Contrib. Astron. Obs. Skalnaté Pleso **53/4**, 115 – 126, (2023)
https://doi.org/10.31577/caosp.2023.53.4.115

Redshift dependence of GRBs' observed parameters

I.I. Racz[1,2], L.G. Balazs[3,4] and I. Horvath[1]

[1] *University of Public Service, Budapest, Hungary (E-mail: racz.istvan@uni-nke.hu)*

[2] *Department of Astronomy, Eötvös University, Budapest, Hungary*

[3] *Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Budapest, Hungary*

Received: June 28, 2023; Accepted: October 9, 2023

Abstract. GRBs are extremely energetic short cosmic transients. Due to their huge energy output in a short time they can be observed at very large cosmological distances. Actually, they sample the whole observable Universe. As a consequence of their large distances, their observed duration, fluence and peak flux depend on the redshift. In the reality, however, this dependence can be observed only in the case if the intrinsic variance of these quantities in comoving frame do not exceed significantly that coming from different redhifts of the GRBs. Nevertheless, it is an important question whether the redshift dependence of the observed quantities could be extracted from the observational data. Using a training set consisting of GRBs having measured physical parameters and redshifts we are looking for the effect of the redshift on the observed data, using techniques available in multivariate data analysis. Creating a 3D parameter space from duration, fluence and peak flux, we define partitions in the distribution of data points and compare the redshift distributions within these partitions. Partitioning will be made by some hierarchical clustering algorithm and cutting the obtained agglomeration tree at different places to get partitions of different numbers. The distributions of redshifts within the partitions, obtained in this way, will be compared to see if there is any difference in redshift distribution between partitions at all.

Key words: gamma-ray burts – cosmology – statistical

1. Introduction

The Gamma-ray bursts (GRBs) are the most energetic events in the far Universe (Mészáros, 2006; Kumar & Zhang, 2015; Zhang, 2018). There are two main different physical model for the origin these events (Kouveliotou et al., 1993) but some studies raise the possibility of more models. First the collapse of the most massive stars (collapsar model) (MacFadyen & Woosley, 1999; Zhang & Mészáros, 2002) and second the merging of compact objects (like black holes or neutron stars) (Eichler et al., 1989; Hakkila et al., 2018). The discovery of

GW170814/GRB170814A had validated the second model (Abbott et al., 2017; Goldstein et al., 2017; Bagoly et al., 2016; Tóth et al., 2019). Since then, it has been a recurring theme that there may be other sub-types of bursts (Horváth et al., 2018, 2019). The two types of GRBs have different duration and hardness. The long GRBs have softer and the short GRBs have harder spectra. In 1998, Horváth (1998); Mukherjee et al. (1998) identified a third group on the duration–hardness plane (Horváth et al., 2006). These events can be associated with the X-ray flash events (Veres et al., 2010; Horváth et al., 2010; Pinter et al., 2017; Bi et al., 2018).

Balazs et al. (1998) suggested that the distribution of GRBs may show some angular anisotropy, and after the millennium many studies dealt with the GRBs angular and spatial distribution ((Mészáros et al., 2000a,b; Vavrek et al., 2008; Tarnopolski, 2017)). Of this, there were discovering the two largest structures in the Universe, the Giant GRB Ring (Balázs et al., 2015, 2018) and the Hercules-Corona Borealis Great Wall (Horváth et al., 2014, 2015; Horvath et al., 2020). In addition to all this, several other anomalies (differences from isotropy and homogeneity) were identified based on the angular and spatial distribution of GRBs (Balázs et al., 1999; Pinter, 2018; Tóth et al., 2019; Horvath et al., 2022) It became clear shortly after the first redshift measurement that the distance of the GRBs shows a relation to their duration: the short GRBs are located closer than the long GRBs. But since GRBs occur over a tremendous time scale, it can be suggested that certain properties of them change based on the distance (Bagoly et al., 2003; Pérez-Ramírez et al., 2010; Kovács et al., 2019; Hatsukade et al., 2019; Toth et al., 2019; Suleiman et al., 2022). Among other things, De Cia et al. (2012) discovered that the host galaxy must possess very particular chemical characteristics in order for long GRBs to form. We must acknowledge, however, that the chemical composition of galaxies and the entire universe is subject to change over time. This change can be seen in the characteristics of GRBs, such as the lack of absorption lines (De Cia et al., 2011b) or the rapidity of GRB light curves (Vetere et al., 2006; De Cia et al., 2011a).

