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THE PEAK ENERGY–DURATION CORRELATION AND POSSIBLE IMPLICATIONS ON GAMMA RAY BURST PROGENITOR

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ABSTRACT

We investigate the correlation between the peak energy and the burst duration using available long GRB data with known redshift, whose circumburst medium type has been suggested via afterglow light curve modeling. We find that the peak energy and the burst duration of the observed GRBs are correlated both in the observer frame and in the GRB rest frame. For our total sample we obtain, for instance, the Spearman rank-order correlation values ~ 0.75 and ~ 0.65 with the chance probabilities $P = 1.0 \times 10^{-3}$ and $P = 6.0 \times 10^{-3}$ in the observer frame and in the GRB rest frame, respectively. We note that taking the effects of the expanding universe into account reduces the value a bit. We further attempt to separate our GRB sample into the "ISM" GRBs and the "WIND" GRBs according to environment models inferred from the afterglow light curves and apply statistical tests, as one may expect that clues on the progenitor of GRBs can be deduced directly from prompt emission properties other than from the ambient environment surrounding GRBs. We find that two subsamples of GRBs show different correlation coefficients. That is, the Spearman rank-order correlation are ~ 0.65 and ~ 0.57 for the "ISM" GRBs and "WIND" GRBs, respectively, after taking the effects of the expanding universe into account. It is not yet, however, statistically very much significant that the GRBS in two types of circumburst media show statistically characteristic behaviors, from which one may conclude that all the long bursts are not originated from a single progenitor population. A larger size of data is required to increase the statistical significance.

Keywords: gamma rays: bursts – methods: data analysis

1. INTRODUCTION

Gamma-ray bursts(GRBs) are brief and intense phenomena, whose peak energy in their spectra ranges from ~ 30 to ~ 400 keV (e.g., Barraud et al. 2003). Since they were first detected in the late 1960s (Klebesadel, Strong, & Olson 1973), we have learned a great deal of the observed GRBs with their counterparts in lower energy bands, so called afterglows (e.g., Costa et al. 1997, Frail et al. 1997, Metzger et al. 1997, van Paradijs et al. 1997). Follow-up observations of afterglow of long GRBs have played crucial roles in establishing facts that (1) GRBs are cosmological (Mao & Paczyński 1992, Meegan et al. 1992, Piran 1992), (2) opening angle corrected energy is clustered around 10^{51} ergs which is comparable to ordinary supernova energy (Panaitescu & Kumar 2001b, Piran et al. 2001, Frail et al. 2001, Bloom, Frail, & Kulkarni 2003), (3) GRBs, at least long bursts, are closely related to the death of massive young stars (Woosley 1993, Paczyński 1998, MacFadyen & Woosley 1999), and (4) the afterglow emission is due to the electron synchrotron radiation from a decelerating relativistic blast wave, which suggests an indirect hint of the emission mechanism of GRBs (Paczyński & Rhoads 1993, Sari & Piran 1995, Waxman 1997a,b, Wijers, Rees, & Mészáros 1997).

It is widely accepted that the fireball internal/external shock model succeeds in explaining both the prompt emission and afterglow, in which highly relativistic shocks with Lorentz factor $\gamma \sim 10^2$ collide each other and are subsequently decelerated by the circumburst medium (Mészáros & Rees 1993, Rees & Mészáros 1994, Kobayashi, Piran, & Sari 1997, Daigne & Mochkovitch 1998, 2000). The shock may be spherical or initially confined to a narrow cone. An engine of GRBs is, however, apparently to power conical ejecta to produce the observed GRBs and their afterglows. For, in many cases the rate of decay in afterglow flux has been observed to steepen, which is naturally accounted for by a collimated conical jet (Rhoads 1999, Sari, Piran, & Halpern 1999). After all, an afterglow light curve depends fairly strongly on physical properties of a whole GRB system, especially the mass-loss rate of the progenitor and the ambient density distribution (Chevalier & Li 1999, Panaitescu & Kumar 2001a,b, 2002). Hence, afterglow observations are well suited to determining not only the geometry of the explosion but also the distribution of circumburst matter.

