Gamma-ray burst as a probe for the high-z Universe

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X-RAY EVENTS

Part 1

- Semi-analytical estimative of the Pop III star formation rate
- Redshift distribution of Pop III Gamma-ray bursts
- Radio afterglows
- Upper limits from radio transients survey
- Expected rate by present and future missions
LOOKING FOR ORPHAN AFTERGLOWS

- Predicted number of orphans
- Afterglow model
- Mock sample
- GAIA mission
STAR FORMATION HISTORY FROM GAMMA-RAY BURSTS

- How to estimate the star formation history up to high z from current observations?
- GRBs as a probe for SFH
- Principal Component Analysis
- Swift dataset.
The first stars in the Universe played a crucial role in the early cosmic evolution, by emitting the first light and producing the first heavy elements.

The first stars are probably responsible for reionization of the Universe.

Observations of Gamma ray bursts are probably the only way to probe the death of first stars.
TWO METAL FREE POPULATIONS

Pop III.1 the first generation of metal free stars that formed from initial conditions determined cosmologically (no astrophysical feedback).

Pop III.2 zero-metallicity stars that formed from a primordial gas, but were affected by radiation from other stars. Typically are formed in initially ionized gas.
GAMMA-RAY BURST RATE

We assume that the formation rate of GRBs is proportional to the star formation rate (Totani 1997; Ishida et al. 2011). The number of observable GRBs per comoving volume per time is expressed as

\[ \Psi_{GRB}^{obs}(z) = \frac{\Omega_{obs}}{4\pi} \eta_{GRB} \eta_{beam} \Psi_{*}(z) \int_{\log L_{lim}(z)}^{\infty} p(L) d \log L, \]

The intrinsic GRB rate is given by

\[ \Psi_{GRB}(z) = \eta_{GRB} \Psi_{*}(z). \]
THE NUMBER OF COLLAPSED OBJECTS

Assuming that stars are formed in collapsed dark matter haloes, we adopt the Sheth- Tormen mass function, $f_{ST}$, (Sheth & Tormen 1999) to estimate the number of dark matter haloes, $n_{ST}(M,z)$, with mass less than $M$ per comoving volume at a given redshift:

$$f_{ST} = A \sqrt{\frac{2a_1}{\pi}} \left[ 1 + \left( \frac{\sigma^2}{a_1 \delta_c^2} \right)^p \right] \frac{\delta_c}{\sigma} \exp \left[ -\frac{a_1 \delta_c^2}{2\sigma^2} \right]$$

$$f_{ST} = \frac{M}{\rho_m} \frac{dn_{ST}(M, z)}{d \ln \sigma^{-1}}$$

$$\sigma^2(M, z) = \frac{b^2(z)}{2\pi^2} \int_0^{\infty} k^2 P(k) W^2(k, M) dk$$

CAMB code [http://camb.info/](http://camb.info/)
SFR follows the number of collapsed objects unless for a couple of feedbacks.

- Radiative Feedback, prevents the collapse
- Reionization, switches from Pop III.1 to III.2
- Metal Enrichment, switches from Pop III to Pop II/I
RADIATIVE FEEDBACK

The star formation efficiency in the early Universe largely depends on the ability of a primordial gas to cool and condense. Hydrogen molecules (H2) are the primary coolant in a gas in small mass “minihaloes”. H2 are also fragile to soft ultra-violet radiation, and thus a ultra-violet background in the Lyman-Werner (LW) bands can easily suppress star formation inside minihaloes.

Minimum mass able to collapse in the presence of LW background

\[ M_{\text{Min-H}_2} = \exp \left( \frac{f_{\text{cd}}}{0.06} \right) \left( 1.25 \times 10^5 + 8.7 \times 10^5 F_{\text{LW}, -21}^{0.47} \right), \]

**LW flux**

\[ J_{\text{LW}} = \frac{hc}{4\pi m_H} \eta_{\text{LW}} \rho_*(z)(1 + z)^3 \]
is the baryonic mass fraction. For the star formation efficiency, similar properties to Pop III.2 stars. We assume that virialization, and thus the formation rate of metals via galactic winds (see Sect. 2.4), terminated according to our definition. The formation rate of Q\_\text{H\_II} is calculated to account for the evolution of ionization fraction (\frac{dQ_{\text{H\_II}}}{dt} = \frac{N_{\text{ion}}}{0.76} \frac{dF_{\text{col}}}{dt} - C \frac{\alpha_B}{a^3} \bar{n}_H^0 Q_{\text{H\_II}}.

