Parameters of the prompt gamma-ray burst emission estimated with the opening angle of jets

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We present in this paper an approach to estimate the initial Lorentz factor of gamma-ray bursts (GRBs) without referring to the delayed emission of the early afterglow. Under the assumption that the afterglow of the bursts concerned occurs well before the prompt emission dies away, the Lorentz factor measured at the time when the duration of the prompt emission is ended could be estimated by applying the well-known relations of GRB jets. With the concept of the efficiency for converting the explosion energy to radiation, this Lorentz factor can be related to the initial Lorentz factor of the source. The corresponding rest frame peak energy can accordingly be calculated. Applying this method, we estimate the initial Lorentz factor of the bulk motion and the corresponding rest frame spectral peak energy of GRBs for a new sample where the redshift and the break time in the afterglow are known. Our analysis shows that, in the circumstances, the initial Lorentz factor of the sample would peak at 200 and would be distributed mainly within (100, 400), and the peak of the distribution of the corresponding rest frame peak energy would be 0.8keV and its main region would be (0.3keV, 3keV).

Keywords: gamma rays: bursts — hydrodynamics — relativity — shock waves

1. Introduction

One of the recent exiting discoveries in gamma-ray bursts (GRBs) is the break detected in the afterglow light curve of some bursts which could be interpreted as a consequence of the beamed emission (e.g., Ref. 1,2). If the afterglow emission is beamed, how is the prompt emission? Whether the latter emission is isotropic or strongly beamed in our direction has been an open question for some years. As mentioned in Ref. 2, this question has implications on almost every aspect of the phenomenon, from the energetics of the events

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to the engineering of the inner engine and the statistics and the luminosity function of the sources. Frail et al. (2001) studied a sample of GRBs with good afterglow follow-up and known redshifts. They interpreted the breaks in the scenario of the beamed model and found that most bursts with large values of the isotropic-equivalent gamma-ray energy, $E_{\text{iso}}$, possess the smallest beaming fraction, $f_b = 1 - \cos \theta_{\text{jet}}$. The collimation-corrected energy, $E_\gamma = f_b E_{\text{iso}}$, of this sample is strongly clustered. This was independently confirmed by Panaitescu & Kumar (2001)\(^3\). Bloom et al. (2003) collected a larger sample of GRBs and found that the distribution of $E_\gamma$ clusters around $1.3 \times 10^{51}$ ergs\(^5\). All these were regarded as evidence supporting the beamed emission scenario.

The isotropic gamma-ray energy $E_{\text{iso}}$ was found to be correlated with the cosmological co-moving frame peak energy $E_p$ by different authors (see, e.g., Refs. 6–10). More recently, Ghirlanda et al. (2004) found\(^11\) a tight correlation between $E_\gamma$ and $E_p$, which sheds light on the still uncertain radiation processes for the prompt GRB emission. In computing $E_\gamma$, it is essential that the beaming fraction is available. According to Refs. 2, the opening angle of the jet can be calculated with

$$\theta_{\text{jet}} = B \left( \frac{t_{\text{jet}}}{1+z} \right)^{3/8} \left( \frac{\xi n}{E_{\text{iso}}} \right)^{1/8}$$

in the case of a homogeneous circumburst medium, where $B$ is a constant which can be found in Ref. 12, $t_{\text{jet}}$ is the afterglow jet break time, $z$ is the redshift, $\xi$ is the efficiency for converting the explosion energy to radiation, $n$ is the density of the ambient medium, and $E_{\text{iso}}$ is the energy in $\gamma$-rays calculated assuming that the emission is isotropic. This enables us to estimate the opening angle of jets and with it to peep into other parameters associated with the mechanism of radiation.

Indeed, under the scenario of jets, parameters such as the total energy in the relativistic ejecta, the jet opening angle, the density and profile of the medium in the immediate vicinity of the burst, and those associated with the microphysical shocks could be estimated by modeling the broadband emission of GRB afterglows for various bursts (see Refs. 4,13–15). Assuming that the observed GRB durations are a good measure of the ejecta deceleration timescale, the jet Lorentz factors at the deceleration radius were found to be within 70 and 300 for 10 GRBs\(^15\).

In addition to the break time observed in the afterglow, Sari & Piran (1999) suggested\(^16\) that the reverse shock of a burst could provide a crude measurement of the initial Lorentz factor. In the case of GRB 990123, they showed that the initial Lorentz factor $\Gamma \sim 200$ could be obtained from the prompt optical flash observed in the burst.