It is still questionable how the distance of GRBs can cause differences in other physical parameters within different groups, i.e. how GRBs produced at different distances, in different eras differ in their main physical parameters.

2. Data and Methods

We used the data available at the GRB table of the Swift satellite[1], which we preliminarily cleaned of faulty records. Instead of the observed values one may use these values' logarithms to reduce the effect of outliers. In some cases, however, it is necessary to exclude the outliers altogether from further computations, since they significantly distort the linear correlation between the variables.

[1] https://swift.gsfc.nasa.gov/archive/grb_table/

For this we made a comprehensive outlier diagnostics using *boxplot* procedure (McGill et al., 1978) of **R** package (R Core Team, 2021).

2.1. Outlier diagnostics

Outlier is a data point that differs significantly from other observations. An outlier may be due to variability in the measurement or it may indicate experimental errors. In the following we use **R** packages **outliers** (Tukey, 1977). The definition of an outlier is somewhat arbitrary. The scores routine of the **outliers** package assigns some probability to all of the cases of an univariate sample. The critical probability for identifying a case as an outlier can be a fixed error probability of rejecting a sample element although it comes from the parent distribution.

(Fisher, 1992) suggested $p = 0.05$ value for critical probability. We used this threshold, for rejecting the null hypothesis and we will conclude that the lowest/highest value is an outlier. Due to the nature of the problem, this level of significance is acceptable to us, without significantly increasing second kind of errors. Accordingly, if the scores procedure assigns $p_s < p/N$ (N is the sample size), we may reject this case as an outlier.

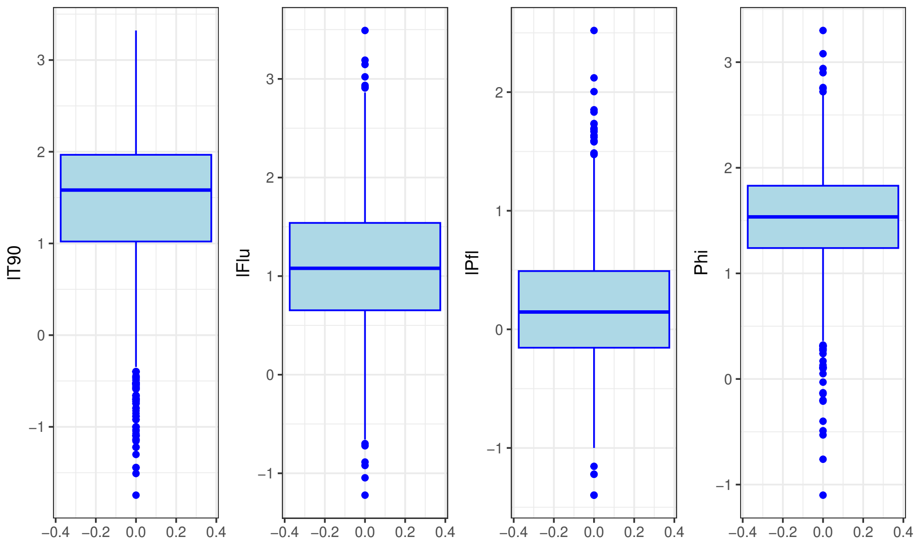

Figure 1. Outliers' diagnostics in BAT data with R boxplot procedures. The critical probability was $p = 0.05$, and the blue points show the excluded data.

After excluding the outliers, we studied the correlations between the main observed parameters of Swift GRBs. This can be seen in the Fig. 2. We used four parameters from the database, the T_{90} duration, Gamma Fluence, Gamma Peak Flux, and the Gamma Photon index. We can see a weak correlation between the fluence and duration or peak flux. This is easy to understand, since the fluence is the summed energy emitted during the entire duration, i.e. the integral of the instantaneous brightness over time, and the peak flux is the brightness measured at the interval around the maxima of the burst.

