Studying the variability of the X-ray spectral parameters of high-redshift GRBs’ afterglows

Istvan I. Racz*1,2,3 | Agnes J. Hortobagyi**1

1Department of Physics of Complex Systems, Eötvös Loránd University, Budapest, Hungary
2Department of Natural Science, National University of Public Services, Budapest, Hungary
3Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budapest, Hungary

Correspondence
*Email: racz@complex.elte.hu
**Email: ajhortobagyi@caesar.elte.hu

Present Address
5-th floor, office: 5.80, 1/A Pázmány Péter sétány, 1117 Budapest, Hungary

Funding Information
Hungarian OTKA, NN-111016. Hungarian Ministry of Human Capacities, UNKP-17-3.

ARTICLE TYPE

INTRODUCTION

Gamma-ray bursts (GRBs) are the brightest explosions that have been observed in the distant Universe (see the review paper of Kumar & Zhang (2013)). GRBs can be observed at all wavelengths, from gamma-rays to radio (Amati et al., 2013; P. Mészáros, Asano, & Veres, 2014). The duration of GRBs can be characterized by the $T_{90}$ – or less commonly by $T_{50}$ – which is the time taken to accumulate 90% (50%) of the total observed photons. Several thousand GRBs have been detected so far, but only about 500 have measured distance/redshift (Bagoly et al., 2003b, 2003d, 2006).

There are 2 major groups of GRBs based on their durations: short and long. However, there exists evidence for the existence of a third group: intermediate. (de Ugarte Postigo et al., 2002; Horváth, 1998; 2002; Horváth, Balázs, Bagoly, Ryde, & Mészáros, 2006; Horváth, Balázs, Bagoly, & Veres, 2008; Veres, Bagoly, Horváth, Mészáros, & Balázs, 2010; Zhang, Yang, Choi, & Chang, 2016). The mean durations of these groups depend on the observing detector, e.g. for the Swift BAT they are $T_{90} \approx 0.3$ s, $T_{90} \approx 8.5$ s, and $T_{90} \approx 40$ s, respectively (Horváth et al., 2010). According to the widely accepted theoretical assumptions there are two main central engines producing GRBs: compact cosmic objects merging and the collapse of high-mass stars. The merging of neutron stars or black holes can cause the short GRBs, while the collapsars are responsible for the long GRBs. The recently observed gravitational wave event GRB170817A/GW170817 had an electromagnetic counterpart in the form of a GRB and originated from merging two compact objects of 1.36 and 2.26 $M_\odot$. Horváth et al. (2018) classified this event as an intermediate-duration object, and pointed out the possibility that the intermediate GRBs originate from neutron stars merging. The long GRBs are believed to be indicators of star formation and, as such, indicate the large scale structures of the Universe (Bagoly, Mészáros, Horváth, Balázs, & Mészáros, 1998; Balázs, Mészáros, Horváth, & Vavrek, 1999; A. Mészáros, Bagoly, Horváth, Balázs, & Vavrek, 2000; A. Mészáros, Bagoly, & Vavrek, 2000; Vavrek, Balázs, Mészáros, Horváth, & Bagoly, 2008; Veres, Bagoly, Horváth, Balázs, et al., 2010). Recently,
the Hercules-Corona Borealis Great Wall was found by Horváth, Bagoly, Hakkila, & Tóth (2015); Horváth, Hakkila, & Bagoly (2014) and the Giant GRB Ring was found by Balázs et al. (2015); Balázs, Rejtő, & Tusnády (2018).

Both central engine models produce collimated high-energy jets responsible for the observed radiation in the gamma-range. The jet produces two types of emission: the prompt emission and the afterglow emission from its collision with the circumstellar matter (Kumar & Zhang, 2015; P. Mészáros, 2006). The prompt emission basically refers to the operation of the central engine, while the afterglow provides information on the local, intergalactic and galactic medium (Starling et al., 2013).

Any matter between the detector and the GRB source attenuates the X-rays emitted by the source and modulates the intrinsic X-ray spectrum. There are three kind of interfering matter: the galactic foreground, the intergalactic matter and the interstellar matter surrounding the source. The magnitude of the effect depends on the column density of a given absorber, e.g. as the external shock wave, responsible for the afterglow, is proceeding in the interstellar matter the X-ray absorption is changing.

One may expect a change in the observed column density modulating the intrinsic X-ray spectrum as the jet transmits through the surrounding interstellar matter. Such effect was observed by Amati et al. (2013) and the aim of our paper is to look for this effect in some bright Swift GRBs.

