Chin. J. Astron. Astrophys. Vol. 7 (2007), No. 3, 428–434
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Relationships between Relative Spectral Lags and Relative Widths of Gamma-ray Bursts*

Zhao-Yang Peng[1,4], Rui-Jing Lu[2], Yi-Ping Qin[1,2,3] and Bin-Bin Zhang[1,4]

[1] National Astronomical Observatories / Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011; *pzy@ynao.ac.cn*
[2] Physics Department, Guangxi University, Nanning 530004
[3] Center for Astrophysics, Guangzhou University, Guangzhou 510400
[4] Graduate School of Chinese Academy of Sciences, Beijing 100049

Received 2006 August 8; accepted 2006 November 20

Abstract The phenomenon of gamma-ray burst (GRB) spectral lags is very common, but a definitive explanation has not yet been given. From a sample of 82 GRB pulses we find that the spectral lags are correlated with the pulse widths, however, there is no correlation between the *relative* spectral lags and the *relative* pulse widths. We suspect that the correlations between spectral lags and pulse widths might be caused by the Lorentz factor of the GRBs concerned. Our analysis on the relative quantities suggests that the intrinsic spectral lag might reflect other aspect of pulses than the aspect associated with the dynamical time of shocks or that associated with the time delay due to the curvature effect.

Key words: gamma-rays: bursts — methods: statistical — gamma-rays: theory

1 INTRODUCTION

Much progress has been made since the discovery of gamma-ray bursts (GRBs) in 1967, especially with the recent launch of SWIFT. However, there has no consensus on the physics underlying their defining characteristics. Both the light curves and the spectra of GRBs are diverse in morphology. In the past few years, many attempts have been made to interpret the light curves and various interpretations of the observed gamma-ray pulses have been put forward mostly based on the standard fireball model (Rees & Meszaros 1992) because of the large energies and the short timescales involved. Some light curves only consist of a single, well-shaped pulse, often with a fast rise and an exponential decay (FRED) (see Fishman et al. 1994), while others exhibit very complex and ragged profiles. Several flexible functions describing the profiles of individual pulses based on empirical relations were proposed (see, e.g. Norris et al. 1996; Lee et al. 2000a,b; Ryde & Svensson 2000; Ryde & Petrosian 2002). Fitted with these functions many statistical properties of GRB pulses have been revealed. Phenomena such as the hardness-intensity correlation and the FRED form of pulses were recently interpreted as signatures of the relativistic curvature effect (see, e.g. Fenimore et al. 1996; Kocevski et al. 2003; Qin 2002; Qin et al. 2004).

In early statistical analyses, the light curves of GRB pulses were found to become narrower at higher energies (see, e.g. Link et al. 1993). The average dependence of the pulse width on energy is approximately a power law (see, e.g. Fenimore et al. 1995; Norris et al. 1996, 2000; Costa 1998; Piro et al. 1998; Nemiroff 2000; Feroci et al. 2001; Crew et al. 2003; Qin et al. 2005; Peng et al. 2006). It was suggested that the power law form could be attributed to synchrotron radiation (see, e.g. Fenimore et al. 1995; Cohen et al. 1997) or synchrotron cooling (see Kazanas et al. 1998; Chiang 1998; Dermer 1998; Wang et al. 2000). In addition,

* Supported by the National Natural Science Foundation of China.

it was suspected that the power law might result from a relative projected speed or a relative beaming angle (Nemiroff 2000).

Delay between the light curves in different energy bands is observed not only in GRBs but also in other astrophysical objects. Many authors have investigated the observed spectral lags of GRBs. Cheng et al. (1995) first measured the difference in arrival times between high- and low-energy photon peaks and quantified the delays of the low-energy photons. Several relations involving the spectral lags and other quantities are investigated by many authors (see, e.g. Norris et al. 2000; Ramirez-Ruiz & Fenimore 2000; Schaefer et al. 2001; Salmonson & Galama 2002). Kocevski & Liang (2003) argued that the observed lags are the direct result of spectral evolution. Shen et al. (2005) tentatively studied the contributions of the curvature effect of fireballs to the lags and showed that the observed lags can be accounted for by this effect. Lu et al. (2006a) further investigated the issue based on Qin et al.'s model (Qin 2002; Qin et al. 2004) and further confirmed their conclusions. Based on these studies, many statistical characteristics have been revealed.