Some insights about the GRB progenitor can be obtained from properties of the circumburst medium surrounding GRBs, which can be inferred from features of the afterglow emission. GRB ambient environments are grouped into two types in general: "ISM" and "WIND". One may consider a constant circumburst matter density, the "ISM" case. If the ejecta is expelled during the merging of two compact objects, it is expected that the medium surrounding the GRB source is homogeneous. We also note that a quasi-homogeneous environment around a massive star can be created by the pre-shock wave (e.g., Chevalier, Li, & Fransson 2004). Another possibility is that the circumburst medium is dominated by a wind outflow from a progenitor star, the "WIND" case. If a collapsing massive star is the origin of the relativistic fireball, the circumburst medium is the wind ejected by the star prior to its collapse, in which case a constant mass-loss rate and wind speed results in an r^{-2} profile. The question of a wind versus a constant-density surrounding medium is a crucial issue for the progenitor of GRBs (e.g., Mirabal et al. 2003). Density profiles derived from afterglow modelling are particularly intriguing, in the sense that most of events are consistent with a constant density environment and only in a few cases a wind profile is preferred. This immediately has raised the question of why such evidence is not seen in all GRBs with afterglows. The absence of clear wind signature in some afterglow light curves can be explained by different classes of progenitors of the long bursts (e.g., Chevalier & Li 1999, 2000).

The analysis of the prompt emission from GRBs may provide us with valuable hints to the central source accelerating the outflow from which the radiation emanates (Fenimore, Madras, & Nayakshin 1996, Kobayashi, Piran, & Sari 1997, Beloborodov, Stern, & Svensson 1998, Fenimore 1999, Chang & Yi 2000, Amati et al. 2002, Ghirlanda, Ghisellini, & Lazzati 2004, Liang & Dai 2004, Liang, Dai, & Wu 2004). The significant advances in our understanding of the nature of GRBs have been made through statistical studies of GRB light curves. For instance, statistical studies of the direction and of the observed flux of GRBs have restricted models of the spatial distribution of GRBs to a cosmological distribution (e.g., Chang & Yi 2001). Recently, the emission properties of GRBs are studied in terms of the peak energy of the νF_ν spectrum $E_{\rm peak}$ (Ghirlanda, Ghisellini, & Celotti 2004, Yamazaki, Ioka, & Nakamura 2004). Correlations between $E_{\rm peak}$ and the time-integrated isotropic emitted energy $E_{\rm iso}$ (or $L_{\rm iso}$) and collimated emission $E_{\rm jet}$ (or $L_{\rm jet}$) are

Table 1. GRBs Used in the Analysis.

GRB	Redshift	E_{peak} (keV)	T_{90} (sec)	Environment
970228	0.695 (1)	115.0 (1)	80.0 (1)	WIND (4)
970508	0.835 (1)	79.0 (1)	20.0 (1)	WIND (4), (5), (6)
980326	1.0 (2)	33.8 (1)	9.0 (1)	WIND (4), (7), (8)
980425	0.0085 (1)	118.0 (1)	37.41 (1)	WIND (4), (7)
980703	0.966 (1)	255.0 (1)	102.37 (1)	ISM (9), (10), (11)
990123	1.6 (1)	781.0 (1)	100.0 (1)	ISM (4), (9)
990510	1.619 (1)	163.0 (1)	75.0 (1)	ISM (4), (9)
991216	1.02 (1)	318.0 (1)	24.9 (1)	ISM (9), (12), (13)
010222	1.477 (1)	>358.0 (1)	130.0 (1)	ISM (13)
011121	0.36 (1)	>700.0 (1)	75.0 (1)	WIND (14), (15), (16)
020405	0.69 (1)	364.0 (1)	60.0 (1)	ISM (17), (18)
021004	2.3 (3)	79.79 (3)	53.22 (3)	WIND (19), (20), (21)
021211	1.01 (1)	47.0 (1)	2.41 (1)	ISM (19), (22)
030329	0.1685 (1)	68.0 (1)	23.0 (1)	ISM (23), (24)