F(z', z) = -\frac{2}{3} \frac{\alpha_B n_0^H}{\sqrt{\Omega_m} H_0} C [f(z') - f(z)],

f(z) = \sqrt{(1 + z)^3 + \frac{1 - \Omega_m}{\Omega_m}}.

Neutral Hydrogen

\begin{itemize}
  \item \(z \sim 30\)
    \begin{itemize}
      \item First stars form
      \item \(H_2\) dissociates
    \end{itemize}
  \item \(z \sim 15\)
    \begin{itemize}
      \item Stars form in more massive halos
    \end{itemize}
  \item \(z \sim 10\)
    \begin{itemize}
      \item HII regions overlap
      \item UV intensity rises
    \end{itemize}
\end{itemize}

\(T_{\text{vir}} < 10^4 \text{ K}\)

\(T_{\text{vir}} > 10^4 \text{ K}\)
CHEMICAL ENRICHMENT

Define when the star formation switches from the Pop III to Pop II/I
Main contribution comes from galactic metal enriched winds

\[ R_{\text{wind}} = \int_{z_*}^{z} v_{\text{wind}} (1 + z') \frac{dt}{dz'} dz'. \]

The fraction of cosmic volume enriched by the winds can then be written as

\[ \zeta(z, v_{\text{wind}}) = \frac{1}{\rho_m} \int dM f_b f_* f_{\text{chem}}(M, z, v_{\text{wind}}) M n_{\text{ST}}(M, z). \]

\[ f_{\text{chem}}(M, z, v_{\text{wind}}) = \frac{4\pi R_{\text{wind}}^3}{3 V_H}, \]
Star formation history of Pop III stars

We compare the star formation rates for Pop III.1 and Pop III.2 with different values of $z$ (red and blue lines, respectively). This model provides an "optimistic" estimate for the Pop III.1 star formation rate for weak and strong chemical feedback models and a moderate star formation rate for three different values of $z$:

1. $z = 0.001$
2. $z = 0.01$
3. $z = 0.1$

We also compare the Pop III.2 SFR history with a compilation of independent measures from different works:

- BL06
- TS09
- Mod Op
- T07

For Pop III.1, the star formation rate is moderate with $z = 0.1$ and long-lived with $z = 0.01$. For Pop III.2, the star formation rates are low and have a distribution of 30 km/s, 50 km/s, 100 km/s, and 75 km/s.

We also consider the impact of metal enrichment on the star formation history. The fraction of cosmic volume enriched by the cosmic gas at different cosmic scales is shown.

We compare the Pop III.1 star formation rate with weak and strong chemical feedback models and a moderate star formation rate for three different values of $z$.

For Pop III.2, the star formation rate is low with $z = 0.001$ and has a distribution of 30 km/s, 50 km/s, 100 km/s, and 75 km/s.

We also consider the impact of metal enrichment on the star formation history. The fraction of cosmic volume enriched by the cosmic gas at different cosmic scales is shown.

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OBSERVED GAMMA RAY BURST RATE

\[
\Psi_{GRB}^{obs}(z) = \frac{\Omega_{obs}}{4\pi} \eta_{GRB} \eta_{beam} \Psi_\star(z) \int_{L_{lim}(z)}^{\infty} p(L)dL,
\]

- \(\Omega_{obs}\) is the field of view of the experiment
- \(\eta_{GRB}\) is GRB formation efficiency
- \(\eta_{beam}\) is the beaming factor of the burst
- \(\Psi_\star\) is the cosmic star formation rate (SFR) density
- \(p(L)\) is the GRB luminosity function
INITIAL MASS FUNCTION AND GRB EFFICIENCY

\[ \phi(m) \propto m^{-2.35} \]

\[ \phi(m)m \, dm = \frac{1}{\sqrt{2\pi\sigma_c}} e^{-\frac{(m-\bar{M})^2}{2\sigma_c^2}} \, dm \]

\[ \eta_{\text{GRB}} = f_{\text{GRB}} \frac{\int_{M_{\text{GRB}}}^{M_{\text{up}}} \phi(m) \, dm}{\int_{M_{\text{low}}}^{M_{\text{up}}} m\phi(m) \, dm} \]

