On the Connection of Gamma-Ray Bursts and X-Ray Flashes

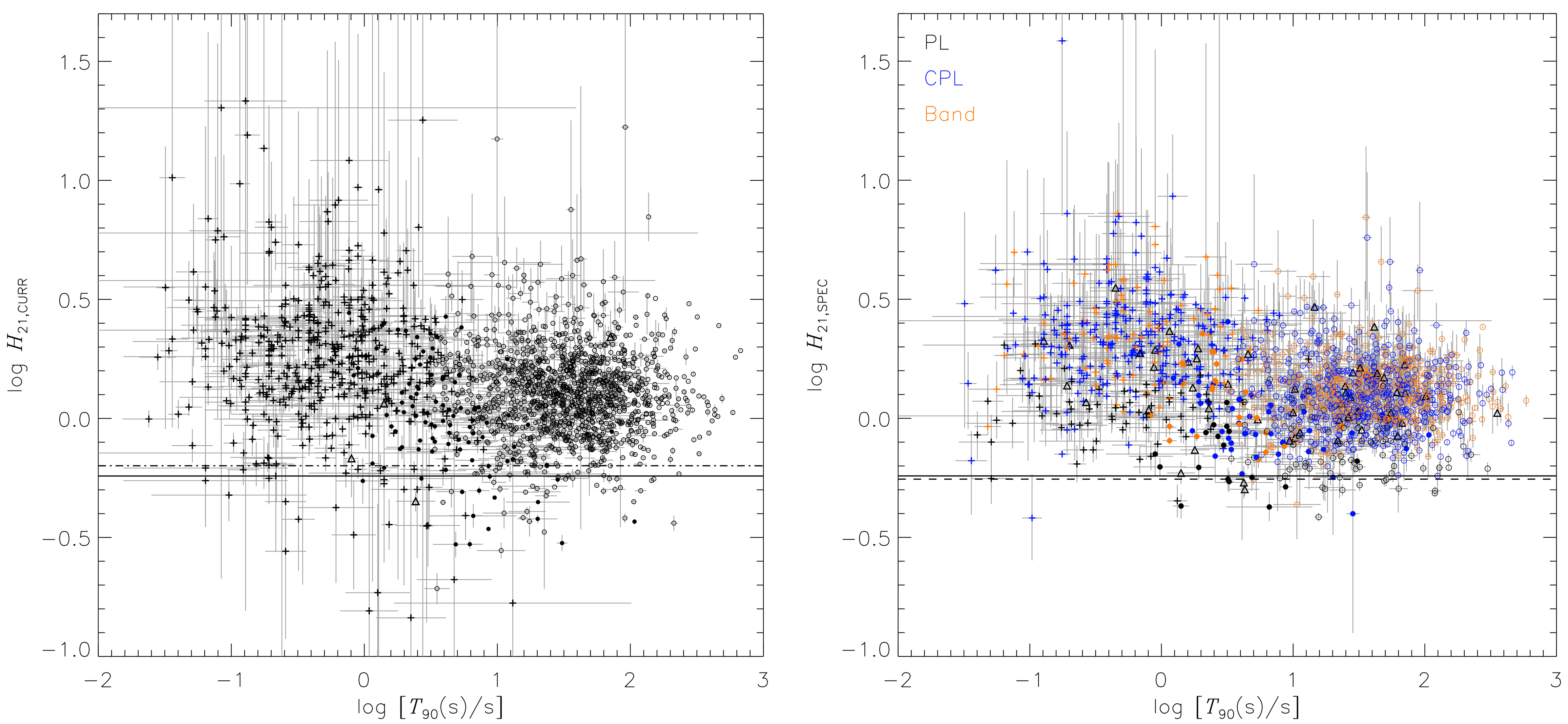
Jakub Řípa[1] and Attila Mészáros[2]

[1]former affiliation: LeCosPA, National Taiwan University, Taipei, Taiwan, ripa.jakub@gmail.com;
[2]Astronomical Institute of Charles University, Prague, Czech Rep., meszaros@cesnet.cz