refs.: (1) Ghirlanda, Ghisellini, & Lazzati 2004, (2) Bloom et al. 1999,
(3) HETE Fregate Archival Data, http://space.mit.edu/HETE/Bursts/GRB021004,
(4) Chevalier & Li 2000, (5) Panaitescu & Kumar 2002, (6) Frail, Waxman, & Kulkarni 2000,
(7) Chevalier & Li 1999, (8) Chevalier, Li, & Fransson 2004, (9) Panaitescu & Kumar 2001a,
(10) Frail et al. 2003, (11) Yost et al. 2003, (12) Halpern et al. 2000, (13) Panaitescu 2005,
(14) Price et al. 2002, (15) Greiner et al. 2003, (16) Piro et al. 2005, (17) Price et al. 2003,
(18) Berger et al. 2003, (19) Smith et al. 2005, (20) Starling et al. 2005, (21) Li & Chevalier 2003,
(22) Kumar & Panaitescu 2003, (23) Taylor et al. 2005, (24) Granot et al. 2005

also derived (Amati et al. 2002, Ghirlanda, Ghisellini & Lazzati 2004, Lamb, Donaghy & Graziani 2004, Yonetoku et al. 2004, Ghirlanda, Ghisellini, & Firmani 2005, Ghirlanda et al. 2005). These correlations may shed light on the central radiation engine for the prompt GRB emission.

In this paper we investigate the correlation between the peak energy E_{peak} and the burst duration T_{90}. The peak energy of the νF_{ν} spectrum E_{peak} is an important quantity of GRBs in the fireball model in that E_{peak} in the source frame depends on the fireball bulk Lorentz factor Γ. We are also interested in the question of whether GRBs show similar behaviors in the prompt emission when they are divided, as mentioned earlier, by two types of the circumburst medium derived from afterglow light curves. We attempt to look for in the prompt emission of GRBs fingerprints left by the progenitor of GRBs. By doing so, one may wish to deduce whether their central engine really works in a different way as density profiles derived from afterglow modelling imply a different kind of the GRB progenitor. To study spectral features of the prompt emission of GRBs is a complementary, yet direct approach to constrain the nature of the progenitor. Particularly, using data of the GRBs whose redshift z is known we are also able to infer how the correlation changes by the cosmological expansion of the universe, that is, cosmological time dilation and redshift in energy. This paper is organized as follows. In §2 we describe GRB data we use in this analysis and present results obtained from a study of the correlation between the peak energy and the duration. In §3 discussions and conclusion are presented.

2. CORRELATION BETWEEN PEAK ENERGY AND DURATION

In order to investigate a relation between the peak energy and the duration we have compiled data of the observed GRBs from published literatures and public databases as indicated in Table 1.