Norris et al. (2005) analyzed the temporal and spectral behavior of wide pulses in 24 long-lag bursts and found that the pulse widths were strongly correlated with the spectral lags. Zhang et al. (2006) investigated the relative spectral lags and found that they are strongly correlated with the redshifts and peak luminosities. Since the spectral lags are related to pulse widths and the relative spectral lag is an important quantity, we investigate in this paper whether the spectral lags are related to the pulse rise and decay widths and whether there exist relationships between the relative spectral lags, relative rise widths and relative decay widths. This paper is organized as follows. We describe the sample selection and the analysis methods in Section 2. The results of analysis are presented in Section 3. In the last section we give a discussion and our conclusions.

2 SAMPLE SELECTION AND ANALYSIS METHODS

Two GRB samples, one from Kocevski et al. (2003) one from Norris ea al. (1999), with 19 pulses in common, were used by Peng et al. (2006) to investigate relationships between the pulse width and energy of GRBs. They tested the platform-power-law-platform relationship predicted by the curvature effect (Qin et al. 2005), and found that the two samples share the same statistical characteristics. Here, we combine these two samples to study the relation between the spectral lag and the pulse width, the latter having been well estimated and available from Peng et al. (2006). We select only those pulses that can be modeled with equation (22) of Kocevski et al. (2003) (the KRL function) in the first and third BATSE channels since these two channels are involved in calculating the spectral lag. Some pulses in these channels possess low signal-to-noise ratios that they can not be modeled with the function. Under this selection criterion, we obtain 82 GRB pulses to serve as the sample for our analysis.

Following many previous authors (e.g., Link et al.1993; Cheng et al. 1995; Band 1997; Norris et al. 2000, 2005; Chen et al. 2005), we use the cross-correlation function (CCF) to measure the time lag between the pulses of the same burst seen in the BATSE channels 1 and 3. With $\{\upsilon_1\}$ and the $\{\upsilon_2\}$ denoting the light curves in the two different energy bands, the CCF is defined as a function of τ,

$$\mathrm{CCF}(\tau = \mathrm{k}\Delta\mathrm{t}; \upsilon_1, \upsilon_2) = \frac{\langle \upsilon_1(\mathrm{t})\upsilon_2(\mathrm{t}+\tau)\rangle}{\sigma_{\upsilon_1}\sigma_{\upsilon_2}}, \quad (1)$$

where $\sigma_{\upsilon_i} = \langle \upsilon_i^2 \rangle^{1/2}$, and Δt is a time bin. A positive τ which is the dominant behavior observed in GRBs indicates a soft lag (higher energy gamma-ray photons arriving earlier than lower energy ones), while the negative lag means that of the reverse.

Peng et al. (2006) adopted the KRL function to fit all of the light curves pulses of their selected samples and evaluated the five parameters of the function. Then they worked out the full width at half-maximum (FWHM) as well as the rise FWHM (r_{FWHM}) and decay FWHM (d_{FWHM}) for all the selected pulses in the BATSE channels. We adopt the same method as Peng et al. (2006) here. The uncertainties of these widths are calculated with the errors of the fitting parameters through the error transfer formula. In this paper, r_{FWHM1} and r_{FWHM3} denote the rise FWHMs in channels 1 and 3, and d_{FWHM1} and d_{FWHM3}, the decay FWHMs in channels 1 and 3, respectively.

3 RESULTS OF ANALYSIS

3.1 Spectral Lags vs. Rise and Decay Widths

The method we used is similar to that in Norris et al. (2000), where the time lag between two light curves of the BATSE channels 1 and 3 is measured (which we denote as τ_{13}). The cross-correlation is performed in the region down to the fraction of 0.1 of the peak intensity (i.e. we limit the analysis to regions with count rates greater than 0.1 of the peak intensity). The reason for doing this is to minimize the inclusion of the post-non-burst emission and to make a uniform standard for our selected pulses, where manual intervention would be minimized. The observed light curves contain noise. Hence the CCF may not peak symmetrically about τ_0. In order to reduce the scatter caused by noise, we adopt a quadratic form to fit the region around the CCF peak, and take the peak of the quadratic form as the lag, rather than simply read off the lag from the peak of the CCF curve. The error in the average CCF lag, τ_{13}, is found by simulations with Gaussian noise added to each of the two channels. Figure 1 shows that the average CCF lags of our sample are mostly narrowly clustered near 100 ms, which is consistent with the result obtained by Band (1997) and Norris et al. (2000).