Abstract

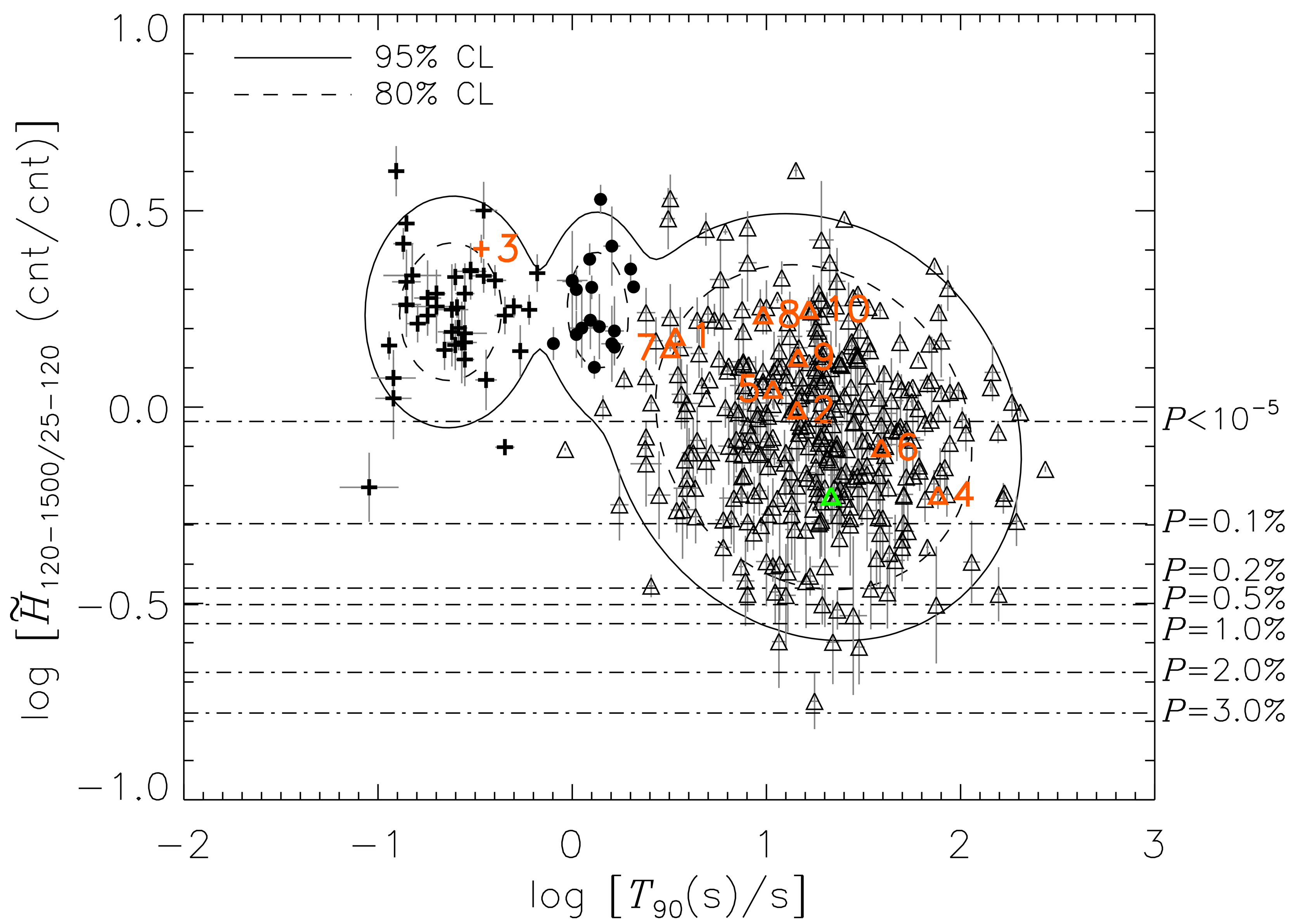
Classification of gamma-ray bursts (GRBs) into groups has been intensively studied by various statistical tests since 1998. It has been suggested that next to the groups of short/hard and long/soft GRBs there could be another class of intermediate durations. For the Swift/BAT database Veres et al. 2010 (ApJ, 725, 1955) it was found that the intermediate-duration bursts might be related to X-ray flashes (XRFs). On the other hand, Řípa and Mészáros 2016 (Ap&SS, 361, 370) and Řípa et al. 2012 (ApJ, 756, 44) found that the intermediate-duration GRBs in the RHESSI database are spectrally too hard to be given by XRFs. Also, in the BATSE database the intermediate-duration GRBs can be only partly populated by XRFs. The key ideas of the **Řípa and Mészáros 2016 (Ap&SS, 361, 370)** article are summarized in this poster.