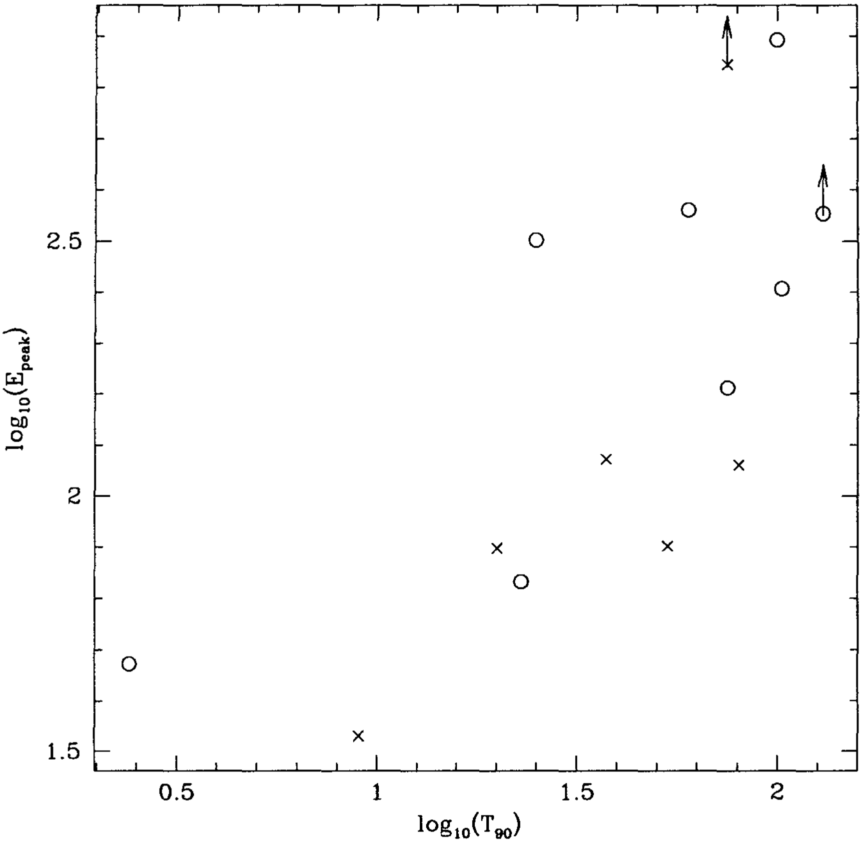

Figure 1. The relation between the peak energy $E_{\rm peak}$ and the burst duration T_{90} is shown in log-log plot for the two GRB subsamples grouped by the environment type. Open circles and crosses represent "ISM" and "WIND" GRBs, respectively. Vertical arrows indicate that quoted peak energy values are lower limits.

We choose the GRBs whose afterglow light curves are modeled in terms of the density profile of their ambient medium so that one can determine what kind of environment the source resides in. Some of GRBs are equally well (or poorly) described by the two types of media at the same time. We exclude these cases in our analysis. Of those chosen bursts, we further select the GRBs whose redshift z, peak energy $E_{\rm peak}$, and the burst duration T_{90} are all known. We then divide our sample into two subsamples so that we separate GRBs into the "ISM" GRBs and the "WIND" GRBs. The selected bursts are observed by BATSE[1], BeppoSAX[2], Ulysses[3], HETE-2[4]. We list the GRBs used in our analysis in Table 1 with the environment type.

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[1] ftp://cossc.gsfc.nasa.gov/pub/data/batse/

[2] http://www.asdc.asi.it/bepposax/

[3] http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/ulysses.html

[4] http://space.mit.edu/HETE/Bursts/

Table 2. Obtained correlation coefficients and the chance probability. The linear correlation coefficient, the Spearman rank-order correlation, the Kendall's τ, and corresponding chance probabilities for the total sample and two subsamples of the "ISM" and the "WIND" GRBs are shown.

	Uncorrected			Corrected		
	all	ISM	WIND	all	ISM	WIND
r	0.7193	0.7813	0.7288	0.6057	0.6446	0.6803
P	1.8×10^{-3}	1.1×10^{-2}	5.0×10^{-2}	1.0×10^{-2}	4.2×10^{-2}	6.8×10^{-2}
r_s	0.7494	0.5952	0.7142	0.6483	0.5714	0.7142
$P(r_s, N)$	1.0×10^{-3}	5.9×10^{-2}	5.5×10^{-2}	6.0×10^{-3}	6.9×10^{-2}	5.5×10^{-2}
τ	0.5824	0.5000	0.6000	0.4945	0.4285	0.6000
P_τ	3.7×10^{-3}	8.3×10^{-2}	9.1×10^{-2}	1.3×10^{-2}	0.137	9.1×10^{-2}

Note. Calculations are repeated before and after correction of effects of the cosmological expansion by a factor of $1 + z$.