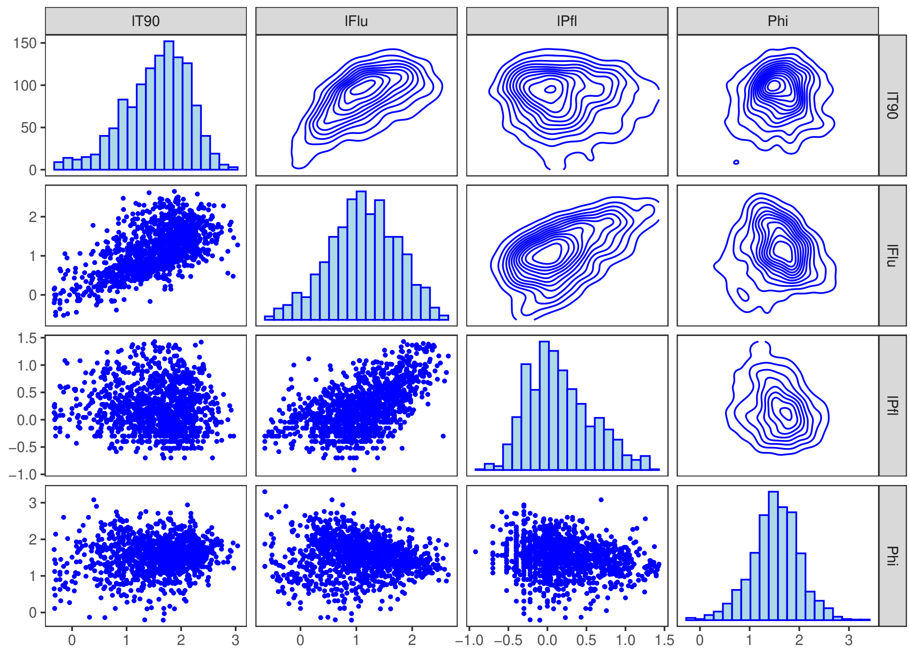

Figure 2. Distributions of Swift BAT data without the outliers. In the diagonal we show the histogram of T_{90}, Fluence, Peak flux, and Photon index, respectively. On the top and bottom triangle the 2D density and scatter plots are shown for each pairs of observed parameters, respectively. For example, the connection between Fluence and T90 parameters is clearly visible.

3. Results

3.1. Measuring the similarity between GRBs

To study the relationship between the characteristic physical parameters of GRBs and the redshift, we divide the parameter space into regions of similar objects in their parameters. The distance (similarity) between GRBs will be measured in Euclidean metrics. The orthogonal coordinates required for the Euclidean metric can be obtained from the original variables using PCA (Principal Component Analysis) (Jolliffe, 1986). For performing PCA we used the *PCA()* procedure in **FactoMineR** library (Lê et al., 2008) of the **R** statistical package. Our final goal was to look for dependence of the observed physical parameters (duration, fluence, peak flux, photon index) on the redshift. The strength of this dependence is a function of the ratio between the variance of redshift within and between partitions.

3.2. Partitioning parameter space of PCs

After getting orthogonal coordinates (principal components (PCs) from PCA) we perform hierarchical cluster analysis. We cut the cluster tree (dendrogram) resulted to a given number of partitions. We divide the redshifts of GRBs according to the partitions obtained in order to see significant differences, if any, in redshift distributions between partitions. The significance of difference in redshift distributions between partitions was tested using the Kruskal-Wallis non-parametric test (Kruskal & Wallis, 1952).

3.3. Estimating optimal number of partitions

For getting the optimum number of partitions we use *NbClust()* procedure in **NbClust**(Charrad et al., 2014) library of **R**. After getting the optimum number of clusters we performed hierarchic clustering using *hcut()* procedure in R's **Factoextra** library cutting the dendrogram obtained at the optimum number of clusters getting above (see Fig.3,4) and we calculated the relevant values within each group (Table 1).

The clustering yielded three as an optimal number of groups in the PC1–PC2 plane according to the Kruskal-Wallis rank summary test, with a chi-square of 10.839 and a significance p-value of 0.004429.

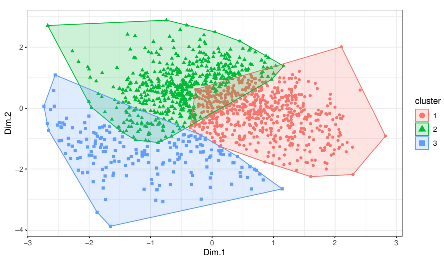

Figure 3. Clustering results of the three groups in the first and second PC plane.

