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LETTERS

# Gamma-ray Bursts: a Probe of Black Holes

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**Abstract** There is strong evidence for the existence of black holes (BHs) in some X-ray binaries and in most galactic nuclei based on different types of measurement, but black holes have not been definitely identified for the lack of very firm observational evidence up to now. Because direct evidence for BHs should come from determination of strong gravitational redshift, we expect an object can fall into the region near the BH horizon where radiation can be detected. Therefore the object must be a compact star such as a neutron star (NS), and intense astrophysical processes will release highly energetic radiation that is transient and fast-varying. These characteristics may point to the observed gamma-ray bursts (GRBs). Recent observations of iron lines suggest that afterglows of GRBs show properties similar to those observed in active galactic nuclei (AGNs), implying that the GRBs may originate from intense events related to black holes. A model for GRBs and afterglows is proposed here to obtain the range of gravitational redshifts ($z_{\rm g}$) of GRBs with known cosmological redshifts. Here, we provide a new method that, with a search for high-energy emission lines (X- or $\gamma$-rays) in GRBs, one can determine the gravitational redshift. We expect $z_{\rm g}$ to be 0.5 or even larger, so we can rule out the possibility of other compact objects such as NSs, and identify the central progenitors of GRBs as black holes.

**Key words:** black hole physics – accretion, accretion disks – gamma rays: burst

## 1 INTRODUCTION

Approaches to the search for observational evidence for the existence of black holes are in the form of various measurements, such as stellar dynamics (Ghez et al. 1998, 2000), optical emission lines from gas disks (Ferrarese, Ford & Jaffe 1996; Macchetto et al. 1997), water maser disks (Miyoshi et al. 1995), X-ray lines (e.g. Fe K$\alpha$ line, Nandra et al. 1997) and the strength of ultrasoft component of X-ray spectra (Zhang, Cui & Chen 1997). However, all these methods are related only to gaseous processes at locations at least two gravitational radii out where the gravitational field is weak. To probe the very strong gravitational field, the radiation should result from places closer to the BH horizon where a large number of high-energy photons can

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be released. If high-energy emission lines can be identified, then we can determine the expected large gravitational redshift. Here, we propose that GRBs may be the best approach.

Our method is partly motivated by the recent observational evidence for the existence of Fe K$\alpha$ lines in the X-ray afterglows of GRB 990705 (Amati et al. 2000), 990712 (Frontera et al. 2001), 991216 (Piro et al. 2000) and 000214 (Antonelli et al. 2000); in fact, GRB 970508 (Piro et al. 1999) and 970828 (Yoshida et al. 1999) had also shown the same evidence. According to the observed line flux, the mass of iron should amount to about $10^{-4} - 0.1\,M_{\odot}$, which contradicts the standard fireball model for GRBs, because there cannot enough iron in the interstellar medium around the progenitors and if the iron is produced during the bursts, it will involve the famous problem of baryon contamination. To explain the iron line, various mechanisms have been proposed: with energy injection, only a small mass of Fe is required (Rees & Mészáros 2000); or Fe comes from a supernova, which requires that a supernova explosion precedes the GRB event by several months to years (Antonelli et al. 2001).

However, the existence of iron lines indicates a similarity of GRB afterglows to AGNs, suggesting that the origin of GRBs and their afterglows may be related to black holes and accretion process. In this Letter, we propose a model of GRBs, in which a massive black hole captures a neutron star to produce a GRB as well as a normal star to form an accretion disk and produce the afterglow. Then, an alternative mechanism is also proposed for the origin of the iron line: the Fe line may come from the disk formed by the normal star.

In the following section, we will give a brief description of our GRB and afterglow model and we will show that some GRBs may be good candidates of black holes. In Section 3, the method of getting a firm evidence for black holes is explained. A summary and an outlook are presented in Section 4.

## 2 GRB AND AFTERGLOW MODEL

Our GRB model is simply described as follows. When a massive black hole catches a neutron star, a large number of $\gamma$-ray photons through intense astrophysical processes are produced on a short timescale. In this case, we could observe only a burst. And the minimum variability timescale of the burst light curve is related to the size of the NS, $\Delta t \geq \frac{R}{c}(1+z)(1+z_{\rm g})$, of the order of milliseconds, consistent with GRB observations, where $R$ is the NS radius, $c$ is light speed and $z$ is the cosmological redshift. But if a binary consisting of a neutron star and a normal star, rather than an isolated neutron star, falls into a black hole, then the normal star is disrupted and forms an accretion disk around the black hole, and X-ray and optical radiation are released. Then both a burst and afterglows are observed. Of course, normal stars captured by black holes in galactic centers will produce flares in the optical or X-ray band without bursts, which also may be observable (Rees 1988, 1990). And our group now is trying to survey such optical flares.