The paper is organized in four sections. In Section 2, we give an overview on X-ray observation for the Swift GRBs. The X-ray spectral fitting tools are shown in Section 3. Then we present the intrinsic N(H) column density evolution in Section 4. Finally, in Section 5, we summarize our results.

## 2 | X-RAY OBSERVATION

The Neil Gehrels Swift Observatory (formally known as 'Swift' space telescope) (Roming et al., 2005; Burrows et al., 2005; Dorman et al., 2003). The Swift telescope has 3 different instruments: the Burst Alert Telescope (BAT), the X-ray Telescope (XRT), and the UV/Optical Telescope (UVOT). The three instruments detect the following energy ranges: 15-150keV for the BAT, 0.3-10keV for the XRT, and 170-600nm for the UVOT. The Swift BAT, XRT and UVOT observe the outbursts in gamma, X-ray, and ultraviolet/optical respectively. The Swift detected ≥ 1350 GRBs until mid-April 2018. From these 1350 GRBs the XRT has found more than 970 X-ray afterglow emissions.

The radiation leaving the GRB travels through the intergalactic and galactic foreground, which significantly affects the spectrum we observe (Evans et al., 2007). The gamma-rays usually don’t interact noticeably with the interstellar medium but the X-ray and shorter wavelength photons do (Evans et al., 2009; Kumar & Zhang, 2015; Wilms, Allen, & McCray, 2000).

The galactic foreground is not as homogeneous as we have previously thought (Rácz et al., 2017; Toth et al., 2017). It seems to be heavily structured and clumpy. The estimation of the foreground base on the radio surveys of atomic hydrogen having an angular resolution of magnitude of degrees. The GRBs are point-like sources, therefore the fine structure of the foreground is very important.

## 3 | X-RAY SPECTRAL FITTING

To determine the X-ray spectrum we used XSpec, which is a widely used X-Ray Spectral Fitting Software Package (K. A. Arnaud, 1996; Dorman & Arnaud, 2001; Dorman, Arnaud, & Gordon, 2003). One can set many parameters like cosmological or solar abundances, and use some models constructed from individual components.

The GRBs’ X-ray light curves can be well approximated by a sectioned power law function (in time) with breakpoints separating the different phases. The Swift data pipeline produces the phases and corresponding X-ray spectra automatically. In this study, the publicly available XRT spectra is used. The UK Swift Science Data Centre (UKSSDC) provides a semi-automatic algorithm for the Swift XRT spectral analysis (Evans et al., 2007, 2009). This study used that method with the standard initial settings and parameters: flat Universe, standard photoionization cross-sections by Verner, Ferland, Korista, & Yakovlev (1996), and low metallicity stellar abundances by Wilms et al. (2000). We used multiplicative models employing the Tuebingen-Boulder ISM absorption models (twice for the foreground and the intrinsic), the simple photon power law, and the convolution model to calculate the flux.

The X-ray spectrum observed by the satellite is modified by the attenuation of N(H) column density in the line of sight; therefore we examined the dependence of intrinsic column density on each starting parameter and how sensitive the fitting is to these changes. The background and the data contains Poissonic noise, hence we applied the C-statistic process. To investigate the impact of the foreground galactic N(H) and the redshift on the intrinsic N(H), we calculated those column densities for the GRB150424A. On Fig. 1 the dependence of the intrinsic column density on the N(H) galactic foreground density and on the redshift are shown. Results indicate a linear connection between galactic and intrinsic N(H) densities, while a quadratic relationship is apparent with the redshift.
No intergalactic N(H) was assumed. The figure shows that there is a linear connection between galactic and intrinsic N(H) densities, while they have a quadratic relationship with the \( \lg(1+z) \).

The quadratic relationship can be explained by a simple model, where both the attenuating material and the intrinsic spectral energy distribution shapes the spectra (K. Arnaud, Smith, & Siemiginowska, 2011). For an optically thin N(H) column the observed spectral intensity, \( M(E) \) will be given by:

\[
M(E) = \exp[-N(H) \cdot \sigma(E)]
\]  

where \( N(H) \) and \( \sigma(E) \) are the hydrogen column density and the photo-electric cross-section, respectively. The \( \sigma(E) \) without the "0" index refers to the frame moving with a speed of the observer, relative to the rest frame.

\[
\sigma^0(E_0) = \sigma(E_0/(1 + z))
\]

The distances of most GRBs are not determined, the Eq. \( \text{(1)} \) shows that in the frame moving with the observers the observed spectral intensity will be:

\[
M(E) = \exp[-(N(H)^* \cdot \sigma(E))]
\]  

where

\[
N(H)^* = \frac{N(H) \sigma([E(1 + z)])}{Q(E)}
\]  

One can see that the \( N(H)^* \) also depends on \( E \) besides fixed column density, the quotient at the right side of Eq. \( \text{(4)} \) depends only on \( (1 + z)^{\alpha} \). The XSpec software uses the Born approximation (Born, 1926), where the \( \alpha \) value equals 2.