- \( \phi(m) \propto m^{-2.35} \) \text{ Salpeter}
- \[ \frac{1}{\sqrt{2\pi\sigma_c}} e^{-\frac{(m-\bar{M})^2}{2\sigma_c^2}} \, dm \] \text{ Gaussian}
- \[ \int_{M_{\text{GRB}}}^{M_{\text{up}}} \phi(m) \, dm \] \text{ GRB efficiency formation rate}
REDSHIFT DISTRIBUTION OF GRBs

\[ \frac{dN_{\text{GRB}}}{dz} = \Psi_{\text{GRB}}(z) \frac{\Delta t_{\text{obs}}}{1+z} \frac{dV}{dz}. \]

Pop III.1

Pop III.2

Optimistic case

Pop III.2

Pop III.1
ORPHAN AFTERGLOWS

As the GRB jet sweeps the interstellar medium, the Lorentz factor of the jet is decelerated. When the Lorentz factor drops below $\theta^{-1}$, the jet starts to expand sideways and becomes detectable by the off-axis observers. These afterglows are not associated with the prompt GRB emission. Even if the prompt emission is highly collimated, the Lorentz factor drops $\gamma_d < \theta^{-1}$ around the time

$$t_\theta \sim 2.14 \left( \frac{E_{\text{iso}}}{5 \times 10^{54}} \right)^{1/3} \left( \frac{\theta}{0.1} \right)^{8/3} n^{-1/3} (1 + z) \text{ days}$$

and the jet starts to expand sideways. Finally the shock velocity becomes nonrelativistic around the time

$$t_{\text{NR}} \sim 1.85 \times 10^2 \left( \frac{E_{\text{iso}}}{5 \times 10^{54}} \right)^{1/3} \left( \frac{\theta}{0.1} \right)^{2/3} n^{-1/3} (1 + z) \text{ days}$$
Radio Afterglow light curve

![Graph of Radio Afterglow light curve showing emission at 10 GHz, 1.4 GHz, 500 MHz, ALMA, EVLA, LOFAR, and SKA. The graph plots the flux density (F in mJy) against time (t in days). The ordinate shows a logarithmic scale from $10^{-4}$ to 1, and the abscissa shows a logarithmic scale from 0.1 to $10^5$ days. Different lines represent emissions at various frequencies and telescopes.]
Fig. 4.— Transient surface density from this and other surveys as a function of flux density. Result from this survey is labeled 3C 286. Curves and lines indicate detected values and upper limits from a deep VLA search (B07, B07.1, B07.2; Bower et al. 2007), the comparison of the 1.4 GHz NVSS and FIRST surveys (G06; Gal-Yam et al. 2006), from additional VLA searches (C03 and F03; Carilli et al. 2003; Frail et al. 2003), from the first and second ATATS papers (ATATS-I and ATATS-II; Croft et al. 2010b,a), from the first data release of PiGSS (PiGSS-I; Bower et al. 2010), from the Matsumura et al. (M09; 2009) survey, and from the MOST search (Bannister et al. 2010). The dashed line is proportional to $S^{-1.5}$ and is normalized to B07 estimates. Lines with arrows indicate 1σ upper limits; otherwise the results are indicative of detected transients (B07, MOST, and M09).
Theoretical predicted rate

Predicted Pop III.1 observed GRB rate. Those observed by Swift, dashed red line; SVOM, dot-dashed black line; JANUS, dotted blue line; and EXIST, green line. We adopt a GRB rate model that is consistent with the current upper limits from the radio transients; Gaussian IMF, $v_{\text{wind}} = 50 \text{ km s}^{-1}$, $f^* = 0.1, f_{\text{GRB}} = 0.1$.