In Figure 1, we show the relation between the peak energy $E_{\rm peak}$ and the burst duration T_{90} in log-log plot for the two subsamples of GRBs divided by the environment type. Open circles and crosses represent the "ISM" GRBs and the "WIND" GRBs, respectively. Vertical arrows indicate that quoted peak energy values are to be considered as lower limits. We calculate a linear correlation coefficient r with all the data in the total sample and with those in two subsamples. We also calculate the single-sided chance probability that $|r|$ has an equal or larger value than its observed in the null hypothesis. According to the obtained probability the whole data set shows a significant correlation, that is, $r \simeq 0.72$ with $P = 1.86 \times 10^{-3}$. To examine additional statistical tests of data sets, we employ the Spearman rank-order correlation test. It returns a correlation value r_s and the single-sided probability $P(r_s, N)$ that N pairs of uncorrelated variables would yield a value of r_s equally or more discrepant than the one obtained from the data set. We find again with the total sample that the peak energy of GRBs appears to correlate quite significantly with the duration, that is, $r_s \simeq 0.75$ with $P(r_s, N) = 1.01 \times 10^{-3}$. We also calculate Kendall's τ and the probability P_τ whose meaning is similar to that of $P(r_s, N)$. General trends of test results are similar to those of the Spearman rank-order correlation test. We find that linear correlations in two subsamples become different, that is, $r \simeq 0.78$ with $P = 1.11 \times 10^{-2}$ and $r \simeq 0.73$ with $P = 5.01 \times 10^{-2}$, for the "ISM" GRBs and the "WIND" GRBs, respectively. The "ISM" GRBs and the "WIND" GRBs statistically differ in the Spearman r_s value. That is, the "WIND" GRBs seem more correlated than the "ISM" GRBs, that is, $r_s \simeq 0.60$ for the "ISM" GRBs and $r_s \simeq 0.71$ for the "WIND" GRBs, respectively. One may wish to check with a larger sample in the future whether it is ascribed to the small size of the sample or it is intrinsic. The obtained statistical parameters are summarized in Table 2. Note that when we calculate slopes and correlations, we take the lower limit of the peak energy $E_{\rm peak}$ for the two GRBs as the value at the duration.

Cosmological objects should be redshifted in energy, as well as extended in time due to the cosmological expansion of the universe. For a cosmological source at redshift z, the observed peak energy $E_{\rm peak}$ is related to the redshift-corrected peak energy $E_{\rm peak,c}$ in the source frame by $E_{\rm peak} = E_{\rm peak,c}/(1 + z)$. Similarly, the observed duration T_{90} is prolonged due to cosmological time dilation by an amount proportional to $1 + z$, that is, $T_{90} = T_{90,\rm c}(1 + z)$. To see effects of the cosmological expansion, we rescale the peak energy $E_{\rm peak}$ and the duration as mentioned. Having corrected effects of the cosmological expansion, we show the relation between the peak energy $E_{\rm peak,c}$ and the burst duration $T_{90,\rm c}$ in Figure 2 for the two subsamples of GRBs. In order to compare the correlation coefficients with those obtained before taking cosmological expanding effects into account, we repeat same calculations after rescaling the GRB parameter to a factor of $1 + z$. The correlation coefficients resulted from the whole data tend to become less steep as redshift is corrected. For instance, the Spearman r_s value for the whole data is $r_s \simeq 0.65$ with corresponding probability $P(r_s, N) = 6.07 \times 10^{-3}$. We also find that the "ISM" GRBs and the "WIND" GRBs statistically differ in the Spearman r_s value, that is, $r_s \simeq 0.57$ for the "ISM" GRBs and $r_s \simeq 0.71$ for the "WIND" GRBs, respectively. A summary of parameters that we have investigated and their corresponding r_s and $P(r_s, N)$ values are shown in Table 2.