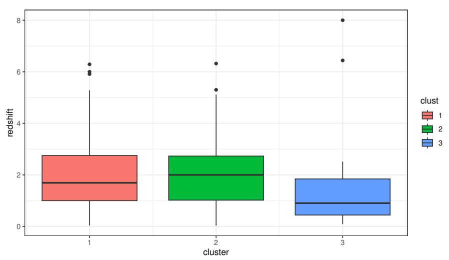

Figure 4. Comparing the redshift within the three groups.

Table 1. We clustered the GRBs with NbClust() procedure, and the optimal number of cluster was three. The table contains the median observed parameters of each group.

Groups no.	Redshift	T90	Fluence	Peak Flux	Photon index
1	1.6920	64.00	37.00	3.10	1.47
2	1.9990	36.25	6.00	0.80	1.90
3	0.9035	1.60	3.65	1.73	0.88

3.4. Redshift dependence of parameters with 6 partitions

Although the *NbClust* procedure yielded 3 as the optimal number of GRB groups, there is a second maxima in the number of optimal clusters histogram, at the number of 6. We repeat the previous procedure with a cluster number of 6 (see Fig. 5,6 and Table 2). The Kruskal-Wallis rank summary test has yielded a chi-square of 22.095 and a significance p-value of 0.0005022.

As one can see, the clusters' dependence on redshift is much stronger than in the previous case, where there were only three groups.

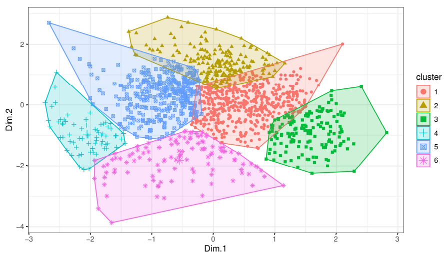

Figure 5. Clustering results of the six groups.

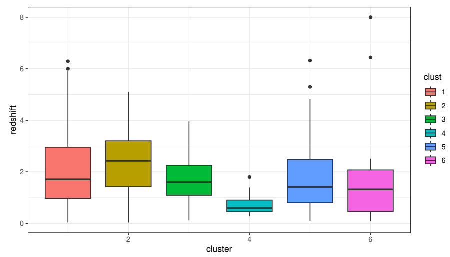

Figure 6. Comparing the redshift within the six groups.

Table 2. The table shows the 6 groups' median values similar to Table 1.

Groups no.	Redshift	T_{90}	Fluence	Peak Flux	Photon index
1	1.7100	64.00	25.70	2.50	1.530
2	2.4281	154.50	13.55	0.65	1.965
3	1.6034	65.15	138.00	12.35	1.280
4	0.5960	0.30	0.44	1.00	1.280
5	1.4160	11.15	3.39	0.98	1.810
6	1.3195	4.20	6.70	3.86	0.820

3.5. Redshift dependence of T90, Fluence, Peak flux and Photon index

The redshift-dependent relationship between the duration, fluence, peak flux, and photon index values obtained from GRB observations can be seen in Fig.7 and 8. In these figures significant internal variances can be seen in each parameter. Their corresponding values in a co-moving system can be obtained from the currently best-fitting world model, however, this can only be done if the intrinsic value of the relevant parameters is known. With the present data, the scattering within the parameters covers their weak redshift dependence. Therefore, the position of the groups according to distance cannot be investigated with adequate statistical significance in this work.

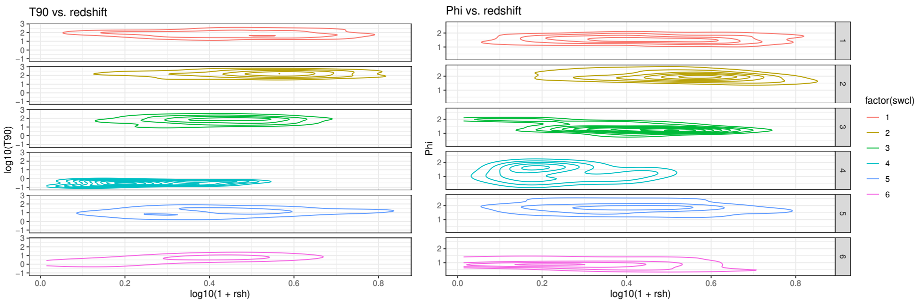

Figure 7. T90 and Photon index vs. redshift

4. Conclusions

The T90 duration appears to have the tightest correlation with redshift. In contrast, peak flux has no correlation with redshift. Fluence correlates with redshift due to its positive correlation with T90 (since fluence can be approximated with the product of peak flux and duration).

