity bursts. Regular, long bursts emit a total isotropic energy of $10^{52}\,\mathrm{erg}$ for a duration (t_{90}) of the burst of $\approx 10\,\mathrm{s}$. Low-luminosity bursts last longer and and have a lower luminosity. Although only few low-luminosity bursts are observed yet, they are expected to be much more frequent than regular GRBs. For this class, we expect an energy release of $\sim 10^{50}\,\mathrm{erg}$ within around 1000 s. The closest burst observed so far was GRB980425, which was found to be associated with the supernova SN1998bw [12]. The host galaxy lies at a redshift of only $z = 0.0085$. This burst shows a total energy release of $\sim 10^{47}\,\mathrm{erg}$, which is an extremely low-luminosity burst. As the luminosity distribution is not well-known at this point, due to low statistics, we use a fixed value of $10^{51}\,\mathrm{erg}$. An actual burst can be about one order of magnitude more or less luminous. Now, to estimate the neutrino flux from a standard GRB for a single starburst in the sample, dependent on the distance of the starburst, the normalization is calculated. The other parameters are kept constant and hence the results can only serve as a rough estimate. Both, the break energies as well as the spectral indices vary for each individual burst as described in [13].

A. Expected event rates in IceCube

As shown in figure 3, 0.02 GRBs per year are expected to occur in the 96 starbursts in the sample in the northern hemisphere, IceCube's FoV. However, this rate can be enhanced if all sources in the northern hemisphere would be taken into account. For completeness reasons only the brightest ones were considered here. This enhances the possibility to detect a GRB from a starburst in the super galactic plane within the lifetime (10 years) of IceCube. The prospects for KM3NeT are slightly worse, since only 0.01 GRB per year is expected in the southern hemisphere, where KM3NeT's FoV will be focused.

The number of events per GRB expected in IceCube can be calculated by folding IceCube's effective area
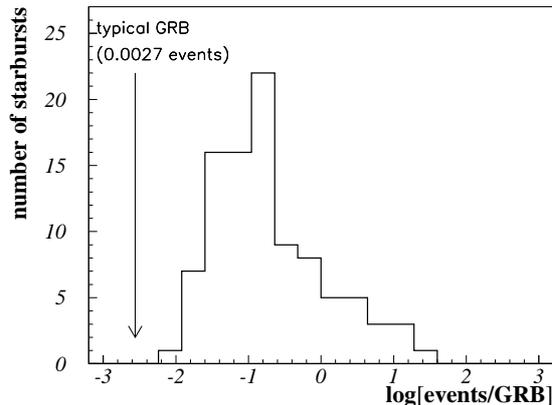
Fig. 4. Histogram of the number of events in IceCube from the 96 starburst galaxies in the northern hemisphere. Depending on the distance of the starburst, a burst would result in between 0.1 and several 100 events in IceCube in a small time window of $10 - 100$ seconds. A regular burst at $z \sim 1 - 2$ gives only 0.027 events as indicated in the figure. The main reason for the increased signal is that the bursts would come from starbursts closer than $z = 0.03$.

A_{eff} [14] with the GRB spectrum dN_ν/dE_ν

$$N_{\text{events}} = \int_{E_{\text{th}}}^{\infty} A_{\text{eff}}(E_\nu) \cdot \frac{dN_\nu}{dE_\nu}\, dE_\nu \qquad (11)$$

Here, the weak dependence of the A_{eff} from the declination of the burst is neglected. For the threshold energy $E_{\text{th}} = 100\,\text{GeV}$ is used. This is the general detection threshold of IceCube [15]. Since events can be selected in a small time window with the typical duration of a long GRB, $10 - 100\,\text{s}$, the atmospheric background can be reduced close to zero. Figure 4 shows the histogram of the numbers of events expected in IceCube from an average GRB with an isotropic energy of $E_\gamma^{\text{iso}} = 10^{51}$ erg from the 96 starbursts in the sample. These numbers range from 0.1 to about 300 events per burst, depending on the distance of its host galaxy. These numbers lie between 1 and 5 orders of magnitude above the numbers of events for GRBs typically observed by satellite experiments like Swift, BATSE and Fermi. If such GRB occurs in our sample of starburst galaxies it is a unique opportunity to study the hadronic component of GRBs.

V. CONCLUSIONS AND OUTLOOK

A sample of 127 nearby starburst galaxies has been presented, where we selected sources with $z < 0.03$ and radio (FIR) luminosities above $S_{60\mu} > 4\,\text{Jy}$ and $S_{1.4\,\text{GHz}} > 20\,\text{mJy}$.

The expected event rates for high energy neutrinos in the IceCube detector have been calculated to reach up to more than 100 events per year. If a GRB occurs in one of the 127 starbursts, for detectors with a wide field of view the detection probability is best. IceCube should be able to see the strongest events (~ 100 neutrinos) immediatly, while the weaker events ($\sim 5-10$ neutrinos) can be found in a specific analysis for the selected starbursts. Since most of the sources are located in the northern hemisphere, detectors like IceCube, HAWC and Auger north are optimal for such a study. A detection of neutrinos from a GRB would enable detailed studies of hadronic emission processes of GRBs.

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