Predicted Pop III.2 observed GRB rate. Those observed by Swift, dashed red line; SVOM, dot-dashed black line; JANUS, dotted blue line; and EXIST, green line; for our model with Salpeter IMF, $v_{\text{wind}} = 100 \text{ km s}^{-1}, f^* = 0.01, f_{\text{GRB}} = 0.01$. 
Upper limits for the observed GRB rate of EXIST satellite

![Graph showing the observed GRB rate for Pop III.1 and Pop III.2](image)

- Pop III.2
- Pop III.1

The graph plots the observed GRB rate (yr⁻¹) against redshift (z). The black line represents the observed rate for Pop III.1, while the dashed line represents Pop III.2. The limits are calculated using the current surveys and acknowledge the uncertainties in the final mass distribution of the formed stars. The figure is based on recent predictions by Fryer & Heger (2005) and A&A 533, A32 (2011).
REMARKS

- We follow a recent suggestion that massive Pop III stars could trigger collapsar gamma-ray bursts. Observations of such energetic GRBs at very high redshifts will be a unique probe of the high redshift Universe.

- Using a semi-analytical approach we estimate for the first time the star formation rate for Pop III.1 and III.2 stars including all relevant feedback effects: photodissociation, reionization and metal enrichment.

- Orphan afterglows are a natural prediction of GRB jets. Using radio transient sources we are able to derive constraints on the intrinsic rate of GRBs. We estimate the predicted GRB rate for both Pop III.1 and Pop III.2 stars, and argue that the latter is more likely to be observed with future experiments. We expect to observe maximum of $N < 6$ GRBs per year at $z > 6$ for Pop III.2 and $N < 0.01$ per year for Pop III.1 at $z > 10$ with EXIST.
One type of possible transients to be detected by Gaia are gamma-ray burst optical afterglows.

We calculate the Pop III GRB orphan afterglows rate detectable by GAIA.

We make use of a star formation rate derived by a semi-analytical approach to predict the GRBs cumulative number. The orphan afterglows events are generated by a Monte-Carlo method, and realistic simulations of the Gaia observational conditions are taken into account in order to derive their observation probability expectation.
We calculated the afterglow light curves for Pop III GRBs following the standard prescription from Sari et al. (1998, 1999) and Mészáros (2006). The spectrum consists of power-law segments linked by critical break frequencies. These are $v_a$ (the self absorption frequency), $v_m$ (the peak of injection frequency), and $v_c$ (the cooling frequency), given

\[ F_{\nu} = \begin{cases} 
(\nu_a/\nu_c)^{1/3}(\nu/\nu_a)^{2}F_{\nu,\text{max}}, & \nu_a > \nu, \\
(\nu/\nu_c)^{1/3}F_{\nu,\text{max}}, & \nu_c > \nu > \nu_a, \\
(\nu/\nu_c)^{-1/2}F_{\nu,\text{max}}, & \nu_m > \nu > \nu_c, \\
(\nu_m/\nu_c)^{-1/2}(\nu/\nu_m)^{-p/2}F_{\nu,\text{max}}, & \nu > \nu_m.
\end{cases} \]

The electron Lorentz factor, $\gamma$, is

\[ \gamma \equiv (1 - \beta)/(1 - \beta \cos \theta_{\text{obs}}) \]

\[ \beta = \sqrt{1 - 1/\Gamma^2} \]

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Example of afterglow light curve as a function of observed angle $\theta_{\text{obs}}$. We show the evolution of afterglow flux $F$ (mJy) as a function of time $t$ (days) and observed angle $\theta_{\text{obs}}$ for typical parameters: isotropic kinetic energy $E_{\text{iso}} = 10^{54}$ erg, electron spectral index $p = 2.5$, plasma parameters $\epsilon_e = 0.1$, $\epsilon_B = 0.01$, half opening angle jet $\theta_j = 0.1$, interstellar medium density $n = 1 \text{cm}^{-3}$, frequency $\nu = 4.5 \times 10^{14}$. The horizontal dotted line is the GAIA flux limit; dashed blue line, $\theta_{\text{obs}} = 0$; dashed red line, $\theta_{\text{obs}} = 0.1$; dashed green line, $\theta_{\text{obs}} = 0.20$. 

