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High Energy neutrino signals from the First Stars

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Abstract. We perform a new estimate of the high energy neutrinos expected from GRBs associated with the first generation of stars in light of new models and constraints on the epoch of reionization and a more detailed evaluation of the neutrino emission yields. In disagreement with most optimistic results in previous literature, we find that high energy neutrinos from Population III stars will not be observable with current or near future neutrino telescopes. This rules them out as a viable diagnostic tool for these still elusive metal-free stars. We also perform an estimate of the flux at Earth of neutrinos from Dark Matter annihilation in the recently proposed "Dark Stars" obtaining equally negative results; in particular the very low peak-energies of this flux buries it several orders of magnitude below the atmospheric ones. Similar considerations (with different backgrounds) apply to the gamma-ray background by DM annihilation.

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POPULATION 3 STARS AND GRBS

Gamma Ray Bursts are believed to be associated to the explosion of massive stars, and be caused by the formation of an accretion disk around the central Black Hole left from the stellar collapse, if any. Although there is not full agreement on the exact mass range Population III stars are widely thought to be massive; it is reasonable to expect that the relative GRB rate within Population III is higher than within younger population of stars. In the current "internal shock" models for GRBs, neutrinos are produced by the decay of pions and kaons, which are the products of photomeson interactions of the accelerated protons with gamma-rays, or via hadronic (proton-proton) interactions. It is accepted that if such models are correct a diffuse high energy neutrino flux at Earth, due to the continuous contribution of GRBs at different redshifts, should be present. Present works in literature support the idea that, for some zones of the parameter space for the astrophysical model, the diffuse high energy neutrino flux from GRBs associated with Population III stars only, should have clear characteristic features. This would make them clearly detectable and potentially discriminated from neutrino telescopes as AMANDA or IceCube, thus carrying information on the Population III. We show that even under maximal assumptions, within the limit of the currently accepted astropohysical models, the HE neutrino flux from Population III stars falls underneath the IceCube sensitivity, is subdominant with respect to the "standard" diffuse flux from PopII GRBs, and is overwhelmed by atmospheric neutrinos.

GRB rates

Any signature of neutrinos from PopIII GRBs should have to be discriminated from the other fluxes, in particular from its "direct competitor" the PopII GRB flux. Therefore to estimate the GRB neutrino fluxes we will adopt mutually consistent Stellar Formation Rates (SFR) for the two populations. Namely, we use the recent papers [1, 2], in which the authors perform self-consistent calculations which take into account the current observational bounds on Reionization, implementing three different sources of radiation (PopII, PopIII and Quasi Stellar Objects) and the relative feedbacks. SFRs are obtained for different parameter sets and we use the PopII and PopIII ones for our calculations under assumptions about the Initial Mass functions (IMF) of the two populations. Consistently with the assumptions of the original model we in fact adopt a Salpeter mass function, $S(m)$, for PopII and a delta-like IMF peaked at $300\mathrm{M}_\odot$ for PopIII; we also explore the case of an hypothetical low-mass Population III by implementing a Salpeter in one of the models.

An analytical expression for the energy flux in neutrinos expected at Earth, at a neutrino energy E_ν reads:

$$E_\nu^2\Phi_\nu = \frac{c\,b}{4\pi}\int \mathrm{d}z\frac{J_\nu[E_\nu(1+z)]\,G(z)}{(1+z)^2H(z)}. \qquad (1)$$

where $J_\nu[E(1+z)]$ is the average energy spectrum in neutrinos for a GRB expressed in the energy in its cosmological reference frame E'=$E_\nu(1+z)$, $H(z)$ is the Hubble function, $G(z)$ is the comoving GRB rate and b is a geometrical "beaming" factor which is used to estimate the fraction of GRBs pointing towards us.

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In order to obtain the GRB rate, G, from the SFR, R, it is necessary to take into account the fraction of Supernovae within the population, σ, and the fraction of GRBs with respect to the Supernovae, γ.