Fractions of XRFs in BATSE Catalogs



Left: Hardness $H_{21,\mathrm{CURR}}$ vs. T_{90} duration of 1932 GRBs derived from BATSE Current Catalog. Dash-and-dot line marks a confidence interval from simulated data. An event above the line has probability $< 10^{-5}$ to be an XRF. *Right:* Hardness $H_{21,\mathrm{SPEC}}$ vs. T_{90} duration of 1626 GRBs derived from BATSE Complete Spectral Catalog. Dashed line is the highest hardness of an event in this catalog still classified as XRF by Sakamoto et al. (2008). *Both:* Assigned are clusters of short- (crosses), intermediate- (full circles), long-duration GRBs (open circles) and those without group-membership (triangles). The horizontal solid line is an XRF limit obtained by extrapolation of the limiting XRF hardness defined by Sakamoto et al. (2008). Events below this line are classified as XRFs. From Řípa and Mészáros (2016).

Fractions of XRFs in *RHESSI* sample



The "pseudo-hardness" $\widetilde{H}_{\frac{120-1500}{25-120}}$ (cnt cnt^{-1}) vs. T_{90} duration of 427 *RHESSI* GRBs as published by Řípa et al. (2012) with assigned short- (crosses), inter.- (full circles), and long-duration (triangles) GRBs. The CL marks the confidence levels of the best maximum likelihood fit with three bivariate lognormal functions. Dash-and-dot lines mark the confidence intervals (obtained from simulated data) meaning that any event above the given line has a probability of $< 10^{-5}$, 0.1 %, 0.2 %, 0.5 %, 1.0 %, 2.0 %, and 3.0 %, respectively, to be an XRF by using an extrapolation of the limiting XRF hardness defined by Sakamoto et al. (2008). From Řípa and Mészáros (2016).

Introduction

The existence of two astrophysically different groups of gamma-ray bursts (GRBs), denoted as short GRBs and long GRBs, is well established. In addition, the **occurrence of a group of intermediate-duration GRBs in data samples of several satellites has been intensively studied using various statistical methods** (Horváth 1998, Mukherjee et al. 1998, Balastegui et al. 2001, Horváth 2002, Horváth et al 2008, Horváth 2009, Řípa et al 2009, Huja et al. 2009, Horváth et al. 2010, Mészáros et al. 2010). However, different statistical tests applied on different datasets of different satellites give varying significance claiming its existence and its astrophysical meaning remains unclear. Recently, two essential steps were taken in the clarification of the astrophysical meaning of these intermediate-duration bursts. First, a detailed statistical **analysis of data from the *Swift*/BAT instrument arrived at the conclusion that they are related to X-ray flashes (XRFs) (Veres et al. 2010, Kóbori et al. 2013)**. Second, a similar detailed statistical **analysis of the *RHESSI*[a] database showed that the intermediate-duration bursts in this database were similar to the short ones (Řípa et al. 2012)**. This means that in this database the intermediate-duration bursts are spectrally as hard as the short ones, and thus they hardly can be identified with the spectrally soft XRFs. The purpose of this article is to study the **connection of GRBs and XRFs both for the BATSE and *RHESSI* datasets**. The main aim is to **estimate the fraction of XRFs among the intermediate-duration GRBs** separately for both databases.

[a]https://hesperia.gsfc.nasa.gov/rhessi3/

Definition of XRFs

We use a **definition of XRFs introduced by Sakamoto et al. (2008)** for the sample of the *Swift*/BAT instrument. They defined an event as XRF if $0.76 > S_{50-100}/S_{25-50} = H_{\frac{50-100}{25-50}}$, where S_{50-100} and S_{25-50} are fluences in ranges $50-100\,\mathrm{keV}$ and $25-50\,\mathrm{keV}$. It was derived based on the typical spectral parameters of XRFs: $\alpha = -1$ for the low-energy spectral index and $\beta = -2.5$ for the high-energy spectral index with peak energy $E_{\mathrm{peak}} = 30\,\mathrm{keV}$ of the so-called Band function (Band et al. 1993). If we adopt this definition, we can **extrapolate the limiting hardness of XRFs** for another energy band. The energy fluence is

$$S_{E_1-E_2} = \int_{E_1}^{E_2} E N_E(E) dE,$$

where the differential photon spectrum $N_E(E)$ can be described by power law (PL), power law with exponential cutoff (CPL) or Band function. Then for hardness $H_{21} = S_{50-100}/S_{20-50}$, used in our **BATSE data samples, the "extrapolated" XRF limiting hardness is $\mathbf{H_{21,\mathrm{XRF}} \approx 0.6}$**. For hardness $H_{\frac{120-1500}{25-120}} = S_{120-1500}/S_{25-120}$, used in the **RHESSI sample, the "extrapolated" XRF limiting hardness $\mathbf{H_{\frac{120-1500}{25-120},\mathrm{XRF}} \approx 0.6}$**.