$\theta_{\text{obs}} = 0.0$

$\theta_{\text{obs}} = 0.1$

$\theta_{\text{obs}} = 0.20$

$z = 3$

$\theta_j = 0.1$

$R = 20$
PROBABILITY DISTRIBUTION OF EACH PARAMETER

Redshift PDF. Shown is the probability of a given event appear in a certain range of redshift.

\[ P_{\theta_j}(\theta) \propto \theta^{-2} \]

Half opening angle jet PDF. Shown is the probability of a given GRB have a given \( \theta_j \).

\[ P_z(z) = \frac{dN/dz}{\int_0^z (dN/dz) dz} \]
GAIA

✧ One of the most ambitious projects of modern Astronomy. It aims at the creation of a very precise tridimensional, dynamical and chemical census of our Galaxy, from astrometric, spectrophotometric and spectroscopic data.

✧ Gaia satellite will perform observations of the entire sky in a continuous scanning created from the coupling rotations and precessions movements, called ‘scanning law’.

✧ For point-sources, these observations will be unbiased and the data of all the objects under a certain limiting magnitude (G=20), will be transferred to the ground. Certainly, among all those objects, not only galactic sources will be present, but also extragalactic ones.
GAIA SCANNING LAW

In order to estimate the probability for the observation of a single event by Gaia, \( \text{Prob}(\Delta t, l_{\text{gal}}, b_{\text{gal}}) \), only two quantities play an important role: the time that the orphan remains brighter than \( G=20 \), \( \Delta t \), and the coordinates \((l_{\text{gal}}, b_{\text{gal}})\) where the event takes place in the sky.

In order to be as realistic as possible, we adopt the Gaia Data Processing and Analysis Consortium’s nominal implementation of it, as to derive the a transit time list comprising the instants when Gaia’s telescopes will be pointing at that coordinate.
GAIA OBSERVATIONAL PROBABILITY

PDF of $\Delta t$(days). Shown is the probability of an afterglow stays above the Gaia flux limit for a given time interval.
PARTIAL REMARKS

- We estimate the possibility to observe OA events during the 5 nominal operational years of the Gaia mission. We obtain the expected average number of observed events $\sim 203 \pm 80$ for $N = 60000$ events and $\sim 2.3 \pm 0.8$ for $N = 60$ events.

- However, the detection of those events among the Gaia data will be quite a challenging task. Gaia will observe more than one billion objects all over the sky, and each object will be independently detected around eighty times during the mission, comprising a total of around $10^{12}$ astrometric, spectrophotometric and spectroscopic observations. One can promptly imagine that finding the orphans events among all that data will probably be highly non-trivial.

- Would be necessary apply some kind of classification method based only in the afterglow light curves to seek for Pop III OA candidates.

- For a outstanding review about photometric classification methods, don’t miss the next talk of Emille Ishida *A novel approach for supernova photometric classification*
Given a SFR I am able to make a estimative of GRB redshift distribution if I assume that GRB follows SFR.

If this procedure is correct, I should be able in principle to recover the SFR history using GRB redshift distribution.

How to test such hypothesis against real data?
Probing cosmic star formation up to $z \sim 9.4$ with gamma-ray bursts

We propose a novel approach, based on Principal Components Analysis, to the use of Gamma-Ray Bursts (GRBs) to investigate the cosmic star formation history (SFH) up to high redshifts as suggested by the collapsar model of long GRBs.

Observational quantity: Cumulative number of GRBs

\[
N_{th}(z, \Delta t_{obs}) = \int_0^z \frac{dN_{GRB}}{dz} \, dz.
\]

\[
\Psi_{GRB}(z) = \frac{\Omega_{obs}}{4\pi} f_{GRB} f_b P_z \rho_\ast(z) \int_{L_{lim}(z)}^{\infty} p(L) \, dL.
\]
Aiming at model independence and simplicity, we represent the SFH as a sum of window functions

\[ \rho_*(z, \beta) = \sum_{i=1}^{n_{\text{bin}}} \beta_i c_i(z), \]

where \( \beta_i \) are constants, \( n_{\text{bin}} \) is the total number of redshift bins and \( c_i(z) \) is a window function which returns 1 if \( z_i < z < z_{i+1} \) and 0 otherwise.