Early afterglow which could overlap the main burst was predicted previously (see, e.g., Ref. 17). According to the analysis of Ref. 18 based on the internal-external shocks model, for short bursts the peak of the afterglow will be delayed, typically, by few dozens of seconds after the burst while for long ones the early afterglow emission will overlap the GRB signal, and a delayed emission, with the characteristics of the early afterglow, can be used to measure the initial Lorentz factor of the relativistic flow (see, also Refs. 19–21).

Hinted by the previous works, we wonder if the initial Lorentz factor could be estimated with an independent approach in case the delayed emission is not available. An investiga-
ation on this issue is organized as follows. In section 2, we present appropriate formulas and show how to estimate the concerned parameters with them. A new GRB sample for which the redshift and the break time in the afterglow are known is studied in section 3. Conclusions are summarized in the last section, where a brief discussion is present.

2. Formulas employed

As the initial explosion of GRBs is not at all in the stage of afterglow, we cannot estimate parameters of the former from the measurements of the latter according to the law of the afterglow. To connect the two phases, we need to find a particular moment which satisfies the following requirements: a) at that moment, the afterglow has already begun so that the law of the afterglow is applicable; b) parameters associated with that moment are well related with those of the initial explosion.

As predicted above, for long bursts the early afterglow emission will overlap the GRB signal. Indeed, it was reported recently that a bright optical emission from GRB 990123 was detected while the burst was still in progress\textsuperscript{22}. Revealed in Ref. 23 is the discovery of the optical counterpart of GRB 021004 only 193 seconds after the event. The time (measured from the trigger) is slightly longer than the duration of the event. Li et al. (2003) showed\textsuperscript{24} that the faintness of GRB 021211, coupled with the fast decline typical of optical afterglows, suggests that some of the dark bursts were not detected because optical observations commenced too late after the GRB.

Accordingly, we assume that to the time the prompt emission of GRBs is going to be undetectable, which is generally represented by the concept of duration $t_{\text{dur}}$ (in BATSE, it is associated with $T_{90}$), the afterglow of the source has already emerged. Under this assumption, $t_{\text{dur}}$ is the moment that can satisfy the first requirement. Shown in the following one will find that $t_{\text{dur}}$ can also satisfy the second requirement. In addition, $t_{\text{dur}}$ is fortunately always available.

The observed complex structure of GRB light curves suggests that, during the prompt emission of a burst, several ejecta with different masses and different Lorentz factors might be involved. We assume that, after the process of the prompt emission, all ejecta are merged as a single one which has mass $m$ and bears a Lorentz factor $\Gamma_{\text{dur}}$ (which is measured at the end of the duration of the burst). Let’s define an average initial Lorentz factor of the early phase ejecta as

$$\Gamma \equiv \frac{1}{m} \sum_i \Gamma_i m_i,$$  \hspace{1cm} (2)

with

$$m = \sum_i m_i,$$  \hspace{1cm} (3)

where $\Gamma_i$ and $m_i$ are the initial Lorentz factor and the mass of the $i$th ejecta, respectively. One can check that, for a burst associated with a shock produced by the collision of two shells with roughly equal masses, $\Gamma \simeq (\Gamma_{\text{in}} + \Gamma_{\text{out}})/2$, where $\Gamma_{\text{in}}$ and $\Gamma_{\text{out}}$ are the Lorentz factors of the inner and outer shells, respectively, while for a burst containing several shells
with roughly equal masses, $\Gamma \simeq \sum_i \Gamma_i/N$, where $N$ is the number of shells. Note that the initial kinetic energy of all these early phase ejecta is the product of the explosion of the burst (where a number of sub-explosions might be involved). It is well known that it is the losing of the kinetic energy of the GRB ejecta that gives rise to the energy of the radiation observed during the prompt emission as well as the increasing of the thermal energy during this period, regardless what the radiation mechanism is. According to the conservation of energy, one finds

$$\Gamma mc^2 - \Gamma_{dur} mc^2 = \xi(\Gamma - 1)mc^2 + \Delta E_{th}, \quad (4)$$