It is worth mentioning that the range of $\log_{10}(T90)$ is much higher than of $\log_{10}(1+z)$ so the obtained relationship can not interpreted as a simple cosmological time dilatation. The distribution of absolute brightness is different in within different groups, so the detection threshold defines different sampling volumes and differences in the median of redshift data.

The angular distributions reflect the selection effect due to the galactic foreground extinction (see Fig. 9). The top left panel shows some density enhancement by visual impression, not seen in other ones. The bottom right panel seems to have an asymmetry in galactic latitudes but it based on a low number of sample points.

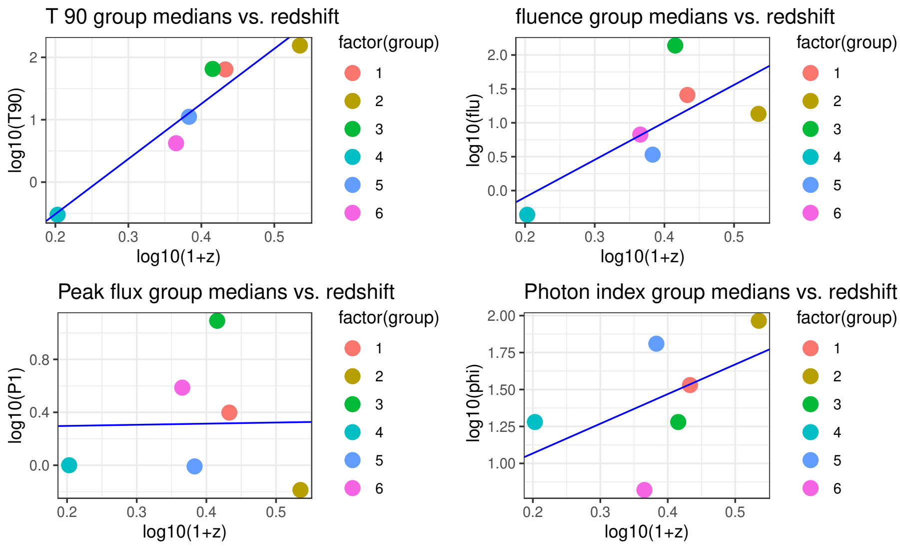

Figure 8. Redshift dependence of T90, Fluence, Peak flux, Photon index of the different partitions. Blue lines in the Figures represent the best fitting linear relationship between redshift and GRB variables.

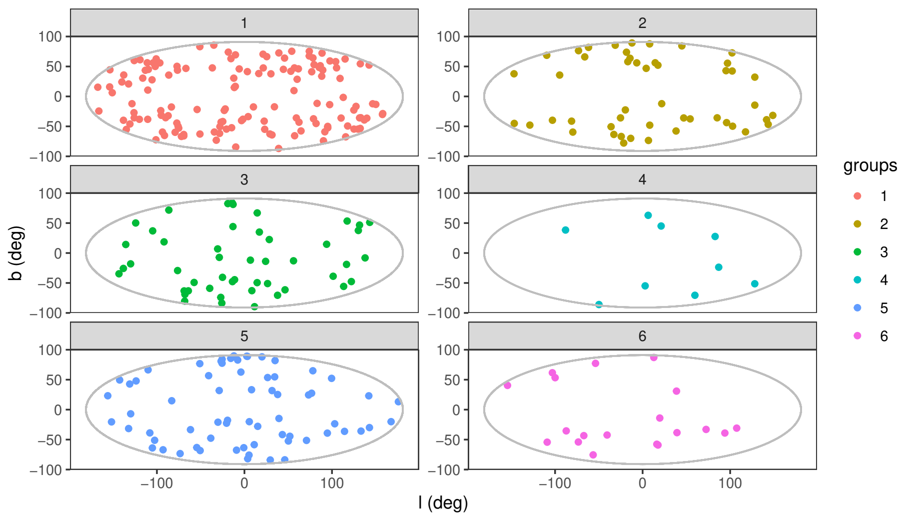

Figure 9. Aitoff projection of angular distributions of the 6 groups. The bottom right panel appears to have an asymmetry in galactic latitudes, but it is based on a small sample size.