Data samples

For BATSE we employ two types of catalogs. The first one is **BATSE Current Catalog**[a]. It contains 2702 GRBs and uses 4-energy channel data in the energy range from $20\,\mathrm{keV}$ to $> 300\,\mathrm{keV}$. For our purpose we used a sample of 1927 GRBs which have simultaneously measured T_{90} and fluences $S1$ $(20-50\,\mathrm{keV})$, $S2$ $(50-100\,\mathrm{keV})$ and $S3$ $(100-300\,\mathrm{keV})$ with $1\,\sigma$ statistical uncertainties. We used the measured fluences from this catalog to calculate the hardness ratios. The second one is the **BATSE Complete Spectral Catalog**[b] Goldstein et al 2013. It contains time integrated spectral fits (fluence spectra) for 2106 events and uses 14 channels out of 16 energy channels in energy range $\sim 25\,\mathrm{keV}$ to $\sim 1.8\,\mathrm{MeV}$. We used the best fit spectral parameters to calculate the hardness ratios.

For ***RHESSI*** we employ the **sample** published in Řípa et al. (2009) and (2012) which contains 427 GRBs. In this sample the fluence in a given energy band is given in instrumental counts C. Thus we define a "pseudo-hardness" as a ratio of such counts in different energy bands: $\tilde{H}_{\frac{120-1500}{25-120}} = C_{120-1500}/C_{25-120}$ $(\mathrm{cnt\,cnt^{-1}})$.

[a]http://gammaray.msfc.nasa.gov/batse/grb/catalog/current/
[b]http://www.batse.msfc.nasa.gov/~goldstein/

Methods

In the **determination of the fraction of XRFs in the BATSE database we use the hardness $\mathbf{H_{21} \equiv H_{\frac{50-100}{20-50}} = S_{50-100}/S_{20-50}}$** because its energy range ensures sensitivity at 30 keV, which is the typical peak energy in the Band function of XRFs. For the **separation of bursts into three groups we use the classification published by Horváth et al. (2006) in their Fig. 1 on the hardness $\mathbf{H_{32} \equiv H_{\frac{100-300}{50-100}} = S_{100-300}/S_{50-100}}$.**

Since the energy ranges used in hardness H_{21} are not identical to the ranges of the hardnesses used by XRF definition by Sakamoto et al. (2008) one can use two different procedures to decide if there are XRFs in the BATSE database. In the **first procedure (Proc1)**, one can either calculate the hardnesses for the energy ranges used in the XRF definition by Sakamoto et al. (2008) for any burst (using the measured spectral parameters), and then compare these calculated hardnesses with the XRF definition by Sakamoto et al. (2008). In the **second procedure (Proc2)**, one can compare the "extrapolated" limiting XRF hardness $H_{21,\mathrm{XRF}} \approx 0.6$ with the calculated H_{21} values.

