Konus-Wind observations of gamma-ray bursts with known redshifts


Ioffe Institute, St. Petersburg, Russia
Motivation

- ~500 GRBs with known $z$ (~172 observed by KW in triggered mode);
- Redshift => distance, age, rest-frame energetics & $E_p$;
- The unbiased comparison between GRBs;
- Possibility to test GRB models;
- GRB population properties (Luminosity function, GRBFR, ...)
- GRBs could probe the properties of high-redshift universe:
  - Cosmic expansion
  - Star formation history at high redshifts
  - Reionization history
  - Metal evolution
  - History of cosmic acceleration
  - Evolution of dark energy
Joint Russian-US Konus-\textit{Wind} experiment

Records the light curves (LCs) in three energy windows:

- G1 ($\sim 20$–$80$ keV, at present),
- G2 ($\sim 80$–$300$ keV),
- G3 ($\sim 300$–$1200$ keV).

Two modes

**Triggered mode:**
LC res. is 2 ms –256 ms, 
LC is recorded from $T_0-0.512$ s to $T_0+230$ s; 

**Waiting mode:**
G1, G2, G3 with 2.944 s resolution
GRBs with known redshifts

KW triggered mode:
- multichannel spectra
- 20 keV-20 MeV,
- LC with 2 ms–256 ms resolution

- 172 events;
- $0.1 \leq z \leq 5$;
- 14 Type I GRBs: short/hard,
  - merger-origin;
- 158 Type II GRBs: long,
  - collapsar-origin.

KW waiting mode:
- 20-1500 keV, 3-channel spectra,
- LC with 3 s resolution

- ~200 weak/soft GRBs detected by Swift/BAT (15-150 keV) and
  by KW in the waiting mode;
- $0.04 \leq z \leq 9.4$;
- 5 short GRBs & 6 XRFs.

KW+BAT joint analysis


Tsvetkova et al., in preparation
The burst sample

- ~500 GRBs with known z;
- 172 triggered KW GRBs;
- ~ 200 Swift/BAT & waiting-mode KW GRBs with z.
KW waiting-mode + Swift/BAT joint data analysis

Targeted search of BAT GRBs with z in the KW waiting-mode LCs:
Selection of the TI & peak spectrum accumulation times based on the
Bayesian block decomposition of KW LCs and S/N

+ Swift/BAT spectra

Joint spectral analysis of KW+BAT data with CPL and Band functions in the
wide 15 keV – 1.5 MeV energy range

Selection of models for the energy estimation

+ LC Swift/BAT

Total energy fluence (S) & peak energy flux ($F_p$)

+ redshift

Rest-frame $E_p$ & energetics
Joint spectral fits of w-m KW & BAT data

171 GRBs have at least one spectral fit with the CPL or/and BAND models

Models used for further calculations:

- BAND, if $\beta > -3.5$ and $\alpha$ & $E_p$ are constrained;
- CPL.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>CPL</th>
<th>BAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-integrated</td>
<td>59%</td>
<td>41%</td>
</tr>
<tr>
<td>Peak</td>
<td>60%</td>
<td>40%</td>
</tr>
</tbody>
</table>
Peak energy distributions

- \( E_p = 15 \text{ keV} \ldots 700 \text{ keV}, E_{p,z} = (1+z)E_p = 25 \text{ keV} \ldots 3.1 \text{ MeV}; \)
- Medians: \( E_{p,i} = 95 \text{ keV}, E_{p,p} = 120 \text{ keV}, E_{p,i,z} = 291 \text{ keV}, E_{p,p,z} = 385 \text{ keV}. \)
Rest-frame energetics

\( k \)-correction (Bloom et al. 2001, Kovacs et al. 2011):

\[
k' = \frac{F[E_1/(1+z), E_2/(1+z)]}{F[e_1, e_2]}
\]

\( e_1 = 10 \text{ keV}, e_2 = 10 \text{ MeV}; \)
\( E_1 = 1 \text{ keV}, E_2 = (1+z) \cdot 10 \text{ MeV} \)

\( H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_\Lambda = 0.685, \Omega_M = 0.315 \) (Ade et al., 2014)

