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Can the bump in the composite spectrum of GRB 910503 be an emission line feature of gamma-ray bursts? *

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Abstract Appearing in the composite spectral data of BATSE, EGRET and COMPTEL for GRB 910503, there is a bump at around 1600 keV. We perform a statistical analysis on the spectral data, trying to find out if the bump could be accounted for by a blue-shifted and significantly broadened rest frame line due to the Doppler effect of an expanding fireball surface. We made an F-test and adopted previously proposed criteria. The study reveals that the criteria are well satisfied and the feature can be interpreted as the blue shifted 6.4 keV line. From the fit with this line taken into account, we find the Lorentz factor of this source to be $\Gamma = 116^{+9}_{-9}$ (at the 68% confident level, $\triangle\chi^2 = 1$) and the rest frame spectral peak energy to be $E_{0,p} = 2.96^{+0.24}_{-0.18}$ keV. Although the existence of the emission line feature requires other independent tests to confirm, the analysis suggests that it is feasible to detect emission line features in the high energy range of GRB spectra when taking into account the Doppler effect of fireball expansion.

Key words: gamma-rays: bursts — gamma-rays: theory — radiation mechanisms: nonthermal — relativity

1 INTRODUCTION

The detection and analysis of spectral lines in gamma-ray bursts (GRBs) can yield information of extraordinary value on the nature of the objects. Although some line features have been reported by various experiments previously (Mazets et al. 1980; Fenimore et al. 1988; Murakami et al. 1988), so far BATSE has not detected any of the spectral features reported by earlier satellites (Palmer et al. 1994; Band et al. 1996), so throwing doubt upon the previous observations (Piran 1999; Cheng & Lu 2001).

As revealed by the observation of absorption lines of afterglows (Mazets et al. 1981), GRBs were confirmed to be events occurred within the environment of stars. Based on the assumption

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that GRBs reside in the environment of stars, mechanisms of emission as well as absorption lines for the objects are well established. Meszaros & Rees (1998) suggested that gamma-ray burst outflows may entrain small blobs or filaments of dense, highly ionized metal-rich material, which might be accelerated by the flow to Lorentz factors in the range 10–100. In the event of neutron-star collisions or black hole-neutron star collisions, neutrino-antineutrino annihilation can produce electron-positron pairs. Thus it would be natural if there exist in the outer shell of fireballs some high energy emission lines such as the 6.4 keV line or the 511 keV annihilation line.

Due to the observed large output rate of radiation of GRBs, most models envision an expanding fireball (see e.g., Goodman 1986; Paczynski 1986; Cheng & Lu 2001). The gamma-ray emission would arise after the fireball becomes optically thin, in shocks produced when the ejecta collide with an external medium or occurred within a relativistic internal wind (Rees & Meszaros 1992, 1994; Meszaros & Rees 1993, 1994; Katz 1994; Paczynski & Xu 1994; Sari et al. 1996). As the expanding motion of the outer shell of the fireball would be relativistic, the Doppler effect must be at work and in considering the effect the fireball surface itself would play a role.

It was pointed out that within the relativistic fireball model an observed broadened spectral line might be a blue shifted iron X-ray line (Meszaros & Rees 1998). Due to the large value of the Lorentz factor of the fireball, the broadening and blue-shift must be very significant (see, e.g., Hailey et al. 1999; Qin 2003). Therefore, in detecting line features, the Doppler effect associated with the expansion of fireballs should be taken into account. In particular, when searching for emission line features in the observed spectrum of a burst, we should consider rest frame lines of much lower energy, and, instead of searching for narrow lines, one should search for broad lines.

In the following we perform a statistical analysis on the bump appearing in the composite spectral data of GRB 910503, and carry out an F-test assuming it to be an emission line feature.