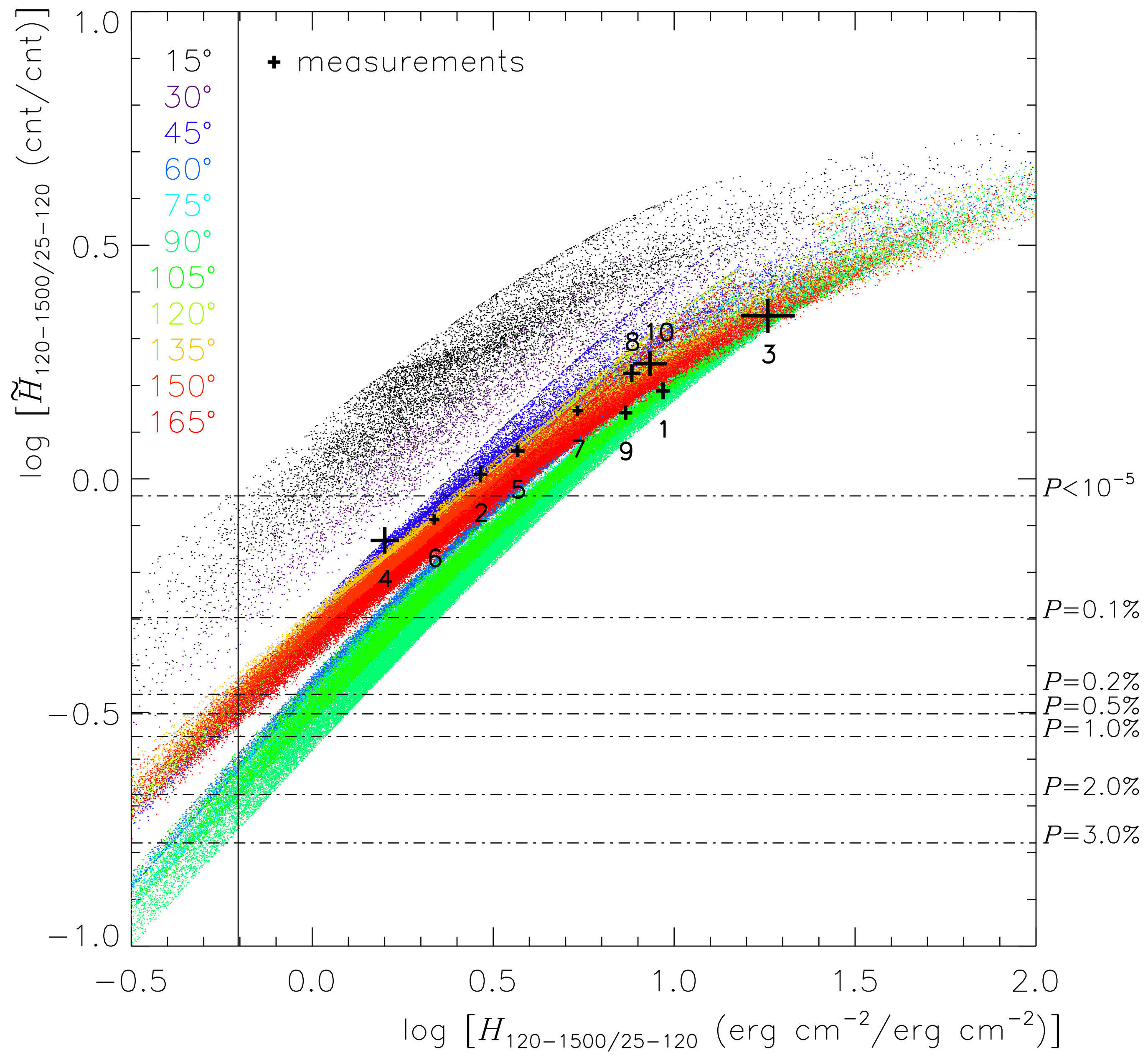
For *RHESSI*, only the Proc2 can be used because the spectral parameters are known only for a small portion of all observed GRBs. In addition, one has to convert the "extrapolated" XRF limiting hardness $H_{\frac{120-1500}{25-120},\mathrm{XRF}}$ to the "pseudo-hardness" $\widetilde{H}_{\frac{120-1500}{25-120},\mathrm{XRF}}$ (cnt/cnt) because in the RHESSI data sample we do not have fluences but detected instrumental counts instead.

Summary of fractions of XRFs for BATSE

Proc.	Total	Short	**Inter.**	Long	No-group
ProcI	1.3 (2.0 ± 0.4)	0.7 $(1.6^{+0.9}_{-0.7})$	**6** $(\mathbf{9^{+28}_{-8}})$	1 $(1.9^{+0.6}_{-0.5})$	4 (4 ± 2)
ProcI Check	1.8	0.9	**10**	1.4	4
ProcII	3.7 $(3.9^{+0.3}_{-0.4})$	4.7 $(3.8^{+1.9}_{-1.3})$	**15** $(\mathbf{31^{+54}_{-25}})$	2.4 (2.9 ± 0.5)	N/A N/A

A summary of the fractions of XRFs [%] in the BATSE samples by different procedures. "Total" means fraction of XRFs in the whole sample. "Short", "Inter.", and "Long" mean fractions in the individual groups. "No-group" means fraction of the events without assigned group-membership. "N/A" means not applicable because in ProcII all events in the sample had assigned group-membership. The fractions written in parentheses were obtained from the median and 90 % CL uncertainties when the uncertainties in duration and hardness of GRBs were considered in our analysis.