16 (1 short & 2 XRFs) GRBs have reasonably-constrained (from optical/IR afterglow or in two spectral band simultaneously) \( t_{\text{jet}} \):

\( 1.3^\circ < \theta_{\text{jet, HM}} < 10^\circ \)
\( 2.4 \times 10^{-4} < 1 - \cos \theta_{\text{jet}} < 0.015 \)

![Energy release vs. number of bursts](image1)

\( E_\gamma = (1 - \cos \theta_{\text{jet}}) E_{\text{iso}} \)

\( E_{\text{iso}} = \frac{4\pi D_L^2(z)}{1+z} \times S \times k \)

![Luminosity vs. number of bursts](image2)

\( L_{\gamma} = (1 - \cos \theta_{\text{jet}}) L_{\text{iso}} \)

\( L_{\text{iso}} = 4\pi D_L^2(z) \times F_{\text{peak}} \times k \)
Hardness-intensity correlations for the KW long GRBs (triggered)

**Amati relation** ($E_{\text{iso}} - E_{p,i,z}$)
- $N=138$, $\rho_S=0.70$, $P=1.4\times10^{-21}$, slope $= 0.47$

**Yonetoku relation** ($L_{\text{iso}} - E_{p,p,z}$)
- $N=137$, $\rho_S=0.73$, $P=1.6\times10^{-23}$, slope $= 0.49$

Color denotes the log of the detection significance.
Hardness-intensity correlations for the long GRBs (triggered + waiting-mode)

**Amati relation**

$N=318$, $\rho_s=0.69$, $P \sim 10^{-46}$, slope = 0.43

**Yonetoku relation**

$N=318$, $\rho_s=0.69$, $P \sim 10^{-46}$, slope = 0.44

Black points – triggered GRBs, colored dots – waiting-mode GRBs; color denotes the redshift.
Hardness-intensity correlations
for the long GRBs (triggered + waiting-mode)
Collimation-corrected

Ghirlanda relation for the time-int. spectra
\( N=43, \rho_S=0.58, P\sim 10^{-5}, \text{slope }= 0.58 \)
Amati relation: \( \rho_S=0.75, P\sim 10^{-9}, \text{slope }= 0.53 \)

Ghirlanda relation for the peak spectra
\( N=43, \rho_S=0.43, P\sim 10^{-3}, \text{slope }= 0.69 \)
Yonetoku relation: \( \rho_S=0.65, P\sim 10^{-6}, \text{slope }= 0.50 \)

Black points – triggered GRBs, colored dots – waiting-mode GRBs,
color denotes the redshift.
Selection effects

KW-specific effects:
- Prompt emission properties (LC, spectral shape, energy fluxes);
- Redshift;
- Observational conditions.

«External biases»:
- GRB localization;
- GRB redshift estimation;
- Swift/BAT-specific selection effects
Luminosity function

Without loss of generality, the total luminosity function (LF; number of bursts per unit luminosity) \( \Phi(L_{\text{iso}}, z) \) can be rewritten as

\[
\Phi(L_{\text{iso}}, z) = \rho(z) \phi(L_{\text{iso}}/g(z), \alpha_s)/g(z)
\]

- \( \rho(z) \) – GRB formation rate (GRBFR)
- \( \phi(L_{\text{iso}}/g(z)) \) – local LF
- \( g(z) = (1 + z)^\delta \) – luminosity evolution
- \( \alpha_s \) – shape of the LF

Non-parametric statistical technique: Lynden-Bell (1971)
Efron & Petrosian (1992)
Selection of threshold fluxes and fluences

- Evolution PL index ($\delta$)
  - $F_{\text{im}} = 1.55 \times 10^{-7}$ erg cm$^{-2}$ s$^{-1}$
  - 99% of the sample, $\delta_{\text{im}} = 1.4$

- Threshold peak flux $F_{\text{im}}$ (10$^{-7}$ erg/cm$^2$/s)
- Threshold fluence $S_{\text{im}}$ (10$^{-6}$ erg/cm$^2$)