4 | EVOLUTION OF \( N(H)^{\text{INTRINSIC}} \)

To investigate the \( N(H)^{\text{INTRINSIC}} \) changes during the GRBs, we randomly selected multiple GRB samples with unknown redshifts and three breakpoints in the Swift X-ray light curve. There are 4+1 spectra for the 3 breakpoints, because of the two modes of XRT: Window Timing and Photon Counting.

Table \( \text{(I)} \) shows the selected GRBs and the time range of each phase. Results from GRB160815A and GRB161202A during the first phase demonstrate that Swift was still settling at the time those readings were taken – therefore these were omitted from the analysis.

One can expect the intrinsic column density to show a decrease in time because the X-ray radiation originates from the interaction between the jet and dropped environment based on previous analysis, e.g. Kumar & Zhang (2015). In this model the jet moves through the medium with relativistic speed, the released X-ray radiation is absorbing less and less hydrogen.

To check this scenario we performed the spectral fitting for the chosen 6 sample GRBs on each 4+1 phase of the spectra (in both WT and PC mode). The intrinsic N(H) is typically between the \( 10^{21} \) and \( 10^{23} \) cm\(^{-2} \) as was published in Sec. 4.2. (Evans et al., 2009) and the 6 chosen GRBs can be considered typical. The results are shown in Fig. \( \text{2} \). In contrast
TABLE 1 The breakpoints of the 6 selected GRBs. These GRBs have 3 breakpoints in their light-curves and both WT and PC mode spectra, so there are 5 time phases. The columns show the starting and ending times (in seconds) of each phase relative to the trigger. The bold faced numbers show the omitted spectra, where the Swift was still in settling.

| ID of GRB   | Phase1 | Phase2 | Phase3 | Phase4 | Phase5 |
|-------------|--------|--------|--------|--------|--------|
| GRB150424A | 94     | 152    | 360    | 682    | 114114 |
| GRB150925A | 146    | 148    | 345    | 394    | 5027   |
| GRB160412A | 85     | 108    | 248    | 378    | 18684  |
| GRB160615A | 95     | 97     | 122    | 177    | 379299 |
| GRB161202A | 64     | 79     | 125    | 236    | 9401   |
| GRB170330A | 104    | 200    | 368    | 800    | 35757  |

TABLE 2 We checked the difference between the first and last NH intrinsic values. Three out of six times the values were found to be decreasing. The typical 1σ errors were comparable to the varying of the N(H) and therefore it cannot be called a significant effect.

| ID of GRB   | ΔN(H)_{intrinsic} [cm^{-2}] | Median errors of the fitting [cm^{-2}] |
|-------------|-----------------------------|---------------------------------------|
| GRB150424A | +2.6 \cdot 10^{21}         | 0.55 \cdot 10^{21}                   |
| GRB150925A | -2.4 \cdot 10^{21}         | 1.33 \cdot 10^{21}                   |
| GRB160412A | -2.6 \cdot 10^{21}         | 1.00 \cdot 10^{21}                   |
| GRB160615A | -0.7 \cdot 10^{21}         | 0.65 \cdot 10^{21}                   |
| GRB161202A | +3.2 \cdot 10^{21}         | 3.05 \cdot 10^{21}                   |
| GRB170330A | +5.1 \cdot 10^{21}         | 0.70 \cdot 10^{21}                   |

FIGURE 3 An example of the variance of the N(H) intrinsic column density for GRB150424A. The X-ray Time-averaged spectrum was fitted, while changing the Galactic foreground between 50% and 200% of the standard values (LAB Survey). Changing the Galactic foreground yields the same magnitude variance as the evolution showed on Fig. 2, where the intrinsic and the foreground column densities are commensurate over a magnitude of changes in the measured column density in small scales.

Results suggest that the variability of the calculated intrinsic column densities was smaller than the statistical errors of the fitting.

5.1 SUMMARY

We analyzed the X-ray spectra of the 6 chosen GRBs that have 3 breakpoints in the light curves. The fitted intrinsic N(H) has linear dependence on the galactic foreground and quadratic relation with the redshift. The galactic ISM shows fine density structures, therefore the precise (high-resolution) N(H) hydrogen column density is necessary to perform accurate fitting. Our results are consistent with the theoretical expectations.