Conversion between H and $\widetilde{H}$



Conversion between hardness $H_{\frac{120-1500}{25-120}}$ and "pseudo-hardness" $\widetilde{H}_{\frac{120-1500}{25-120}}$ for *RHESSI* GRBs. Different color means simulated GRB spectra with photons coming into the detector under different off-axis angles (15° - 165°). The vertical line is the "extrapolated" XRF limit $H_{\frac{120-1500}{25-120}} \approx 0.6$. The dash-and-dot lines mark the confidence intervals meaning that any object above the given line has a $< 10^{-5}$, 0.1 %, 0.2 %, 0.5 %, 1.0 %, 2.0 %, and 3.0 %, chance to be an XRF. They were obtained from a large sets of simulated GRB spectra, *RHESSI*'s off-axis response function and from the distribution of the observed GRB directions. From Řípa and Mészáros (2016).

Conclusions

- For the two different **BATSE** databases we obtained following. There is a **1.3 − 4.2 % fraction of bursts classified as XRFs** among all events. The vast majority of short bursts are not XRFs as only 0.7−5.7 % of short bursts can be given by XRFs. A 1−85 % fraction of intermediate-duration bursts and a 1.0 − 3.4 % fraction of long bursts can be given by XRFs. Thus **not all intermediate-duration bursts can be classified as XRFs**.
- For the ***RHESSI*** dataset we obtained following. **Short and intermediate-duration GRBs are found most likely not to be associated with XRFs**. More than 79 % of short GRBs and at least 53 % of intermediate-duration bursts should not be XRFs. At least 45 % of long bursts are not given by XRFs.
- In the hardness vs. T_{90} duration plots there is not seen any apparent separation between XRFs and GRBs at the hardnesses given by the XRF limits. This suggests that **XRFs could constitute a soft tail of the long GRB population and could arise from the same phenomenon as stated already by Kippen et al. (2003) and Sakamoto et al. (2005)**.
- **A close relation of the intermediate-duration bursts and XRFs, suggested by Veres et al. (2010) from the *Swift* database, does not hold for the BATSE and *RHESSI* databases. The intermediate-duration bursts in the BATSE database can be partly populated by XRFs, but the *RHESSI* intermediate-duration bursts are most likely not given by XRFs.**

References

Balastegui, A., Ruiz-Lapuente, P., Canal, R. 2001, MNRAS, 328, 283

Band, D., Matteson, J., Ford, L., et al. 1993, ApJ, 413, 281

Goldstein, A., Preece, R. D., Mallozzi, R. S., et al. 2013, ApJ Sub. Ser., 208, 21

Horváth, I. 1998, ApJ, 508, 757

Horváth, I. 2002, A&A, 392, 791

Horváth, I. 2009, Ap&SS, 323, 83

Horváth, I., Bagoly, Z., Balázs, L. G., et al. 2010, ApJ, 713, 552

Horváth, I., Balázs, L. G., Bagoly, Z., et al 2006, A&A, 447, 23

Horváth, I., Balázs, L. G., Bagoly, Z., Veres, P. 2008, A&A, 489, L1

Huja, D., Mészáros, A., Řípa, J. 2009, A&A, 504, 67

Kippen, R. M., Woods, P. M., Heise, J., et al. 2003, AIP Conf. Proc., 662, 244

Kóbori, J., Bagoly, Z., Balázs, L. G., et al. 2013, Astronom. Nachrichten, 334, 1028

Mészáros, A. et al. 2010, in 25th Texas Symposium on Relativistic Astrophysics, PoS(Texas 2010)093

Mukherjee, S., Feigelson, E. D., Jogesh Babu, G., et al. 1998, ApJ, 508, 314

Řípa, J., and Mészáros, A. 2016, Ap&SS, 361, 370

Řípa, J., Mészáros, A., Veres, P., Park, I. H. 2012, ApJ, 756, 44

Řípa, J., Mészáros, A., Wigger, C., et al. 2009, A&A, 498, 399

Sakamoto, T., Hullinger, D., Sato, G., et al. 2008, ApJ, 679, 570

Sakamoto, T., Lamb, D. Q., Kawai, N., et al., 2005, ApJ, 629, 311

Veres, P., Bagoly, Z., Horváth, I., et al. 2010, ApJ, 725, 1955