where $\Delta E_{th}$ is the increasing of the thermal energy of the system. Assuming that the radiation is associated with the synchrotron mechanism, as is generally believed, then parts of the increasing thermal energy at any moment must be converted to radiation due to the increasing velocity of individual electrons. Based on this argument, we believe that, as a sum of that of all moments, $\Delta E_{th}$ would be significantly reduced, compared with that obtained in the situation where the synchrotron mechanism is not at work. We accordingly assume that, during the shock, the increasing thermal energy is much smaller than the radiation energy. That is, we assume $\xi(\Gamma - 1)mc^2 \gg \Delta E_{th}$. Omitting the increasing of the thermal energy, we get from (4) that

$$(1 - \xi)\Gamma \simeq \Gamma_{dur} - \xi. \quad (5)$$

When all the initial kinetic energy is converted to photons, we have $\xi = 1$ and then $\Gamma_{dur} = 1$, and when none of the initial kinetic energy is changed to radiation, we get $\xi = 0$ and then $\Gamma_{dur} = \Gamma$. Thus, one always finds $1 \leq \Gamma_{dur} \leq \Gamma$. According to (5), the initial Lorentz factor could be determined as long as $\Gamma_{dur}$ and $\xi$ (when $\xi \neq 1$) are known.

During the period of the afterglow, when the external matter is homogenously distributed, the Lorentz factor would decline following the law of $\Gamma(t) \propto t^{-p}$, where $p = 3/7$ in a radiative phase and $p = 3/8$ in an adiabatic phase (see, e.g., Ref. 25). Thus, we get $\Gamma_{dur} = (t_{jet}/t_{dur})^p \Gamma_{jet}$, where $\Gamma_{jet}$ is the Lorentz factor of the ejecta measured at $t_{jet}$. According to the beamed model, a break in the afterglow light curve of the burst would appear when its bulk Lorentz factor becomes of the order of $1/\theta_{jet}$, i.e., $\Gamma_{jet} \simeq 1/\theta_{jet}$. We then come to

$$\Gamma_{dur} \simeq \left(\frac{t_{jet}}{t_{dur}}\right)^p \frac{1}{\theta_{jet}}. \quad (6)$$

For $\xi < 1$, we get from equations (5) and (6) that

$$\Gamma \simeq \frac{(t_{jet}/t_{dur})^p/\theta_{jet} - 1}{1 - \xi} + 1. \quad (7)$$

As is generally assumed, the jet of bursts is strongly beamed in our direction so that the emission is detectable due to the great Doppler boosting (see, e.g., Ref. 2). According to the Doppler effect, a photon of $E_0$ emitted from the area of $\theta = 0$ within the spherical surface of a uniform jet which moves outwards with a bulk Lorentz factor $\Gamma$ would be blue-shifted to $E = 2\Gamma E_0$. In the case of photons being emitted from a certain area with a rest frame Band function spectrum which peaks at $E_{0,p}$, the spectrum would be blue-shifted...
and would peak at $E_p$ which is proportional to $E_{0,p}$ (see Table 4 in Ref. 27 where $E_p = 1.67 \Gamma E_{0,p}$ can be concluded). Neglecting the minute difference we take in the following that $E_p \simeq 2 \Gamma E_{0,p}$. Following Ref. 2, we consider throughout this paper only an adiabatic phase and then take $p = \frac{3}{8}$. Thus, from equation (7) we get

$$
\Gamma \simeq \frac{(t_{jet}/t_{dur})^{3/8}/\theta_{jet} - 1}{1 - \xi} + 1 \quad (8)
$$

and

$$
E_{0,p} \simeq \frac{(1 - \xi)E_p/2}{(t_{jet}/t_{dur})^{3/8}/\theta_{jet} - \xi} \quad (9)
$$

3. Application

Presented in Ref. 12 are 52 GRB or XRF sources (called the FB sample) where their redshifts as well as the gamma-ray fluences are available. The isotropic energies $E_{iso}$ were calculated assuming a standard cosmology of $(\Omega_M, \Omega_{\Lambda}, h) = (0.3, 0.7, 0.7)$. For some of these sources, break times $t_{jet}$ are available, and then with equation (1) the opening angles $\theta_{jet}$ of the sources could be well determined, where $\xi = 0.2$ is assumed (see also Ref. 3). According to equations (8) and (9), to calculate $\Gamma$ and $E_{0,p}$ for these sources we need to know $t_{dur}$ as well. Listed in Table 1 are the values of $t_{dur}$, which is measured in various bands, for the sources of the FB sample with $t_{jet}$, $\theta_{jet}$, and $E_p$ available. To meet the requirement that the afterglow has already begun (i.e., $t_{aft} \leq t_{dur}$, where $t_{aft}$ is the start time of the afterglow) and the prompt emission is just ended so that the common value of the efficiency $\xi$ can be adopted and the mass of the piled up ambient medium is relatively small, we adopt the largest value of $t_{dur}$ to calculate $\Gamma$ and $E_{0,p}$. The results are presented in Table 2.
Table 1. Data of $t_{dur}$