2 THE BUMP AS A LINE FEATURE

GRB 910503 is a bright burst, to whose BATSE data alone Band et al. (1996) applied an F-test that compares the spectral fits by a continuum-only model and a continuum-plus-line model but detected no line features. Here we apply once more the F-test to this same source, considering the Doppler effect based on the fireball mechanism and for the newly published composite data over a wide energy range (from 20 keV to 300 MeV) (Schaefer et al. 1998). The process of combining the data was described in details in Schaefer et al. (1998). Briefly, GRB 910503 was observed by BATSE, EGRET and COMPTEL. Its light curve consists of two distinct and well separated episodes separated by background. For the energies covered by EGRET and COMPTEL, the first episode had a shorter duration (Schneid et al. 1992; Hanlon et al. 1994). The spectra used cover only the first episode, which contains roughly three-quarters of the burst flux. Each spectrum is rebinned in energy to some standard templates. On a bin-by-bin basis, the various instruments are combined as a weighted average. The result is then a composite spectrum over a broad energy range. As pointed out by Schaefer et al. (1998), the spectrum presented is quantitative and is suitable for theorists to test emission mechanism models over a wide energy range.

To check the presence of a line feature in the composite spectrum, we will adopt the criteria proposed previously by Band et al. (1996). In addition, we propose that any features concerned should be well interpreted. Thus, we construct our criteria as follows: a) there exists at least one emission line, whose mechanism is well established, to account for the concerned feature; b) an F-test probability less than 10^{-4} is obtained for at least one of the fits of the supposed emission lines.

Table 1 Relevant Values of the Fits

χ^2	dof	line (keV)	Γ	$\nu_{0,p}$ (keV h^{-1})	$\alpha_{0,G}$	$\beta_{0,G}$	$h_{0,l}$	σ (keV h^{-1})	C (photons cm^{-2} keV^{-1}) $\times(E/100\,\mathrm{keV})^2$]
44.2	58		14.6	26.7	–0.753	–2.28			0.310
29.9	56	6.4	116	2.96	–0.716	–2.23	0.0331	2.50	0.284
30.2	56	511	1.62	234	–0.723	–2.23	0.0327	198	0.285
30.9	57	6.4	125	2.75	–0.708	–2.24	0.0325	2.02	0.287

One can find a bump at around 1600 keV in the spectrum of GRB 910503. We assume it to be an emission line feature blue-shifted from a much lower energy band. Here, we try to fit this bump with the rest frame lines of 6.4 keV and 511 keV respectively by taking into account the Doppler effect of the fireball surface. The fit will be checked by the F-test.

As described in Qin (2002), the expected spectrum, observed at time t and at frequency ν, based on the fireball mechanism, is

$$\nu f_\nu(t) = \frac{2\pi I_0 \widetilde{R}^2(t)}{D^2}\frac{\nu}{\Gamma^3}\int_0^{\pi/2} g_{0,\nu}(\nu_{0,\theta})\frac{\cos\theta\sin\theta}{(1-\beta\cos\theta)^5}d\theta, \tag{1}$$

where the radiation is assumed to be constant and independent of directions, $\widetilde{R}(t)$ is a function of t, D the distance of the fireball to the observer, Γ the Lorentz factor of the fireball, θ the angle to the line of sight, $\nu_{0,\theta}$ the rest frame emission frequency of the differential surface, of the fireball, with θ ($\nu_{0,\theta}$ and ν are related by the Doppler effect), $g_{0,\nu}(\nu_{0,\theta})$ the relative rest frame intensity of the differential surface, and I_0 the magnitude of the intensity.

To fit the spectrum, we assume a rest frame radiation of the Band function (Band et al. 1993) together with one of the two rest frame lines. To meet the data, which represent an average spectrum, the expected curve is normalized to

$$\nu f_\nu = C\frac{\nu\int_0^{\pi/2} g_{0,\nu}(\nu_{0,\theta})\frac{\cos\theta\sin\theta}{(1-\beta\cos\theta)^5}d\theta}{[\nu\int_0^{\pi/2} g_{0,\nu,G}(\nu_{0,\theta})\frac{\cos\theta\sin\theta}{(1-\beta\cos\theta)^5}d\theta]_{\mathrm{peak}}}, \tag{2}$$

where $\Gamma\equiv 1/\sqrt{1-\beta^2}$, C and Γ are variables, $g_{0,\nu,G}(\nu_{0,\theta})$ the relative intensity of the rest frame radiation bearing the Band function with $\nu_{0,p}$, $\alpha_{0,G}$ and $\beta_{0,G}$ being variables.