- GRB fraction above the threshold
- $L_{\text{iso}}$ (erg s$^{-1}$)
- $E_{\text{iso}}$ (erg)

- 1+z
Luminosity and energy release evolution

Triggered KW GRBs: (Tsvetkova et al. 2017)

\[ L_{iso} : \tau_0 = 1.7\sigma \quad \delta_L = 1.7^{+0.9}_{-0.9} \quad (1\sigma \text{ CL}) \]

\[ E_{iso} : \tau_0 = 1.6\sigma \quad \delta_E = 1.1^{+1.5}_{-0.7} \]

All KW GRBs:

\[ L_{iso} : \tau_0 = 2.2 \sigma; \quad \delta_L \sim 1.4 (-0.6, +0.6) \]

\[ E_{iso} : \tau_0 = 1.6 \sigma; \quad \delta_E \sim 0.95 (-0.6, +1.0); \]
Luminosity and energy release functions for the sample of triggered + waiting-mode GRBs

Cumulative luminosity function

$$\ln \psi (L_i') = \sum_{j=2}^{i} \ln \left( 1 + \frac{1}{N_j'} \right)$$

The existence of a sharp cutoff of the isotropic energy agrees with the results of Atteia et al. (2017), the next talk

GRB Luminosity function
- $\alpha_1 \sim 0.32$
- $L_{\text{break}} \sim 6.3 \times 10^{52} \text{ erg/s}$
- Broken PL prob $> 99$

GRB Energy function
- $\alpha_2 \sim 1.22$
- $\alpha_1 \sim 0.39$
- Broken PL prob $\sim 29$
- Exp. cutoff PL prob $\sim 71$
- $\alpha \sim 0.38$
- $E_{\text{cut}} \sim 2 \times 10^{54} \text{ erg}$

BPL:
$$\psi (x) \propto \begin{cases} x^{\alpha_1}, & x \leq x_b \\ x_{b}^{(\alpha_1-\alpha_2)} x^{\alpha_2}, & x > x_b \end{cases}$$

CutoffPL:
$$\psi (x) \propto x^\alpha \exp(-x/x_{\text{cut}})$$
GRBFR (triggered GRBs)

Cumulative rate evolution:
\[ \ln \psi(z_i) = \sum_{j=2}^{i} \ln \left( 1 + \frac{1}{M_j} \right) \]

Comoving density rate:
\[ \rho(z) = \frac{d\psi}{dz} (1 + z) \left( \frac{dV(z)}{dz} \right)^{-1} \]

Differential comoving volume:
\[ \frac{dV(z)}{dz} = \frac{4\pi D_H D_M^2}{E(z)} \]

\(D_M\) — is the transverse comoving distance

Hubble distance:
\[ E(z) = \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda} \]


The relative excess of GRBFR over SFR at low \(z\) agrees with Yu et al. (2015) and Petrosian et al. (2015).
GRBFR (triggered + waiting-mode KW GRBs)

GRBFR (triggered + waiting-mode KW GRBs)

Summary

- Joint KW+BAT spectral analysis (15–1500 keV) was performed for ~200 waiting mode GRBs, for 171 events spectra are well fitted by CPL or/and Band function;
- The sample of KW GRBs with $z$, and $E_p$ + broadband energetics extended to 343 GRBs ($0.04 \leq z \leq 9.4$);
- The “Amati” and “Yonetoku” correlations were confirmed for the KW sample;
- The correction for the jet collimation does not improve the “Amati” and “Yonetoku” correlations for the KW sample;
- LF and EF evolution is limited at $\delta \ll 1.4$, $\tau_0 \ll 2 \sigma$;
- The exponential cutoff of GRB EF at $E_{\text{iso}} \gg 2 \times 10^{54}$ erg (first reported by Atteia et al. 2017) and its absence for the GRB LF (Tsvetkova et al. 2017) were confirmed;
- The GRBFR follows the SFR at $1 < z < 9.4$, and the relative excess of GRBFR at $z<1$ was confirmed.
On-line catalog of the KW triggered GRBs with z
Thank you!

tsvetkova@mail.ioffe.ru

This work was supported by RSF (grant 17-12-01378)