| GRB trig. NO. (XRF) | Duration Band ($K_{ev}$) | $t_{dur}$ (s) | Ref.  |
|---------------------|--------------------------|----------------|-------|
| 970508 6225         | 20 $\sim$ 1000          | 35             | 30    |
|                     | 50 $\sim$ 300            | 35             | 30    |
|                     |                         | 15             | 31    |
|                     | 25 $\sim$ ($>320$)       | 23.104(3.789)  | BATSE |
| 970828 6350         | 2 $\sim$ 12              | 160            | 32    |
| 980519 6764         | 40 $\sim$ 700            | 30             | 33    |
|                     | 50 $\sim$ 300            | 60             | 34    |
|                     | 2 $\sim$ 28              | 190            | 33    |
|                     | 25 $\sim$ ($>320$)       | 23.808(1.032)  | BATSE |
| 980703 6891         | 40 $\sim$ 700            | 90             | 35    |
|                     | 50 $\sim$ 300            | 400            | 36    |
|                     | 2 $\sim$ 12              | 40             | 37    |
|                     | 2 $\sim$ 20              | 400            | 36    |
|                     | 25 $\sim$ ($>320$)       | 411.648(9.273) | BATSE |
| 990123 7343         | 40 $\sim$ 700            | 100            | 38    |
|                     | 50 $\sim$ 300            | 63.3           | 39    |
|                     | 20 $\sim$ 1000           | 63.3           | 39    |
|                     | 25 $\sim$ ($>320$)       | 63.36(0.264)   | BATSE |
| 990510 7560         | 40 $\sim$ 700            | 80             | 40    |
|                     | 50 $\sim$ 300            | 100            | 41    |
|                     | 20 $\sim$ 1000           | 100            | 41    |
|                     | 25 $\sim$ ($>320$)       | 68.032(0.202)  | BATSE |
| 990705 7633         | 40 $\sim$ 700            | 45             | 42    |
|                     | 2 $\sim$ 26              | 45             | 42    |
| 990712 7648         | 40 $\sim$ 700            | 30             | 43    |
|                     | 25 $\sim$ ($>320$)       | 31.616(3.137)  | BATSE |
| 991216 7906         | 50 $\sim$ 300            | 50             | 44    |
|                     | 20 $\sim$ 1000           | 50             | 44    |
|                     | 25 $\sim$ ($>320$)       | 15.168(0.091)  | BATSE |
| 011211              | 40 $\sim$ 700            | 270            | 45    |
| 020124              | 8 $\sim$ 85              | 70             | 46    |
| 020405              | 25 $\sim$ 1000           | 40             | 47    |
| 020813              | 2 $\sim$ 25              | 125            | 48    |
|                     | 25 $\sim$ 1000           | 125            | 49    |
|                     | 8 $\sim$ 40              | 125            | 49    |
| 021004              | 8 $\sim$ 40              | 100            | 50    |
| 021211              | 8 $\sim$ 40              | 5.7            | 51    |
| 030226              | 30 $\sim$ 400            | 100            | 52    |
| 030328              | 30 $\sim$ 400            | 100            | 53    |
| 030329              | 30 $\sim$ 400            | 50             | 54    |
|                     | 15 $\sim$ 5000           | 35             | 55    |
| 030429              | 30 $\sim$ 400            | 14             | 56    |
| 040511              | 30 $\sim$ 400            | 8              | 57    |
| 041006              | 25 $\sim$ 1000           | 24.6           | 58    |
Parameters of the prompt GRB emission