The majority of the observed X-ray radiation originates from the interaction between the jet and the interstellar matter. The jet advances in the matter, and as the matter gets thinner, the modification of the created X-ray photons can change. Consequently, the intrinsic column density could vary in time. The
errors of the fitting of the Swift X-ray spectra were too big to show the variability of the intrinsic N(H) column densities.

ACKNOWLEDGMENTS

Supported by the Hungarian OTKA NN-111016 grant and supported by the New National Excellence Program of the Hungarian Ministry of Human Capacities UNKP-17-3. We are grateful to Lajos G. Balázs and Zsolt Bagoly for the enlightening discussions. We are thankful to the Anonymous Referee for his helpful suggestions concerning the presentation of this paper.

Author contributions

All authors participated in acquisition, analysis and interpretation of data as well as the preparation of the manuscript.

Financial disclosure

None reported.

Conflict of interest

The authors declare no potential conflict of interests.

REFERENCES

Amati, L., Atteia, J.-L., Balazs, L. et al. 2013, June, White paper, arXiv:1306.5259.
Arnaud, K., Smith, R., & Siemiginowska, A. 2011, Handbook of X-ray Astronomy, Arnaud, K. A. 1996, XSPEC: The First Ten Years. G. H. Jacoby & J. Barnes (Eds.), Astron. Data Anal. Soft. and Sys. V Vol. 101, p. 17.
Bagoly, Z., Csabai, I., Mészáros, A., Mészáros, P., Horváth, I., Balázs, L. G., & Vavrek, R. 2003a, April, Estimation of the Redshifts for Long Gamma-Ray Bursts. GAMMA-RAY BURST AND AFTERGLOW ASTRONOMY 2001: A Workshop Celebrating the First Year of the HETE Mission. AIP Conference Proceedings, Volume 662, pp. 446-449 (2003). Vol. 662, p. 446-449. doi.
Bagoly, Z., Csabai, I., Mészáros, A., Mészáros, P., Horváth, I., Balázs, L. G., & Vavrek, R. 2003b, February, A&A, 398, 919-925. doi.
Bagoly, Z., Mészáros, A., Balazs, L. G. et al. 2006, July, A&A, 453, 797-800. doi.
Bagoly, Z., Mészáros, A., Horváth, I., Balázs, L. G., & Mészáros, P. 1998, May, ApJ, 498, 342-348. doi.
Balázs, L. G., Bagoly, Z., Hakki, I. E., Horváth, I., Köbör, J., Rácz, I. I., & Tóth, L. V. 2015, September, MNRAS, 452, 2236-2246. doi.
Balázs, L. G., Mészáros, A., Horváth, I., & Vavrek, R. 1999, September, A&AS, 138, 417-418. doi.
Balázs, L. G., Rejtő, L., & Tusnády, G. 2018, January, MNRAS, 473, 3169-3179. doi.
Barthelmy, S. D., Barbier, L. M., Cummings, J. R. et al. 2005, October, Space Sci. Rev., 120, 143-164. doi.
Born, M. 1926, November, Zeitschrift für Physik, 38, 803-827. doi.
Burrows, D. N., Hill, J. E., Nousek, J. A. et al. 2005, October, Space Sci. Rev., 120, 165-195. doi.
de Ugarte Postigo, A., Horváth, I., Veres, P. et al. 2011, January, A&A, 525, A109. doi.
Dorman, B., & Arnaud, K. A. 2001, Redesign and Reimplementation of XSPEC. F. R. Hamden Jr., F. A. Primini, & H. E. Payne (Eds.), Astron. Data Anal. Soft. and Sys. X Vol. 238, p. 415.
Dorman, B., Arnaud, K. A., & Gordon, C. A. 2003, March, XSPEC12: Object-Oriented X-Ray Analysis. AAS/High Energy Astrophysics Division #7 Vol. 35, p. 641.
Evans, P. A., Beardmore, A. P., Page, K. L. et al. 2007, July, A&A, 469, 379-â€Š383. doi.
Evans, P. A., Beadmore, A. P., Page, K. L. et al. 2009, July, MNRAS, 397, 1177-1201. doi.
Horváth, I. 1998, December, ApJ, 508, 757-759. doi.
Horváth, I. 2002, September, A&A, 392, 791-793. doi.
Horváth, I., Bagoly, Z., Balázs, L. G., de Ugarte Postigo, A., Veres, P., & Mészáros, A. 2010, April, ApJ, 713, 552-557. doi.