This can be summarized, in our formalism, as:

$$G_i(z) = \sigma_i \gamma_i \frac{R_i(z)}{M_i}, \tag{2}$$

where the index i runs over the two different populations, and M is the average stellar mass of the population.

For PopII we have followed "standard" prescriptions and estimated σ_{II} and γ_{II} assuming that all stars with mass $m > 10 M_\odot$ will end up in Core Collapse Supernovae and adopted, after [7] and [6] the following expression for γ_{II}:

$$\gamma_{II}(z) = \frac{(1+z)^{1.4}}{1250}, \tag{3}$$

where the redshift dependence at the numerator summarizes the correlation of GRBs rate with metallicity, and we have kept it constant for $z > 7$, thus taking into accounting for no metallicity evolution beyond that redshift. For more details we address the reader to our paper [5]. For PopIII stars, by following the assumption of a "monochromatic" generation of stars, with $M=300 M_\odot$, we assume $\sigma_{III}=1$ and, lacking any firm estimate for γ_{III}, we have assumed $\gamma_{III}=1$.

GRB neutrino spectra

In order to estimate the neutrino contribution from a single GRB it is necessary to compute the reactions taking place when the internal shock hits along the star while expanding its way out of it. The neutrino emission does hence depend on a whole set of parameters, among the most relevant are the total energy released in the jet, E_{jet} (or the isotropic equivalent E_{iso}), the angular opening of the jet, which can be summarized by the average geometrical factor b, the radius at which the internal shock is formed r_{is}, the non-thermal baryon loading factor ξ_{acc}. All these paramaters depend on the final mass of the star, its density profile a the moment of the jet propagation, the fraction of energy which goes into the magnetic field but so far the estimates allowed from theory are still very uncertain. In these proceedings we present results for our maximal model among the ones studied in [5]; namely a burst with a $E_{jet}=10^{52}$ ($b=10^{-2}$) and $\xi_{acc}=10$ has been considered our average "GRB candle" for the neutrino spectra J_ν. These are extreme choices for the parameters and can therefore regarded as an upper limit to the neutrino flux, thus making our estimate and of the flux at Earth, together with the choice of a maximal GRB rate, an absolute upper limit

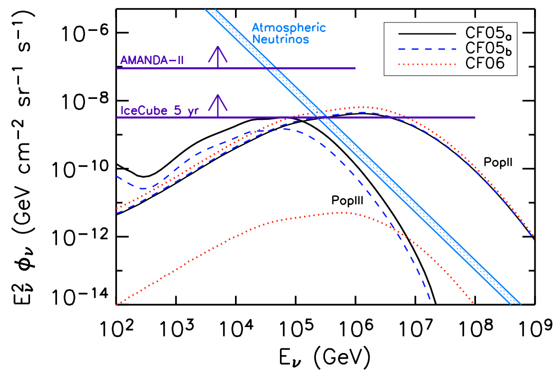

FIGURE 1. The diffuse GRB neutrino fluxes at Earth from PopII and PopIII, from different Reionization models, as from text.

within the current astrophysical models. For PopII, and for the Salpeter PopIII implemented in [2] we adopt instead a more likely neutrino spectrum, using the parameters $E_{jet}=1.24\times10^{51}$ ($b=1.24\times10^{-2}$). These more likely parameters, together with the assumptions performed in order to obtain the GRB rate, make the diffuse neutrino spectra from PopII a sound estimate, in agreement with existing literature [8]. For more details and discussion about the GRB models we address the reader to the paper [5]. In Figure 1 we show the diffuse neutrino fluxes at Earth expected under the assumptions described so far. For each reionization model, $CF05_a$, $CF05_b$ we show the contribution expected from PopII and a massive Population III, while for CF06 we show the contribution expected from PopII and a Salpeter PopII[1]. On the plot we have also shown the current AMANDA sensitivity, the expected five years one for IceCube, and the most up to date prediction for the atmospheric neutrinos [3]. It is straightforward to notice that high energy neutrinos from GRBs associated to PopIII stars are not likely to be observed: as already stated, the curves belonging to PopIII must be seen as an absolute upper limit within the current astrophysical scenarios; even so the flux falls below the IceCube sensitivity. Even worse, it is overwhelmed by the PopII and hidden beneath the atmospheric ones, thus proving high energy neutrinos not to be a viable diagnostic tool for Population III stars. Equally negative conditions apply to low energy neutrinos from Core Collapse, nuclear and thermal processes, as shown in [4].