Table 2. Estimated values of the initial Lorentz factor and the corresponding rest frame peak energy

| GRB/XRF | $E_{0,p}$ | $\Gamma$ |
|---------|------------|----------|
| 970508  | 0.354(0.111) | 206(26) |
| 970828  | 2.081(0.477) | 141(16) |
| 980519  | 2.311(0.594) | 157(26) |
| 980703  | 3.397(0.734) | 75(7) |
| 990123  | 4.027(0.630) | 253(34) |
| 990510  | 0.752(0.086) | 285(17) |
| 990705  | 0.794(0.116) | 220(27) |
| 990712  | 0.330(0.065) | 142(14) |
| 991216  | 1.193(0.335) | 270(54) |
| 011211  | 0.753(0.101) | 124(8) |
| 020124  | 0.723(0.183) | 254(48) |
| 020405  | 1.530(0.405) | 202(36) |
| 020813  | 0.857(0.114) | 188(18) |
| 021004  | 0.930(0.521) | 144(51) |
| 021211  | 0.133(0.033) | 343(68) |
| 030226  | 0.859(0.203) | 170(15) |
| 030328  | 0.837(0.117) | 191(18) |
| 030329  | 0.293(0.024) | 136(10) |
| 030429  | 0.203(0.083) | 317(97) |
| 040511  | 0.697(0.189) | 236(44) |
| 041006  | 0.289(0.106) | 190(59) |

Shown in Fig. 1 is the relation between $E_{0,p}$ and $\Gamma$. It shows clearly that log $E_{0,p}$ and log $\Gamma$ are not correlated at all. The un-correlation between the two quantities seems to suggest that the rest frame peak energy is strongly associated with the mechanism rather than with the expansion speed (one will find in the following that the distribution of $\Gamma$ is much more clustered than that of $E_{0,p}$).

Displayed in Fig. 2 are the distributions of $E_{0,p}$ and $\Gamma$. The rest frame peak energy peaks at $E_{0,p} = 0.8keV$ and is mainly distributed within $(0.3keV, 3keV)$. The Lorentz factor peaks at 200 and it is found mainly within $(100, 400)$, which is very narrow.

As Fig. 3 shows, there is a very tight correlation between $E_{0,p}$ and $E_p$: $\log E_p = (0.85 \pm 0.25) \log E_{0,p} + (2.56 \pm 0.10)$. Note that, relation $E_p \approx 2\Gamma E_{0,p}$ itself could not guarantee the correlation, since if it did, it should also lead to a correlation between $E_{0,p}$ and $\Gamma$, but this is not true (see Fig. 1). The correlation between $E_{0,p}$ and $E_p$ must arise from mechanisms other than from the Doppler effect.

4. Discussion and conclusions

In this paper we propose a method which does not refer to the delayed emission of the early afterglow to estimate the initial Lorentz factor of GRBs, in case the detection of the early afterglows of many bursts might be missed. Due to the fact that the afterglows of some bursts were observed soon after the detection of the main emission, we assume that the afterglows of the bursts concerned occur well before the prompt emission dies away.
Fig. 1. Relationship between $E_{0,p}$ and $\Gamma$. The correlation coefficient between $\log E_{0,p}$ and $\log \Gamma$ is $r = 0.078$ ($N = 21$) and the probability of rejecting the null hypothesis is 0.734. Under this assumption, the bulk Lorentz factor of a burst measured at the break time, $t_{\text{jet}}$, and that measured at the time marking the end of duration, $t_{\text{dur}}$, could be well related by the law of $\Gamma(t) \propto t^{-3/8}$ according to the beaming scenario. Employing the concept of the efficiency for converting the explosion energy to radiation, $\xi$, we can relate the initial Lorentz factor of a burst to that measured at $t_{\text{dur}}$. Combining the two relations one can therefore estimate the initial Lorentz factor of a burst from that measured at $t_{\text{jet}}$. The corresponding rest frame peak energy can hence be estimated from this initial Lorentz factor and the observed peak energy according to the Doppler effect.

Applying this method, the initial Lorentz factors of the bulk motion as well as the corresponding rest frame spectral peak energies of GRBs for a new sample for which the redshift and the break time in the afterglows are available are estimated. The sample employed is that presented currently by Ref. 12. Our analysis shows that the initial Lorentz factor $\Gamma$ peaks at 200 and is distributed mainly within $(100, 400)$, and the peak of the distribution of the corresponding rest frame peak energy is $E_{0,p} = 0.8 keV$ and its main region is $(0.3 keV, 3 keV)$.