\[ \mathcal{L}(\beta) \propto \prod_{i=1}^{T} \exp \left[ -\frac{1}{2} \left( \frac{N_{\text{data}_i} - N(z_i, \beta)}{\sigma_i} \right)^2 \right]. \]

The number of parameters = number of bins!!!
Principal Component Analysis (PCA)

The main goal of PCA is to reduce the dimensionality of the initial parameter space.
The main goal of PCA is to reduce the dimensionality of the initial parameter space.

\[
F_{k,l} = \sum_{i=1}^{T} \frac{1}{\sigma_i^2} \frac{\partial N(z_i, \beta)}{\partial \beta_k} \frac{\partial N(z_i, \beta)}{\partial \beta_l}.
\]

\[
\rho_{rec}(z) = \rho_{fid}(0) + \rho_c + \sum_{i=1}^{M} \alpha_i e_i(z),
\]

\[
\chi^2(\alpha) \propto \sum_{i=1}^{T_{MS}} \frac{(N_{i;data} - N_{rec}(z_i, \alpha))^2}{2\sigma_i^2},
\]

http://www.cs.cornell.edu/courses/cs322/2008sp/images/thumb_PCA.png
PCA reconstructions of SFH obtained from our mock data, using 1 (top-left) to 6 (bottom-right) PCs. The blue-thin line corresponds to our fiducial model $\rho_{\text{fid}}$. The black-thick line is the final reconstruction for each case and the red-dashed-thick lines corresponds to 2$\sigma$ confidence levels. The inset shows the cumulative percentage of total variance, $t\mathcal{M}$. 

Mock sample

$t_1 = 88.9\%$
1 PC

$t_2 = 94.4\%$
2 PC

$t_3 = 96.4\%$
3 PC

$t_4 = 97.4\%$
4 PC

$t_5 = 98.0\%$
5 PC

$t_6 = 98.4\%$
6 PC

$\rho_{\text{rec}} (M_\odot \text{yr}^{-1} \text{Mpc}^{-3})$
Swift data

Being crucial for us to avoid systematics errors which affect the overall redshift distribution, our data sample is composed by the 120 Swift GRBs with redshift measured by absorption lines and photometry.
First (red solid) and second (blue dashed) PCs from Swift.

PCA reconstruction from Swift data using 2 PCs, compared with independent SFH determinations.
We implemented the use of PCA in the estimation of SFH based on gamma-ray burst redshift distribution.

It is important to highlight that our approach is completely independent of our initial choice of $\beta$. This has an obvious advantage of avoiding hypothesis about $\rho_*(z)$,

Given the recent discovered GRB at $z \sim 9.4$, we are able to constraint the star formation history up to the same $z$, being the more distant SFR already estimated.


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HOW CAN WE SEE THE FIRST STARS?

First Stars can trigger high energetic GRBs after died.

Gamma rays are the most powerful explosions of the Universe. They tell us about extreme conditions, powerful processes, and exotic phenomena.

While supernovae explosions have luminosities similar to an entire galaxy

GRBs have luminosities equivalent to all the Universe!!!
Bower et al. (2007) used 22 years of archival data from VLA to put an upper limit of $\sim 2.4 \times 10^5$ over 1-year variability transients above 90 $\mu$Jy for all sky.

Gal-Yam et al. (2006) used FIRST and NVSS radio catalogues to place an upper limit of $\sim 70$ radio orphan afterglows above 6 mJy in the 1.4 GHz band over the entire sky. This suggests less than $\sim 10^3$ sources above 1 mJy on the sky.

In our model a typical GRB’s radio afterglow with isotropic kinetic energy $E_{\text{iso}} \sim 5 \times 10^{54}$ ergs stays above 1 mJy over $\sim 10^{2-3}$ days. Combining the results shown in Figs. 5 and 6, we expect $\sim 10^{-10^4}$ sources above $\sim 1$ mJy.

As a consequence, the most optimistic case for Pop III.2 should be already ruled out by the current observations of radio transient sources, if their luminosity function follows the one assumed in the present paper.