For the continuum-only model we adopt:

$$g_{0,\nu}(\nu_{0,\theta}) = g_{0,\nu,G}(\nu_{0,\theta}). \tag{3}$$

Thus there are five free parameters in this fit. The number of data points is 63 and therefore the number of degrees of freedom of the fit is 58. For the continuum-plus-line model, we use

$$g_{0,\nu}(\nu_{0,\theta}) = g_{0,\nu,G}(\nu_{0,\theta}) + h_{0,l}\exp[-\frac{(\nu_{0,\theta}-\nu_{\mathrm{line}})^2}{2\sigma^2}], \tag{4}$$

with $\nu_{\mathrm{line}} = 6.4\,\mathrm{keV}\ h^{-1}$ and $511\,\mathrm{keV}\ h^{-1}$ respectively, where $h_{0,l}$ and σ are variables. Then there are seven free parameters and the number of degrees of freedom is 56.

We label the fit without any lines as Fit 1, the one with the 6.4 keV line as Fit 2, and the one with the 511 keV line as Fit 3. The relevant numerical values of these fits are listed in Table 1. Together with the error-bars, the Lorentz factor and the rest frame spectral peak energy at the 68% confidence level ($\triangle\chi^2 = 1$) we obtained are $\Gamma = 116^{+9}_{-9}$ and $\nu_{0,p} = 2.96^{+0.24}_{-0.18}\,\mathrm{keV}\ h^{-1}$ for Fit 2, and $\Gamma = 1.62^{+0.07}_{-0.10}$ and $\nu_{0,p} = 234^{+7}_{-9}\,\mathrm{keV}\ h^{-1}$ for Fit 3.

Shown in Figure 1 are the fit with the 6.4 keV line (Fit 2) and that without any lines (Fit 1).

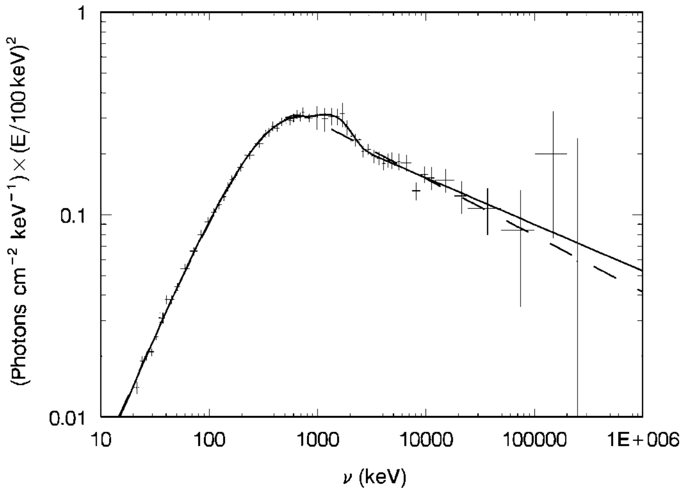

Fig. 1 The dashed line is the fit without any lines (Fit 1) and the solid line is fit with the 6.4 keV emission line (Fit 2) to the spectrum of GRB 910503. Pluses stand for the composite spectral data (the continuum component of Fit 2 is shown in Figure 4).

3 DISCUSSION

From the results of the three fits (see the first three lines in Table 1), one can find that the parameter Γ changes dramatically from 1.62 to 116 and the parameter $\nu_{0,p}$ changes from 2.96 to 234 keV h^{-1}. Shown in Figure 2 are the χ^2 confidence contours (99% confidence level) for the parameters Γ and $\nu_{0,p}$ for the fit without any lines (Fit 1). As can be seen from this figure the two parameters are degenerate: there are many possible values of Γ and $\nu_{0,p}$ for the given confidence level. To approach the given level of confidence, only the product of the two, $\Gamma\nu_{0,p}$, matters (the products are 390, 343, and 379 for Fits 1, 2, and 3, respectively). Neither Γ nor $\nu_{0,p}$ alone could confine the confidence level. According to Qin (2002), the shape of the expected spectrum of an expanding fireball remains almost the same as that of the corresponding rest frame spectrum for constant radiations. In other words, the shape of the spectrum is not affected by Γ. Thus, one cannot determine the value of Γ or $\nu_{0,p}$ merely according to the goodness of fit (but the product of the two can be estimated).