There are some limits in this analysis. First of all, the number of data may be too small to draw a conclusive statement. Particularly, the data set contains two lower limit values. We have repeated same calculations without those data points, yet have obtained similar conclusions in general. For instance, linear correlation coefficients and chance probabilities are $r \simeq 0.70$ with $P = 5.95 \times 10^{-3}$ and $r \simeq 0.53$ with $P = 3.80 \times 10^{-2}$, without and with redshift-correction, respectively. The Spearman correlation and corresponding chance probabilities are $r_s \simeq 0.76$ with $P(r_s, N) = 2.25 \times 10^{-3}$ and $r_s \simeq 0.49$ with $P(r_s, N) = 5.31 \times 10^{-2}$, without and with redshift-correction, respectively. Hence, the correlation between the peak energy $E_{\rm peak}$ and the burst duration T_{90} apparently exist both in the observer frame and in the source frame. Distinction between the "ISM" GRBs and the "WIND" GRBs becomes less obvious. For the "ISM" GRBs and the "WIND" GRBs, $r_s \simeq 0.61$ with $P(r_s, N) = 7.41 \times 10^{-2}$ and $r_s \simeq 0.7$ with $P(r_s, N) = 9.40 \times 10^{-2}$, without redshift correction. When the redshift is taken into account, the data does not show correlations any more. A summary of resulting values are shown in Table 3. Secondly, one must avoid a systematic mismatch in assigning the GRB environment since the conclusion that can be drawn in an attempt such as in this paper is critically based on the grouping of GRBs. Sometimes it may be hard to unanimously distinguish between two circumburst environments by current afterglow light curve modelling since there is a degeneracy of the parameters in the current afterglow model. Hence more cautious study on the GRB environments are desired for the definite classification.

3. DISCUSSIONS AND CONCLUSION

The spectroscopic finding of SN 2003dh in the afterglow light curve from GRB 030329 (Stanek et al. 2003, Hjorth et al. 2003) supports the previous identification of the nearby SN 1998bw with GRB 980425 (Galama et al. 1998, Iwamoto et al. 1998), providing a link between a GRB and the supernova explosion of a massive star. The implication of the supernova light is that the GRB progenitor is a massive star. An essential consequence of a massive star progenitor is that the environment for the progenitor is determined by the mass-loss wind from the star, of which signature is interestingly not found clearly in all afterglow light curves. This is at odds with the simple expectation of massive star progenitors. Several complications in modelling and interpreting the afterglow light curve still await to be fully understood (e.g., Chevalier, Li, & Fransson 2004). At present, however, it is fair to say that only a fraction of long GRB afterglows appears to be associated with the death of massive stars. That is, the observed GRBs have been born in two distinct types of natal environments.

A summary of our findings is as follows. Firstly, we find correlations between the peak energy $E_{\rm peak}$ and the burst duration T_{90} both in the observer frame and in the source frame with high probability (cf. Band et al. 1993). This correlation is expected from an analogous correlation that holds between the hardness-ratio and the duration for long and bright GRBs (Dezalay et al. 1996, Horack & Hakkila 1997). It is also found in Table 2 that removing effects of the cosmological expansion indeed reduces correlation values both in the total sample. The implication of our correlation analysis is that conclusions of the correlation between the hardness-ratio and the duration should be derived