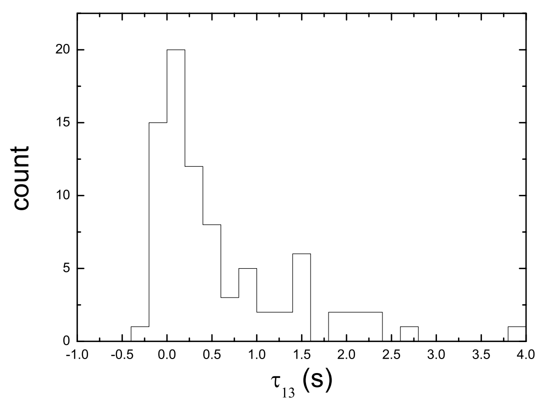

Fig. 1 Histograms of the average CCF lag, τ_{13}, between channels 1 and 3.

Norris et al. (2005) have studied the relationships between the peak and centroid lags and pulse widths in 24 long-lag bursts. Following Norris et al. (2005), let us first check the relationships between τ_{13} and FWHM_1 and FWHM_3 in 82 FRED pulses. Figure 2 shows that linear correlations do exist, with linear correlation coefficients 0.77 for channel 1 and 0.57 for channel 3, respectively; these are also consistent with the result obtained by Norris et al. (2005).

Some authors (e.g. Ryde et al. 2003; Lu et al. 2006b) found that the rise and decay widths of GRB pulses are each correlated with the full widths. Here, we explore the relationship between spectral lags and the rise and decay widths. See Figure 3. Panel (a) displays a strong correlation between τ_{13} and $r_{\rm FWHM1}$. The slope of the linear fit is 0.34 ± 0.03 and the linear correlation coefficient is $R = 0.78$. Panel (b) presents a similar correlation between τ_{13} and $d_{\rm FWHM1}$, with slope 0.14 ± 0.01 and linear correlation coefficient 0.74. The relation between τ_{13} and $r_{\rm FWHM3}$ is shown in panel (c), where the slope is 0.24 ± 0.04 and the correlation coefficient is $R = 0.59$. Panel (d) shows the relation between τ_{13} and $d_{\rm FWHM3}$, with slope 0.20 ± 0.03, and correlation coefficient 0.56. We may note that the correlations between spectral lags (τ_{13}) and full width (FWHM), rise widths ($r_{\rm FWHM}$), and decay widths ($d_{\rm FWHM}$) are less strong in channel 3 than in channel 1. The reason of this difference is not clear, and deserves further investigation.

3.2 Relative Spectral Lags vs. Relative Rise and Decay Widths

As is generally known, the time interval observed from the emission of an expanding fireball is contracted by a factor of $\sim 1/\Gamma^2$, Γ being the Lorentz factor of the expanding motion. The width of pulses measured by the observer is therefore proportional to $1/\Gamma^2$ (see, e.g. Qin et al. 2004). In the case that the Lorentz

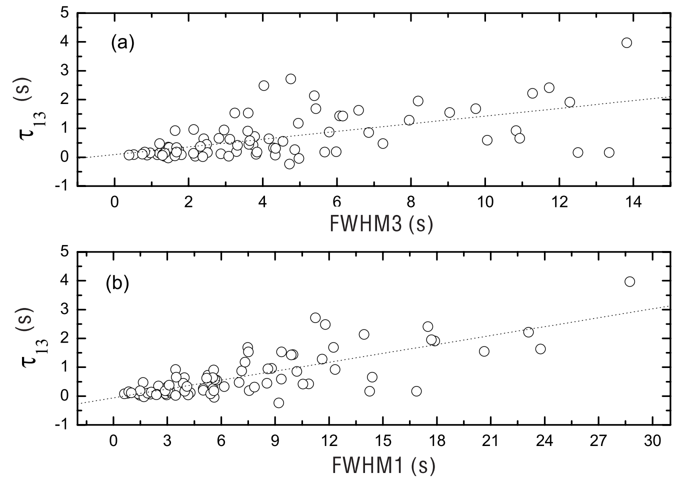

Fig. 2 Relationships between the average CCF lag (τ_{13}) and each of the two pulse widths (FWHM), in the first channel (lower panel) and the third channel (upper panel). The dotted lines mark the regression lines for our selected sample.