Acknowledgements. The authors thank the Hungarian TKP2021-NVA-16 and OTKA K-146092 program for their support. The authors appreciate the anonymous referee's insightful criticism and advice.

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al., GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence. 2017, *Physical Review Letters*, **119**, 141101, DOI: 10.1103/PhysRevLett.119.141101

Bagoly, Z., Csabai, I., Mészáros, A., et al., Gamma photometric redshifts for long gamma-ray bursts. 2003, *Astronomy and Astrophysics*, **398**, 919, DOI: 10.1051/0004-6361:20021724

Bagoly, Z., Szécsi, D., Balázs, L. G., et al., Searching for electromagnetic counterpart of LIGO gravitational waves in the Fermi GBM data with ADWO. 2016, *Astronomy and Astrophysics*, **593**, L10, DOI: 10.1051/0004-6361/201628569

Balázs, L. G., Bagoly, Z., Hakkila, J. E., et al., A giant ring-like structure at $0.78 < z < 0.86$ displayed by GRBs. 2015, *Monthly Notices of the RAS*, **452**, 2236, DOI: 10.1093/mnras/stv1421

Balazs, L. G., Meszaros, A., & Horvath, I., Anisotropy of the sky distribution of gamma-ray bursts. 1998, *Astronomy and Astrophysics*, **339**, 1, DOI: 10.48550/arXiv.astro-ph/9807006

Balázs, L. G., Mészáros, A., Horváth, I., & Vavrek, R., An intrinsic anisotropy in the angular distribution of gamma-ray bursts. 1999, *Astronomy and Astrophysics, Supplement*, **138**, 417, DOI: 10.1051/aas:1999290

Balázs, L. G., Rejtó, L., & Tusnády, G., Some statistical remarks on the giant GRB ring. 2018, *Monthly Notices of the RAS*, **473**, 3169, DOI: 10.1093/mnras/stx2550

Bi, X., Mao, J., Liu, C., & Bai, J.-M., Statistical Study of the Swift X-Ray Flash and X-Ray Rich Gamma-Ray Bursts. 2018, *Astrophysical Journal*, **866**, 97, DOI: 10.3847/1538-4357/aadcf8

Charrad, M., Ghazzali, N., Boiteau, V., & Niknafs, A., NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set. 2014, *Journal of Statistical Software*, **61**, 1

De Cia, A., Jakobsson, P., Björnsson, G., et al., Probing gamma-ray burst environments with time variability: ULTRASPEC fast imaging of GRB 080210. 2011a, *Monthly Notices of the RAS*, **412**, 2229, DOI: 10.1111/j.1365-2966.2010.18046.x

De Cia, A., Ledoux, C., Fox, A. J., et al., Rapid-response mode VLT/UVES spectroscopy of super iron-rich gas exposed to GRB 080310. Evidence of ionization in action and episodic star formation in the host. 2012, *Astronomy and Astrophysics*, **545**, A64, DOI: 10.1051/0004-6361/201218884

De Cia, A., Starling, R. L. C., Wiersema, K., et al., GRB 070125 and the environments of spectral-line poor afterglow absorbers. 2011b, *Monthly Notices of the RAS*, **418**, 129, DOI: 10.1111/j.1365-2966.2011.19471.x

Eichler, D., Livio, M., Piran, T., & Schramm, D. N., Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. 1989, *Nature*, **340**, 126, DOI: 10.1038/340126a0

Fisher, R. A. 1992, *Statistical Methods for Research Workers*, ed. S. Kotz & N. L. Johnson (New York, NY: Springer New York), 66–70

Goldstein, A., Veres, P., Burns, E., et al., An Ordinary Short Gamma-Ray Burst with Extraordinary Implications: Fermi-GBM Detection of GRB 170817A. 2017, *Astrophysical Journal, Letters*, **848**, L14, DOI: 10.3847/2041-8213/aa8f41