It is known that, a large value of the Lorentz factor, $\Gamma > 100$, is essential to overcome the compactness problem (see, e.g., Ref. 25). As individual cases, the optical flash accompanying GRB 990123 provides a direct evidence for a large Lorentz factor $\Gamma \sim 200$. Statistically, Mallozzi et al. (1995) found that the average value of $E_p$ for 82 bright bursts is $\sim 340 keV$. Taking $E_{0,p} = 0.8 keV$ and adopting $E_p \simeq 2\Gamma E_{0,p}$, we find that the average Lorentz factor of these bursts would be $\sim 213$, which is consistent with what we obtained above. Preece et al. (2000) revealed by the analysis of high time resolution spectroscopy...
of 156 bright bursts that the main range of $E_p$ for these sources could be found to be within $\sim [100, 800]$ keV. This would lead to a range of $\Gamma \sim [62, 500]$ when adopting $E_{0,p} = 0.8$ keV and $E_p \simeq 2\Gamma E_{0,p}$, which is also in agreement with what we find in this paper.

As shown in Table 2, the estimated initial Lorentz factor for GRB 990123 is $\Gamma \sim 253 \pm 34$ which is slightly larger than what is obtained with the method referring to the delayed emission of the early afterglow (see Ref. 16, where $\Gamma \sim 200$ was presented). Applying (6), we get $\Gamma_{dur} = 202 \pm 22$ for this source. We argue that the initial Lorentz factor estimated with our method is that associated with the initial explosion of a burst. It is natural that this value is larger than others which are measured at later times. This might be the cause for the detected difference. Ignoring this slight difference, our method is consistent with that referring to the delayed emission of the early afterglow.

We suspect that, a very strong shock might produce higher energy photons, which is characterized by a large value of $E_{0,p}$, and this would lead to a large value of $E_p$ (note that, as shown above, the Lorentz factor does not change much for different sources). We make a statistical analysis for $E_\gamma$ and $E_{0,p}$ and find that they are indeed obviously correlated (the figure is omitted). We then understand why $E_\gamma$ is correlated with $E_p$. It is because that strong shocks produce large values of both $E_\gamma$ and $E_p$, whereas weak shocks lead to smaller values.

We assume through out this paper that the afterglow is dominated by an adiabatic process. However, there is an alternative which is a radiative process, for which, $p = 3/7$ should be adopted. We repeat our work by replacing $p = 3/8$ with $p = 3/7$. We find that, the value of $\Gamma$ is mainly distributed within $(106, 584)$ which is slightly larger than what we expect. Thus, we tend to believe that, during the epoch of the afterglow, the dominated process is adiabatic rather than radiative (this is not certain since the resulted Lorentz factors are still within the acceptable range).

In the above analysis, we assume that $\xi(\Gamma - 1)mc^2 \gg \Delta E_{th}$. Does our analysis strongly depend on this assumption? To find an answer to this, let us assign $\Delta E_{th} \equiv \eta \xi(\Gamma - 1)mc^2$, where $\eta$ is a constant. In this way, equation (4) becomes

$$\Gamma mc^2 - \Gamma_{dur} mc^2 = (1 + \eta)\xi(\Gamma - 1)mc^2.$$  \hspace{1cm} (10)

Taking $\xi' \equiv (1 + \eta)\xi$, we get

$$(1 - \xi')\Gamma = \Gamma_{dur} - \xi'.$$ \hspace{1cm} (11)

According to (10), $\xi' = 1$ suggests that all the explosion energy converts to radiation, which would not be true. Thus, we have $0 < \xi' < 1$. In this case, one finds that formulas (5), (7), (8) and (9) are valid when one replaces $\xi$ with $\xi'$. This indicates that the above analysis does not depend on the mentioned assumption. When the two amounts of energy are comparable, i.e., $\eta \simeq 1$, one has $\xi' \simeq 2\xi$. Adopting $\xi = 0.2$ leads to $\xi' = 0.4$, which would not significantly change the results obtained above.
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Fig. 2. Distributions (solid lines) of $\log E_{0,p}$ (a) and $\log \Gamma$ (b).
Fig. 3. Relationship between $E_p$ and $E_{0,p}$. The correlation coefficient between $\log E_p$ and $\log E_{0,p}$ is $r = 0.960 (N = 21)$ and the probability of rejecting the null hypothesis is $P < 0.0001$.