Is the total χ^2 changing from 44.2 to 29.9, 30.2 for the three fits caused by the inclusion of an additional line component rather than by the change of the continuum parameters? The answer is yes. With the parameters obtained in Fits 2 and 3, we obtain $\chi^2 = 74.8$ (Fit 2) and $\chi^2 = 73.3$ (Fit 3), respectively for the corresponding fits of the continuum (when allowing parameter C to be free, with the other parameters fixed, we obtain $\chi^2 = 65.2$ and C = 0.290 [(photons cm^{-2} keV^{-1}) × (E/100 keV)^2] for that of Fit 2, and $\chi^2 = 65.2$ and C = 0.291 [(photons cm^{-2} keV^{-1})×(E/100 keV)^2] for that of Fit 3, respectively). It shows that, instead of improving the fit, the continuum parameters of Fits 2 and 3 lead to a poor fit when adopting the continuum alone as the rest frame radiation. To illustrate this effect in more details, we present here the plot of $\Delta\chi^2$ calculated at each data point for Fits 1 and 2 and for Fits 1 and 3, respectively. As shown in Figure 3, the fit at the bump is obviously improved by the inclusion of an additional line component.

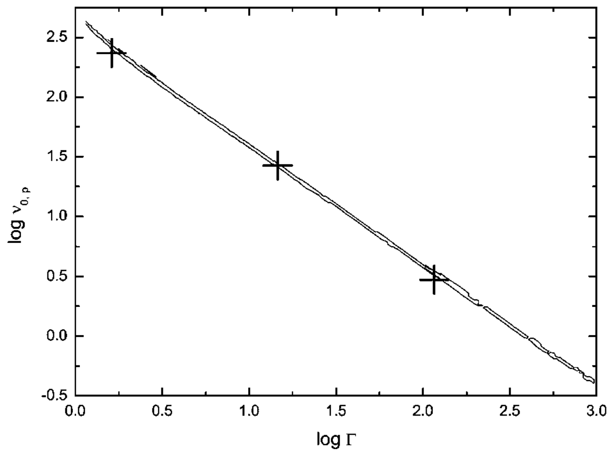

Fig. 2 χ^2 confidence contours (99% confidence level, $\Delta\chi^2 = 9.21$) for parameters Γ and $\nu_{0,p}$ for the fit without any lines (Fit 1). Parameters obtained from the three fits are represented by pluses.

According to Qin (2003), the observed line energy of an expanding fireball should be about 2Γ times the rest frame line energy. The shifting factor being about 2Γ rather than Γ is due to the fact that the contribution from the small area of the expanding fireball surface around the line of sight is the most important one to the observed emission (the so-called beaming effect), when the expanding motion is relativistic. Deriving from the Doppler effect, one finds that the factor shifting the rest frame frequency to the observed frequency is $1/[\Gamma(1-\beta\cos\theta)]$. Setting $\theta = 0$ one obtains $1/[\Gamma(1-\beta\cos\theta)] \simeq 2\Gamma$ for extremely relativistic outflows. Taking this factor, the 6.4 keV line in Fit 2 (where $\Gamma = 116$) should be shifted to around 1500 keV. This is lower than the observed spectral bump (at about 1600 keV). How do we understand this difference? Does it mean that the continuum and the line component have different Lorentz factors? First, we notice that the deviation of the expected position from the observed one is relatively small: $(1600-1500)/1600 \simeq 0.06$. Secondly, we recall that the Lorentz factor alone is not important for the continuum to produce the goodness of fit (see Figure 2). However, the Lorentz factor is essential for shifting a rest frame emission line to a certain observed line. We observe that, data around the bump (about 1600 keV) are poorly measured, where the uncertainties are quite large (see Figure 1). According to the property, arising from the definition, of the χ^2 statistics (for each data point in the definition, the larger the uncertainty, the less contribution to the total χ^2), adopting a slightly different value of the Lorentz factor (which would lead to a small deviation of the position of the expected line) would lead to a small deviation of the total χ^2. To check this, let us take $\Gamma = 125$ which would shift the 6.4 keV emission line to the bump observed (at about 1600 keV), the cosmological redshift being ignored. We fit the spectrum once more with the rest frame line of 6.4 keV when taking $\Gamma = 125$, and then we acquire a goodness of fit which is almost the same as the previous one. Relevant numerical values of this fit are listed in the fourth row of Table 1. Calculating the goodness of fit with the continuum alone when adopting these parameters, we find that the fit becomes obviously worse ($\chi^2 = 69.6$), in agreement with what was shown above (the plot showing these fits is omitted since it is very similar to Figure 1). One finds that, by taking a slightly larger value of the Lorentz factor, the expected line could shift to the energy where the bump is observed and this would not lead to