Hakkila, J., Horváth, I., Hofesmann, E., & Lesage, S., Properties of Short Gamma-ray Burst Pulses from a BATSE TTE GRB Pulse Catalog. 2018, *Astrophysical Journal*, **855**, 101, DOI: 10.3847/1538-4357/aaac2b

Hatsukade, B., Hashimoto, T., Kohno, K., et al., Molecular Gas Properties in the Host Galaxy of GRB 080207. 2019, *Astrophysical Journal*, **876**, 91, DOI: 10.3847/1538-4357/ab1649

Horváth, I., A Third Class of Gamma-Ray Bursts? 1998, *Astrophysical Journal*, **508**, 757, DOI: 10.1086/306416

Horváth, I., Bagoly, Z., Balázs, L. G., et al., Detailed Classification of Swift 's Gamma-ray Bursts. 2010, *Astrophysical Journal*, **713**, 552, DOI: 10.1088/0004-637X/713/1/552

Horváth, I., Bagoly, Z., Hakkila, J., & Tóth, L. V., New data support the existence of the Hercules-Corona Borealis Great Wall. 2015, *Astronomy and Astrophysics*, **584**, A48, DOI: 10.1051/0004-6361/201424829

Horváth, I., Balázs, L. G., Bagoly, Z., Ryde, F., & Mészáros, A., A new definition of the intermediate group of gamma-ray bursts. 2006, *Astronomy and Astrophysics*, **447**, 23, DOI: 10.1051/0004-6361:20041129

Horváth, I., Hakkila, J., & Bagoly, Z., Possible structure in the GRB sky distribution at redshift two. 2014, *Astronomy and Astrophysics*, **561**, L12, DOI: 10.1051/0004-6361/201323020

Horváth, I., Hakkila, J., Bagoly, Z., et al., Multidimensional analysis of Fermi GBM gamma-ray bursts. 2019, *Astrophysics and Space Science*, **364**, 105, DOI: 10.1007/s10509-019-3585-1

Horvath, I., Racz, I. I., Bagoly, Z., Balázs, L. G., & Pinter, S., Does the GRB Duration Depend on Redshift? 2022, *Universe*, **8**, 221, DOI: 10.3390/universe8040221

Horvath, I., Szécsi, D., Hakkila, J., et al., The clustering of gamma-ray bursts in the Hercules-Corona Borealis Great Wall: the largest structure in the Universe? 2020, *Monthly Notices of the RAS*, **498**, 2544, DOI: 10.1093/mnras/staa2460

Horváth, I., Tóth, B. G., Hakkila, J., et al., Classifying GRB 170817A/GW170817 in a Fermi duration-hardness plane. 2018, *Astrophysics and Space Science*, **363**, 53, DOI: 10.1007/s10509-018-3274-5

Jolliffe, I. 1986, *Principal Component Analysis* (Springer Verlag)

Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al., Identification of two classes of gamma-ray bursts. 1993, *Astrophysical Journal, Letters*, **413**, L101, DOI: 10.1086/186969

Kovács, T. O., Burgarella, D., Kaneda, H., et al., Star formation and polycyclic aromatic hydrocarbons in ELAIS N1 galaxies as seen by AKARI. 2019, *Publications of the ASJ*, **71**, 27, DOI: 10.1093/pasj/psy145

Kruskal, W. H. & Wallis, W. A., Use of Ranks in One-Criterion Variance Analysis. 1952, *Journal of the American Statistical Association*, **47**, 583, DOI: 10.1080/01621459.1952.10483441

Kumar, P. & Zhang, B., The physics of gamma-ray bursts & relativistic jets. 2015, *Physics Reports*, **561**, 1, DOI: 10.1016/j.physrep.2014.09.008

Lê, S., Josse, J., & Husson, F., FactoMineR: A Package for Multivariate Analysis. 2008, *Journal of Statistical Software*, **25**, 1, DOI: 10.18637/jss.v025.i01

MacFadyen, A. I. & Woosley, S. E., Collapsars: Gamma-Ray Bursts and Explosions in "Failed Supernovae". 1999, *Astrophysical Journal*, **524**, 262, DOI: 10.1086/307790