factor is as large as ≥ 100, the observed time interval would become smaller than the original one by about 10^4 times. Since any time intervals associated with the emission from a fireball are contracted by the same factor, it is expected that they would be mutually correlated for a sample of fireballs when these fireballs have different values of Γ. Hence we suspect that the correlations shown in Figures 2 and 3 might be caused by the Lorentz factor of the GRBs concerned. We wonder how the relationships would become if the effect of the Lorentz factor is removed.

To remove this effect, one needs to know the values of Γ for the sources concerned. Unfortunately they are not available for the adopted sample. Recalling that any time intervals observed from a source would be contracted by the same factor, we can consider the relative values, τ_{13}/FWHM1, τ_{13}/FWHM3, $r_{\rm FWHM1}$/FWHM1, $d_{\rm FWHM1}$/FWHM1, $r_{\rm FWHM3}$/FWHM3 and $d_{\rm FWHM3}$/FWHM3. Obviously, the time contraction effect is cancelled out in these quantities. See Figure 4, in which Panels (a), (b), (c), and (d) display, respectively, the τ_{13}/FWHM1 versus $r_{\rm FWHM1}$/FWHM1, τ_{13}/FWHM1 versus $d_{\rm FWHM1}$/FWHM1, τ_{13}/FWHM3 versus $r_{\rm FWHM3}$/FWHM3, and τ_{13}/FWHM3 versus $d_{\rm FWHM3}$/FWHM3 relation. We observe from Figure 4 that neither the relative rise width nor the relative decay width correlate with the relative spectral lag.

The disappearance of the correlations shown in Figure 3, when the relative quantities are considered, indicates that the Lorentz factor does play an important role in producing the correlations. According to this result, it seems that the correlations shown in Figure 2 might also be caused by the Lorentz factor (which cannot be checked currently due to the lack of the information on Γ).

4 DISCUSSION AND CONCLUSIONS

Relations between spectral lags and other physical quantities (such as luminosities, variabilities and hardness ratios) have been investigated by many authors. The observed spectral lags can be obtained in different time series in different energy bands, which affords a simple and useful means to explore some physical process. Norris et al. (2005) studied the relation between spectral lags and pulse widths, and found that they are strongly correlated with each other. In this paper, we take a sample of 82 GRBs to investigate the same relations and to check the relations between relative spectral lag and relative rise and decay widths. Our analysis shows that the observed delay is correlated both with the pulse rise width and the pulse decay width, while there are no correlations between the relative spectral lag, relative rise width and relative decay width.

Wu & Fenimore (2000) pointed out it is not always reliable to measure lags with CCF. The calculated CCF lag result can be affected by multi-peaked bursts and the methods used to calculate the CCFs. For