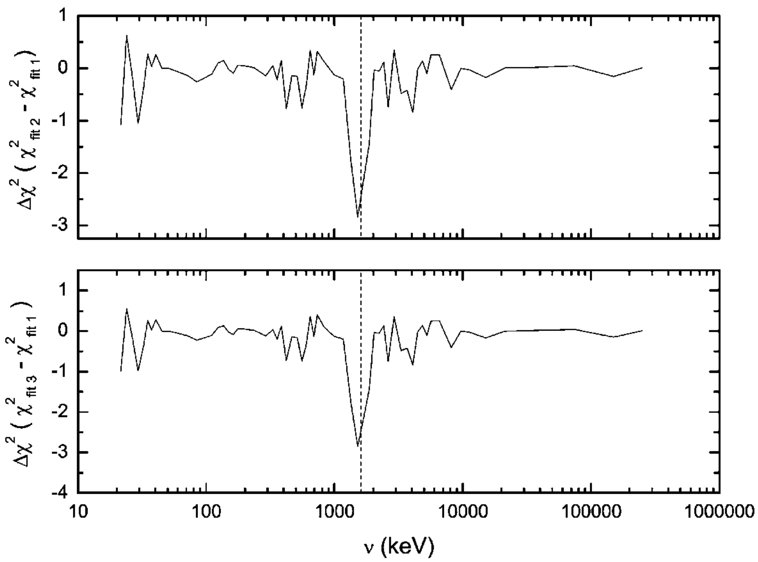

Fig. 3 Plots of $\Delta\chi^2$ calculated at each data point for Fits 1 and 2 (the top panel), and for Fits 1 and 3 (the bottom panel), respectively. The dashed line stands for the energy of 1608 keV at which a bump in the composite spectrum of GRB 910503 is observed (see Schaefer et al. 1998). The fit improves significantly by the inclusion of a line component.

a noticeable change in the confidence level. Note that, in doing so, we obtain a smaller value of $\nu_{0,p}$. This confirms the conclusion that the goodness of fit is sensitive only to the product $\Gamma\nu_{0,p}$, in agreement with what is shown in Figure 2.

When the cosmological redshift is considered, the Lorentz factor might become larger. The redshift distribution of long GRBs peaks at approximately $z = 1$. When $z = 1$ is assumed, the spectrum would shift to higher energy bands by a factor of 2 and then the Lorentz factor might become 2 times larger. However, due to several reasons the effect of the cosmological redshift of GRB 910503 is omitted in our analysis. The most important one is that the redshift of this burst is unavailable. The second is that the effect of redshift could be simply corrected by shifting the observed spectral data to the corresponding higher energy bands which would not change the shape of the spectrum and therefore would not affect the fitting parameters other than the Lorentz factor. The third is that the effect of redshift cannot be separated from the corresponding effect of the Lorentz factor (see the second reason) and thus cannot be determined by fit. The fourth is that the effect of redshift is much less than that of the Lorentz factor, and it is the latter effect that dominates the size of the shift of emission lines (taking $z = 1$ would change the emission line frequency by 2 times while taking $\Gamma = 100$ would shift that frequency by 200 times: the former effect is only 1% of the latter). The last is that GRB 910503 is an extraordinary bright burst and then its redshift would possibly be quite small.