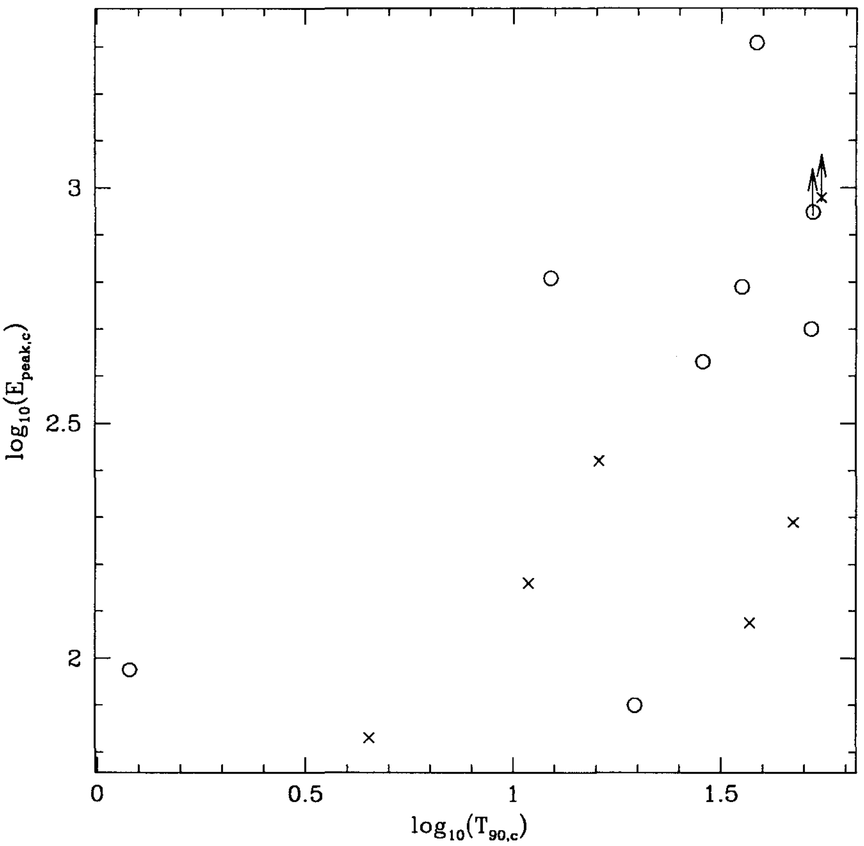

Figure 2. Similar plot as Fig. 1, but the peak energy $E_{\rm peak}$ and the burst duration T_{90} are scaled by a factor of $1 + z$ to remove effects of the cosmological expansion.

with due care, taking effects of the cosmological expansion into account. Secondly, we obtain a possible signature that all the long GRBs are not originated from a single population, as inferred from the properties of the ambient environment surrounding GRBs. That is, the "ISM" GRBs and the "WIND" GRBs might be intrinsically different, one groups has a correlation coefficient above the average value and the other below the average. The two most generally accepted classes of GRBs are those arising from the bimodal distribution of their durations (Kouveliotou et al. 1993), which separates long and short GRBs, the spectrum of short events being, on average, harder than that for longer events. A widely assumed scenario is that short bursts are likely to be produced by the merger of compact objects, while the core collapse of massive stars is likely to give rise to long bursts (e.g., Mészáros 2002 and Piran 2005). However, it is still unclear whether long GRBs consist of more than one population. For instance, various attempts to separate different classes of GRBs have been made (Tavani 1998, Balastegui, Ruiz-Lapuente, & Canal 2001). It should noted, however, that our results are somewhat inconclusive due to a low significance resulting from a small size of data sets.

Table 3. Similar table as Table 2, resulting from the data without two lower limit values in $E_{\rm peak}$.

	Uncorrected			Corrected		
	all	ISM	WIND	all	ISM	WIND
r	0.6961	0.7701	0.8565	0.5304	0.6135	0.5762
P	5.9×10^{-3}	2.1×10^{-2}	3.1×10^{-2}	3.8×10^{-2}	7.1×10^{-2}	0.154
r_s	0.7552	0.6071	0.7000	0.4895	0.4285	0.5000
$P(r_s, N)$	2.2×10^{-3}	7.4×10^{-2}	9.4×10^{-2}	5.3×10^{-2}	0.168	0.195
τ	0.5757	0.5238	0.6000	0.3636	0.3333	0.4000
P_τ	9.16×10^{-3}	9.8×10^{-2}	0.141	9.9×10^{-2}	0.293	0.327

Our finding does not rule out the fact that long GRBs may be originated from different progenitor populations.

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