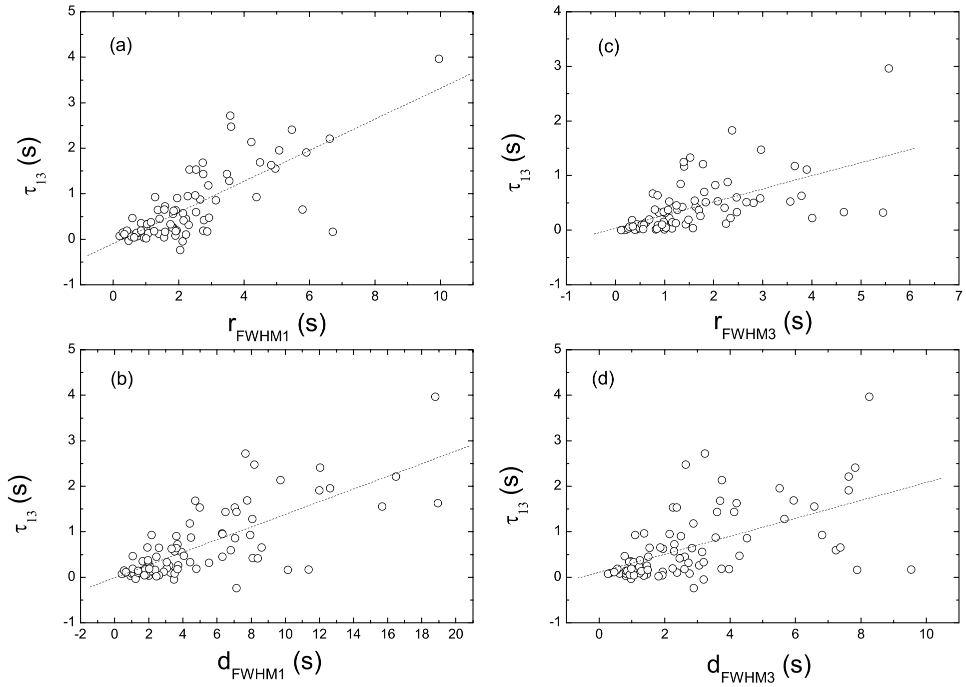

Fig. 3 Relationships between the average CCF lag (τ_{13}), the rise width (the upper panels) and decay width (the lower panels) in channel 1 and 3 in our selected sample. The dotted lines are the regression lines.

instance, the inclusion of time intervals of signal will clearly affect the measurements. Ryde et al. (2005) noted that different pulses within a burst have different lags, and a similar conclusion was drawn by Hakkila & Giblin (2004). We accordingly select only those pulses which can be well fitted with the KRL function. We also change the time interval of signals similar to what Norris et al. (2000) did. We limit the analysis to regions with count rate greater than $0.2\times$ and $0.3\times$ peak intensity, respectively, and obtain very similar results. We also adopt the cubic fit to CCF as many authors did and obtained identical results. Hence we can confirm that our calculation of the CCF is indeed well established.

There are two classes of models that explain different aspects of the duration of GRBs. One is the external shock model (Meszaros & Rees 1993), which is mainly used to interpret the afterglow. The model accounting for the prompt GRB emission is the internal shock model (Rees & Meszaros 1994). If a single relativistic shell with high bulk Lorentz factor (Γ) expands outward from a central engine toward the observer, there would be two factors affecting the observed temporal structure. One is the Lorentz factor, as mentioned above, and the other is the radius of the fireball. Qin et al. (2004) established the following relationship: $\Delta\tau_{\rm FWHM} \simeq R(t_{\theta,0})(\sqrt{2}\text{-}1)/2\Gamma^2 R_c$ ($\Gamma \gg 1$), where $\Delta\tau_{\rm FWHM}$ is the width of the light curve of the local δ-function pulse, $R(t_{\theta,0})$ is the radius of the fireball at the rest-frame time $t_{\theta,0}$, and R_c is a constant.

We find that the Lorentz factor contracts the observed time interval while the fireball radius stretches the time interval. However, we are not aware if the spectral lag is affected by the fireball radius or not. If it is, the relative quantities studied above would have the time contract and stretch effects from the Lorentz factor and the fireball radius cancelled out. If not, then the relative spectral lag would cancel only the time contracting effect arising from the Lorentz factor, while in the same time it introduces a time stretching factor associated with the fireball radius. The latter would cause more scatter in the data. Although we cannot present an analysis on this issue at this moment, we can provide a rough assessment. The above relationship shows that the width of pulses measured by the observer is proportional to $1/\Gamma^2$ and $R(t_{\theta,0})$, respectively, which indicates that the effect of Γ on temporal structure is much larger than $R(t_{\theta,0})$. We think