[1] A massive CF06 PopIII gives a spectrum almost indistinguishable from $CF05_b$; the same plotted curve would be obtained for a Salpeter PopIII in $CF05_b$, conversely.

HIGH ENERGY NEUTRINOS FROM "DARK STARS"

It has been recently proposed in [9, 10], and lively discussed during this conference, that the cooling of the baryonic cloud could be dramatically altered from Dark Matter annihilation. The heating from gamma-rays produced by such annihilation could dominate over the cooling under some conditions of the cloud, and in some regions of the DM parameter space; this would lead to a slow-down and an eventual stop of the collapse of the cloud and subsequent stellar formation: the whole baryonic cloud could be supported against gravitational collapse by the DM annihilation itself. The model presented so far is only semianalitical and this scenario definitely deserves more study, expecially by means of simulations, and we address the reader to the original papers for more details about the physics and most of the calculations. We calculate the neutrino flux at Earth that should be expected by the DM annihilation, which has been suggested in as a possible signature of the process described.

In this case the "Halo Rate" replaces the expression $b \times G(z)$ in Eq. 1, since we are assuming that a single PopIII star forms per halo. For illustrative purposes, we consider the case of a WIMP of mass m_χ=100GeV and adopt the appropriate cross section for a s-wave annihilating thermal relic, leading to a rate $\langle\sigma v\rangle$=3×10^{-26} cm^{3}s^{-1}, required to match the observed dark matter abundance. According to [9], in this case the the DM heating starts dominating over the cooling when the baryonic density gets as high as $n \approx 10^{-13}$cm^{-3} and the size of the baryonic core is $R_b \approx$17 AU. Assuming the baryonic density constant over the entire volume, we can thus estimate an energy production rate of $Q_{ann} \approx 10^{35}$erg s^{-1}. If the whole structure lasted for the DM annihilation scale ($\tau_{DM} \approx$600 Myr, for our choice of parameters) the total energy released would be $E_{DS} \approx 10^{52}$erg.

The most optimistic number flux of neutrinos (or gammas, if the baryonic halo is not opaque to them) is obtained in the unrealistic case where the only annihilation channel is $\chi\chi \to \nu\bar{\nu}$ (or $\chi\chi \to \gamma\gamma$) which at a given redshift would produce a monochromatic line at E_χ=m_χ=100GeV. In Fig 2 we compare the flux thus obtained with the atmospheric neutrino flux [3] and the unresolved gamma-ray background [11]. As clearly shown, even this upper limit falls below the level of fluxes which one can hope to probe.

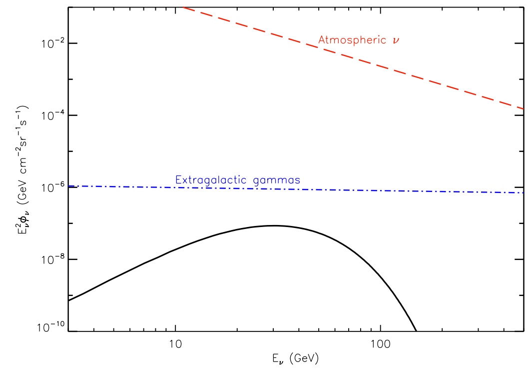

FIGURE 2. Diffuse flux at Earth from "Dark Stars" DM annihiliation process obtained with a generic, order of magnitude estimate, average spectrum at the source.

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