To illustrate individual behaviors of the two components, we present Figure 4 where the contributions of the continuum and the line component to the expected total radiation in Fit 2 are shown. We find from the figure that: a) the 6.4 keV line is indeed shifted to the band where the bump is observed, and it is this line feature that fills up the deficit radiation around this bump when only a continuum rest frame radiation is considered; b) compared with that of the

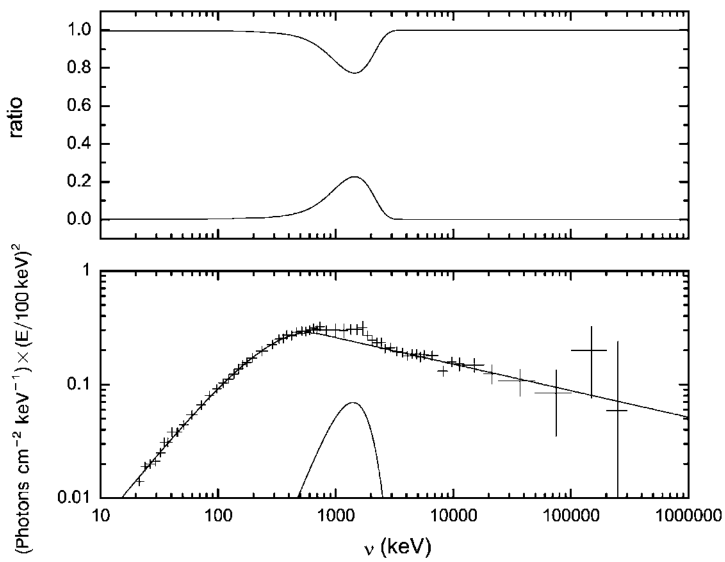

Fig. 4 Contributions (the lower panel) of the continuum (the upper solid line in each panel) and the line component (the lower solid line in each panel) to the expected total spectrum of GRB 910503, and the ratio (upper panel) of the contribution of each component to the total radiation, for Fit 2. The observed data are represented by pluses.

continuum, the contribution of the line component is quite small. This is consistent with the results of the three fits (Fits 1, 2, and 3) and Figure 3.

Since a small step (taking a larger value of the Lorentz factor, i.e., $\Gamma = 125$) could solve the problem, it is unnecessary to introduce an additional assumption that the continuum and the line components have different Lorentz factors (in doing so, one would introduce one more free parameter). However, it is still possible that the two components have different Lorentz factors, especially when they are emitted from different shells expanding at different speeds. Due to the reason presented above (the contribution of the line component, which is obviously related to the Lorentz factor, is relatively small), we cannot specify this with our data.

To calculate the probabilities of the F-test for the above continuum-plus-line model fits, one should be reminded that in combining the data, we allowed a relative "float" between the data of the different instruments, which introduced two additional model parameters and then the number of degrees of freedom would be reduced by two. Therefore, for the fit without any lines we have 56 degrees of freedom, while for one with one emission line we have 54. In this way, we obtain the following probabilities by the F-test: for the fit with the 6.4 keV emission line, 2.29×10^{-5}; for the fit with the 511 keV emission line, 2.99×10^{-5}. However, when ignoring the two additional degrees of freedom, we obtain better results: fit with the 6.4 keV emission line: 1.56×10^{-5}; fit with the 511 keV emission line: 2.05×10^{-5}.

The adopted criteria are well satisfied by the probabilities obtained, suggesting that the bump at around 1600 keV can be interpreted as a blue-shifted emission line of 6.4 keV or 511 keV. (When adopting the pure Band function without considering the expansion of the fireball as the continuum-only model, we obtain a relatively poor fit, but it yields smaller probabilities of the F-test for the two continuum-plus-line model fits due to the smaller number of parameters. It leads to a stronger confirmation of the emission line feature.)

4 CONCLUSIONS

In this paper, we perform a statistical F-test on the bump appearing in the composite spectral data of GRB 910503, taking into account the Doppler effect based on the fireball mechanism, assuming the bump to be an emission line feature. The data employed, published previously, were presented quantitatively and believed to be suitable for testing emission mechanism models (Schaefer et al. 1998).