Horváth, I., Bagoly, Z., Hakkila, J., & Tóth, L. V. 2015, December, A&A, 584, A48. doi.
Horváth, I., Balázs, L. G., Bagoly, Z., Ryde, F., & Mészáros, A. 2006, February, A&A, 447, 23-30. doi.
Horváth, I., Balázs, L. G., Bagoly, Z., & Veres, P. 2009, October, A&A, 489, L1-L4. doi.
Horváth, I., Hakkila, J., & Bagoly, Z. 2014, January, A&A, 561, L12. doi.
Horváth, I., Tóth, B. G., Hakkila, J. et al. 2018, March, Ap&SS, 363. doi.
Kalberla, P. M. W., Burton, W. B., Hartmann, D., Arnal, E. M., Bajaja, E., Morras, R., & Pöppel, W. G. L. 2005, September, A&A, 440, 775-782. doi.
Kumar, P., & Zhang, B. 2015, February, Physics Reports, 561, 1-109. doi.
Mészáros, A., Bagoly, Z., Horváth, I., Balázs, L. G., & Vavrek, R. 2000, August, ApJ, 539, 98-101. doi.
Mészáros, A., Bagoly, Z., & Vavrek, R. 2000, February, A&A, 354, 1-6.
Mészáros, P. 2006, August, Reports on Progress in Physics, 69, 2259-2321. doi.
Mészáros, P., Asano, K., & Veres, P. 2014, March, Gamma-ray bursts: Recent results and connections to very high energy cosmic rays and neutrinos. Journal of Physics Conference Series Vol. 485, p. 012001. doi.
Rácz, I. I., Bagoly, Z., Tóth, L. V., Balázs, L. G., Horváth, I., & Pintér, S. 2017, July, Contributions of the Astronomical Observatory Skalnate Pleso, 47, 100-107.
Roming, P. W. A., Kennedy, T. E., Mason, K. O. et al. 2005, October, Space Sci. Rev., 120, 95-142. doi.
Starling, R. L. C., Willingale, R., Tanvir, N. R. et al. 2013, April, MNRAS, 431, 3159â€Š3176. doi.
Toth, L. V., Doh, Y., Zahorecz, S., Agas, M., Balazs, L. G., Forro, A., & Racz, I. I. 2017, March, Publication of Korean Astronomical Society, 32, 113-116. doi.
Vavrek, R., Balazs, L. G., Mészáros, A., Horváth, I., & Bagoly, Z. 2008, December, MNRAS, 391, 1741-1748. doi.
Veres, P., Bagoly, Z., Horváth, I., Balázs, L. G., Mészáros, A., & Kelemen, J. 2010, October, Directional Anisotropy of Swift Gamma-Ray Bursts. DECEIPHERING THE ANCIENT UNIVERSE WITH GAMMA-RAY BURSTS. AIP Conference Proceedings, Volume 1279, pp. 457-459 (2010). Vol. 1279, p. 457-459. doi.
December, *ApJ*, 725, 1955-1964. doi:
Verner, D. A., Ferland, G. J., Korista, K. T., & Yakovlev, D. G. 1996, July, *ApJ*, 465, 487. doi:
Wilms, J., Allen, A., & McCray, R. 2000, October, *ApJ*, 542, 914-924. doi:
Zhang, Z.-B., Yang, E.-B., Choi, C.-S., & Chang, H.-Y. 2016, November, *MNRAS*, 462, 3243-3254. doi:

**How cite this article:** Istvan I. Racz, and Agnes J. Hortobágyi (2018), Studying the variability of the X-ray spectral parameters of high-redshift GRBs’ afterglows, *AN, 2018;XX:X–X.*

**AUTHOR BIOGRAPHY**

**Istvan I. Racz.** PhD Student, Eötvös Loránd University, Budapest, Hungary; Assistant lecturer, National University of Public Services, Budapest, Hungary; Education: PhD School of Physics (Particle Physics and Astronomy), 2015 –, Eötvös Loránd University, project: Gamma ray bursts and their Cosmic environment. MSc in Astronomy, 2015, Eötvös Loránd University, thesis: Starformation in Planck cold clumps, supervisor: L. Viktor Tóth. BSc in Physics, 2012, Eötvös Loránd University, thesis: Expansion of the Universe, supervisor: Istvan Csabai.

Research interests: Statistical analysis of the spatial distribution of Gamma-ray bursts, studying the central engine and GRB afterglow with X-ray and Gamma spectral fitting.

**How cite this article:** Istvan I. Racz, and Agnes J. Hortobágyi (2018), Studying the variability of the X-ray spectral parameters of high-redshift GRBs’ afterglows, *AN, 2018;XX:X–X.*