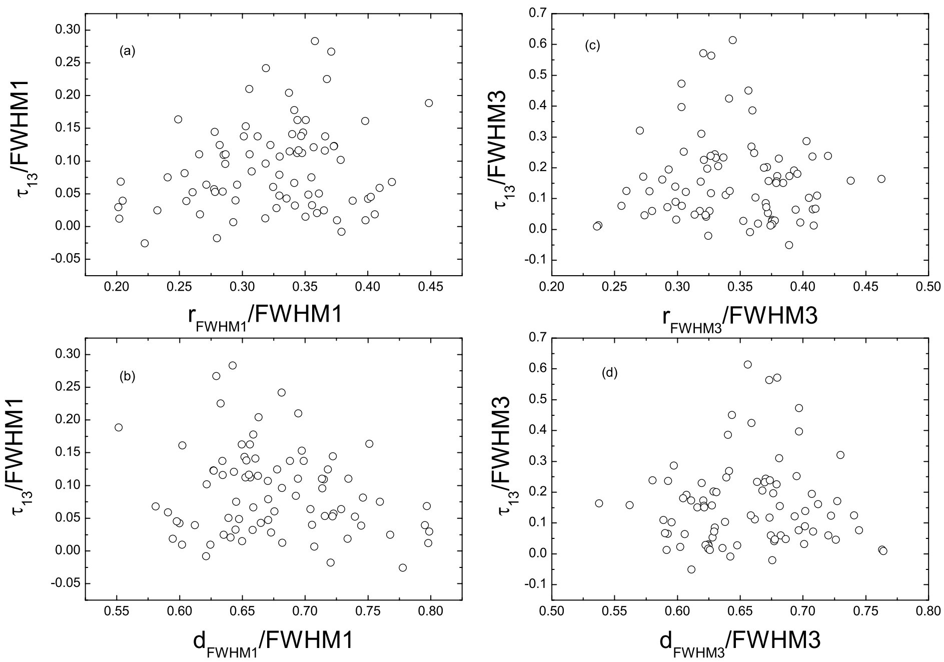

Fig. 4 Relationships between the relative average CCF lag, relative rise widths (the upper panels) and relative decay widths (the lower panels) in channels 1 and 3 relative to FWHM1 (the left panels) and FWHM3 (the right panels), where FWHM1 and FWHM3 are the pulse widths of channels 1 and 3, respectively, for our selected sample.

that the distribution of the fireball radius is not too wide since it is generally acknowledged that the long GRBs are associated with the deaths of massive stars. That is, the long GRBs are thought to have a same origin.

Therefore, if the relative spectral lag is affected by the fireball radius, we think the effect is relatively small. It is pointed out by many authors that the rise pulse phase and the decay pulse provide different information on the GRBs. They showed that the rise pulse phase depends on the time for a reverse shock to cross the shell and also describes the energization of the emitting plasma and the size of the activated region as well. However, the decay pulse phase depends on the curvature of the shell and also provides information on the cooling (see, Fenimore & Ramirez-Ruiz 1999; Ryde & Svensson 2002). Norris et al. (2005) pointed out that the details of pulse evolution are determined by a combination of intrinsic and extrinsic properties. The intrinsic properties relate to the emitting region, including energization and cooling processes and jet profile, and the extrinsic properties include some external factors, such as viewing angle and related absorption. Hakkila & Giblin (2006) also showed that the internal luminosity function power-law index and the spectral lags are two intrinsic GRB parameters rather than extrinsic ones. They argued that the intrinsic characteristics such as bulk Lorentz factor and jet-beaming angle dominate over cosmological effects, which means that the observed quantity is not significantly affected by cosmology or by other observational effects. According to our analysis on the relative quantities, we tend to believe that the intrinsic spectral lag might reflect an aspect of pulses other than the one associated with the dynamical time of shocks or with the time delay owing to the curvature effect.

Shen et al. (2005) showed that the observed lags could arise from the curvature effect of the fireballs. The conclusion was confirmed further by Lu et al. (2006a). However, after removing the time contracting effect of the Lorentz factor, we find no correlations between the relative spectral lag and the relative decay width of pulses. We therefore suspect that the cause that leads to the conclusion might be the Lorentz factor. As a Lorentz factor of $\Gamma = 100$ would contract a time interval by a factor of 10^4, it is not surprising that the time interval caused by the curvature effect could be of the same order of the spectral lag observed so long as the Lorentz factor ranges from 10 to 1000.

Since many factors might be involved, we cannot provide a conclusion about the spectral lag and the curvature effect. It is hoped that the issue will be investigated from other aspects. This issue relates not only the dynamic process but also the kinetic properties of the objects, and deserves further investigations.

Acknowledgements This work was supported by the Special Funds for Major State Basic Research Projects ("973") and National Natural Science Foundation of China (Nos. 10273019 and 10463001).