McGill, R., Tukey, J. W., & Larsen, W. A., Variations of box plots. 1978, *The American Statistician*, **32**, 12

Mészáros, A., Bagoly, Z., Horváth, I., Balázs, L. G., & Vavrek, R., A Remarkable Angular Distribution of the Intermediate Subclass of Gamma-Ray Bursts. 2000a, *Astrophysical Journal*, **539**, 98, DOI: 10.1086/309193

Mészáros, A., Bagoly, Z., & Vavrek, R., On the existence of the intrinsic anisotropies in the angular distributions of gamma-ray bursts. 2000b, *Astronomy and Astrophysics*, **354**, 1

Mészáros, P., Gamma-ray bursts. 2006, *Reports on Progress in Physics*, **69**, 2259, DOI: 10.1088/0034-4885/69/8/R01

Mukherjee, S., Feigelson, E. D., Jogesh Babu, G., et al., Three Types of Gamma-Ray Bursts. 1998, *Astrophysical Journal*, **508**, 314, DOI: 10.1086/306386

Pérez-Ramírez, D., de Ugarte Postigo, A., Gorosabel, J., et al., Detection of the high z GRB 080913 and its implications on progenitors and energy extraction mechanisms. 2010, *Astronomy and Astrophysics*, **510**, A105, DOI: 10.1051/0004-6361/200811151

Pinter, S., Multi-messenger studies of γ-ray bursts and their cosmic environment. 2018, *Astronomische Nachrichten*, **339**, 336, DOI: 10.1002/asna.201813501

Pinter, S., Bagoly, Z., Balázs, L. G., et al., Resolving the structure of the Galactic foreground using Herschel measurements and the Kriging technique. 2017, *Proceedings of the International Astronomical Union*, **12**, 168–169, DOI: 10.1017/S1743921317011097

R Core Team. 2021, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria

Suleiman, N., Noboriguchi, A., Toba, Y., et al., The statistical properties of 28 IR-bright dust-obscured galaxies and SED modelling using CIGALE. 2022, *Publications of the ASJ*, **74**, 1157, DOI: 10.1093/pasj/psac061

Tarnopolski, M., Testing the anisotropy in the angular distribution of Fermi/GBM gamma-ray bursts. 2017, *Monthly Notices of the RAS*, **472**, 4819, DOI: 10.1093/mnras/stx2356

Tóth, B. G., Rácz, I. I., & Horváth, I., Gaussian-mixture-model-based cluster analysis of gamma-ray bursts in the BATSE catalog. 2019, *Monthly Notices of the RAS*, **486**, 4823, DOI: 10.1093/mnras/stz1188

Toth, L. V., Doi, Y., Zahorecz, S., et al., Galactic foreground of gamma-ray bursts from AKARI Far-Infrared Surveyor. 2019, *Publications of the ASJ*, **71**, 10, DOI: 10.1093/pasj/psy123

Tukey, J. W. 1977, *Exploration Data Analysis*, Box-and-Whisker Plots (Addison-Wesley), 39–43

Vavrek, R., Balázs, L. G., Mészáros, A., Horváth, I., & Bagoly, Z., Testing the randomness in the sky-distribution of gamma-ray bursts. 2008, *Monthly Notices of the RAS*, **391**, 1741, DOI: 10.1111/j.1365-2966.2008.13635.x

Veres, P., Bagoly, Z., Horváth, I., Mészáros, A., & Balázs, L. G., A Distinct Peak-flux Distribution of the Third Class of Gamma-ray Bursts: A Possible Signature of X-ray Flashes? 2010, *Astrophysical Journal*, **725**, 1955, DOI: 10.1088/0004-637X/725/2/1955

Vetere, L., Massaro, E., Costa, E., Soffitta, P., & Ventura, G., Slow and fast components in the X-ray light curves of gamma-ray bursts. 2006, *Astronomy and Astrophysics*, **447**, 499, DOI: 10.1051/0004-6361:20053800

Zhang, B. 2018, *The Physics of Gamma-Ray Bursts* (Cambridge University Press)

Zhang, B. & Mészáros, P., An Analysis of Gamma-Ray Burst Spectral Break Models. 2002, *Astrophysical Journal*, **581**, 1236, DOI: 10.1086/344338