The criteria adopted for detecting the line feature are those proposed previously by Band et al. (1996). As rest frame emission lines for an expanding fireball are expected to be blue-shifted and significantly broadened (see, e.g., Meszaros & Rees 1998; Hailey et al. 1999; Qin 2003), a line feature observed might not be interpretable when these effects are ignored. We construct our criteria as: a) there exists at least one emission line, whose mechanism is well established, to account for the concerned feature; b) an F-test probability less than 10^{-4} is obtained for at least one of the fits of plausible emission lines. To fit the spectrum, we assume a rest frame radiation of the Band function together with one of the two rest frame lines (6.4 keV and 511 keV) whose mechanisms are well established.

The analysis shows that the F-test probabilities are $\sim 10^{-5}$ and hence the bump can be well interpreted as a blue-shifted emission line of 6.4 keV or 511 keV. It should be noted that the Lorentz factor cannot be determined by the fit as the goodness of fit is not sensitive to Γ alone (see Section 3). Assuming that the bump is indeed a blue-shifted emission line, we have two alternatives: 6.4 keV and 511 keV. Of the two, we prefer the 6.4 keV line, since the Lorentz factor associated with this line (the fit with this line yields: $\Gamma = 116^{+9}_{-9}$, $\nu_{0,p} = 2.96^{+0.24}_{-0.18}\,\mathrm{keV}\ h^{-1}$) is reasonable while that connected with the 511 keV line ($\Gamma = 1.62^{+0.07}_{-0.10}$, $\nu_{0,p} = 234^{+7}_{-9}\,\mathrm{keV}\ h^{-1}$) is not consistent with the current model of GRB fireballs (see Waxman et al. 1998; Taylor et al. 2004; Zhang & Meszaros 2004). The study suggests that it is feasible to detect emission line features in the high energy range of GRBs when taking into account the Doppler effect of the fireball surface.

One might observe that the spectral bump is seen in the composite spectrum involving parameter floating. It is thus important to test whether the bump is caused by calibration errors between the instruments. Since in this paper we cannot discuss this issue and cannot specify how the "floating" of the data was done in the analysis, we regard our result as preliminary, and is qualitative rather than quantitative. Since GRBs are not repeaters, there is only one average spectrum available for a burst (when data of all instruments are combined). The detection of the line feature must be treated with caution. We appeal for other independent tests to confirm it.

Recently, there are debates on whether the F-test should be used to detect spectral line components. Protassov et al. (2002) argued that the F-test should not be used as a tool to detect spectral line components. In addition, Rutledge & Sako (2003) argued that the significance of the lines detected in some GRB afterglows should be less than what is reported with the F-test, because the redshift of the line in unknown. This situation is similar to the emission component feature in this paper because the Lorentz factor is unknown for the source. The lack of redshift information might possibly mis-identify an observed line to several lines nearby, and then would definitely lower the significant level of the identification. However, if there are no other emission lines nearby and there is only one emission line that can account for the observed feature, then the significant level would not be affected. Assuming that the Lorentz factor is about 100, then there are only the 6.4, 6.7 and 6.9 keV lines that can account for the bump. As the three lines could not be detected separately by the broadening effect of fireballs (see, e.g., Qin 2003), we regard the Gaussian form of the rest frame 6.4 keV line as the line feature that might contain the 6.4 as well as 6.7 and 6.9 keV lines. In this situation, we would call this rest frame Gaussian form as the 6.4 keV feature. The significant level of identifying this feature would not be affected based on the assumption of $\Gamma \sim 100$. However, the Lorentz factor can be as large as 1000 and as small as 2. If the corresponding possibilities could not be neglected, then the above significant level should be reduced. This might deserve a further investigation when the line feature becomes more certain.

Protassov et al. (2002) proposed a method of "posterior predictive p-value", a Monte Carlo simulation approach, to calibrate the sample distribution of the F-statistic, which could be a substitute for the F-test. Unfortunately, we are unable to simulate the data set from the three instruments due to the lack of necessary information. At the same time, we find that the method of "posterior predictive p-value" confirmed the line component with a higher confidence level than the F-test did in other cases (see, e.g., Protassov et al. 2002; Dai et al. 2003). It seems unlikely that the "posterior predictive p-value" method, if applied, would lead to an entirely different result.

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