References

Band D. L., 1997, ApJ, 486, 928
Chen L., Lou Y. Q., Wu M. et al., 2005, ApJ, 619, 983
Cheng L. X., Ma Y. Q., Cheng K. S. et al., 1995, A&A, 300, 746
Chiang J., 1998, ApJ, 508, 752
Cohen E., Katz J. I., Piran T. et al., 1997, ApJ, 488, 330
Costa E., 1998, Nuclear Physics B (Proc. Suppl.), 69/1-3, 646
Crew G. B., Lamb D. Q., Ricker G. R. et al., 2003, ApJ, 599, 387
Dermer C. D., 1998, ApJ, 501, L157
Feroci M., Antonelli L. A., Soffitta P. et al., 2001, A&A, 378, 441
Fishman G. J., Meegan Charles A., Wilson Robert B. et al., 1994, ApJS, 92, 229
Fenimore E. E.; in't Zand J. J. M., Norris J. P. et al., 1995, ApJ, 448, L101
Fenimore E. E., Madras C. D., Nayakshin S., 1996, ApJ, 473, 998
Fenimore E. E., Ramirez-Ruiz E., 1999, astro-ph/9909299
Hakkila J., Giblin T. W., 2004, ApJ, 610, 361
Hakkila J., Giblin T. W., 2006, ApJ, 646, 1086
Kazanas D., Titarchuk L. G., Hua X. M., 1998, ApJ, 493, 708
Kocevski D., Liang E., 2003, ApJ, 594, 385
Kocevski D., Ryde F., Liang E., 2003, ApJ, 596, 389
Lee A., Bloom, E. D., Petrosian V., 2000a, ApJS, 131,1
Lee A., Bloom E. D., Petrosian V., 2000b, ApJS, 131, 21
Link B., Epstein R. I., Priedhorsky W. C., 1993, ApJ, 408, L81
Lu R. J., Qin Y. P., Zhang Z. B. et al., 2006a, MNRAS, 367, 275
Lu R. J., Qin Y. P., Yi T. F., 2006b, Chin. J. Astron. Astrophys.(ChJAA), 6, 52
Meszaros P., Rees M. J., 1993, ApJ, 405, 278
Nemiroff R. J., 2000, ApJ, 544, 805
Norris J. P., Nemiroff R. J., Bonnell J. T. et al., 1996, ApJ, 459, 393
Norris J. P., Bonnell J. T., Watanabe K., 1999, ApJ, 518, 901
Norris J. P., Marani G. F., Bonnell J. T., 2000, ApJ, 534, 248
Norris J. P., Bonnell J. T., Kazanas D. et al., 2005, ApJ, 627, 324
Piro L., Heise J., Jager R. et al., 1998, A&A, 329, 906
Peng Z. Y., Qin Y. P., Zhang B. B. et al., 2006, MNRAS, 368, 1351
Qin Y. P., 2002, A&A, 396, 705
Qin Y. P., Zhang Z. B., Zhang F. W. et al., 2004, ApJ, 617, 439
Qin Y. P., Dong Y. M., Lu R. J. et al., 2005, ApJ, 632, 1008
Ramirez-Ruiz E., Fenimore E. E., 2000, ApJ, 539, 712
Rees M. J., Meszaros P., 1992, MNRAS, 258, 41
Rees M. J., Meszaros P., 1994, ApJ, 430, L93
Ryde F., Svensson R., 2000, ApJ, 529, L13
Ryde F., Petrosian V., 2002, ApJ, 578, 290
Ryde F., Borgonovo L., Larsson S. et al., 2003, A&A, 411, L331
Ryde F., Kocevski D., Bagoly Z. et al., 2005, A&A, 432, 105
Salmonson J. D., Galama T. J., 2002, ApJ, 569, 682
Schaefer B. E., Deng M., Band D. L., 2001, ApJ, 563, 123
Shen R. F., Song L. M., Li Z., 2005, MNRAS, 362, 59
Wang J. C., Cen X. F., Qian T. L. et al., 2000, ApJ, 532, 267
Wu B. B., Fenimore E. E., 2000, ApJ, 535, L29
Zhang Z. B., Deng J. G., Lu R. J. et al., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6, 312