The afterglows will be very similar to the continuum radiation of AGNs: for example, the spectrum of the afterglow of GRB 970508 (Galama et al. 1998a) may like that of a blazar. Then, the accretion process can account for the afterglows decaying in time as a power-law. After the tidal disruption of a normal star, two processes will supply mass to the central black hole. The first has been studied by Rees (1988, 1990): the stream of stellar mass strung out in far-ranging orbits, leading to an infall rate declining as $t^{-5/3}$. The other case involves mass loss from the inner edge of the accretion disk. Cannizzo et al. (1990) discussed this case of late-time mass evolution in which the accretion disk supply rate varies as $t^{-1.2}$.

BH-NS interaction has been studied by some authors with numerical simulations (Lattimer & Schramm 1976; Kluźniak & Lee 1998; Janka et al. 1999), and has been regarded as one of the successful models of GRBs. Here, we re-analyze the process with some simple calculations. Assuming different black hole masses, we derive the gravitational redshift by computing the gravitational radius $r_{\rm g}$ ($=\frac{2GM}{c^2}$, $G$ the gravitational constant) and the critical radius $r$ where a neutron star is tidally disrupted by the central black hole. We suppose the neutron star to have a mass of $1.4\,M_\odot$ and a radius of 10 km. For comparison, the process is computed separately for the Landau potential (Landau & Lifshitz 1975):

$$\phi = -\frac{c^2}{2}\ln\left(1-\frac{r_{\rm g}}{r}\right), \tag{1}$$

and for the pseudo-Newtonian potential (Paczyński & Wiita 1980):

$$\phi = -\frac{GM}{r-r_{\rm g}}\,. \tag{2}$$

In Figure 1, the two dashed lines show $z_{\rm g}$ as a function of the BH mass for the Landau (upper) and pseudo-Newtonian (lower) potential, respectively. We note $z_{\rm g} \gg 1$ when the BH mass is very large, showing that massive black holes may provide better observational tests.

From the above analysis, a black hole capturing an isolated neutron star produces a large number of high-energy photons through a very intense process, and this is observed as a GRB. With the known total energy of the GRB, we can evaluate the gravitational redshift around the critical radius

$$1+z_{\rm g} \le \frac{E_{\rm NS}}{E_\gamma}, \tag{3}$$

where $E_{\rm NS}$ is the total rest energy of a neutron star and $E_\gamma$ is the isotropic $\gamma$-ray energy. Since $1+z_{\rm g} = (1-\frac{r_{\rm g}}{r})^{-1/2}$, we have $r - r_{\rm g} \sim \frac{r_{\rm g}}{(1+z_{\rm g})^2-1}$. Hence, we estimate the duration of a burst to be,

$$T_\gamma \ge \frac{r-r_{\rm g}}{c}(1+z_{\rm g}) \sim \frac{M}{10^5 M_\odot}\frac{1+z_{\rm g}}{(1+z_{\rm g})^2-1}, \tag{4}$$

where $M$ is the mass of the black hole, which incidentally tells us that shorter bursts go with smaller central masses. Equation (4) gives a low limit of $z_{\rm g}$:

$$1+z_{\rm g}-(1+z_{\rm g})^{-1} \ge \frac{1}{T_\gamma}\frac{M}{10^5 M_\odot}. \tag{5}$$

The determination of $z_{\rm g}$ will depend on our constraint on the mass of black holes. With Eqs. (3) and (5), we give a constraint on the mass of black holes

$$\frac{M}{M_\odot} \le 10^5 T_\gamma\left(\frac{E_{\rm NS}}{E_\gamma}-\frac{E_\gamma}{E_{\rm NS}}\right). \tag{6}$$

When a binary falls into a black hole, the normal star will be disrupted to form a accretion disk in a zone far away from the black hole, very similar to the accretion disks in AGNs, and afterglows in X-ray, optical and radio bands can be produced in the disk from where Fe K$\alpha$ lines are also emitted. We consider a thick disk model; then the radial velocity $v_{\rm r} \sim \alpha c_{\rm s}$, where $\alpha$ is the viscosity parameter ($0<\alpha\le 1$) and $c_{\rm s}$ is the sound speed. The viscosity timescale is given by $t_{\rm vis} \sim \frac{r_*}{v_{\rm r}} \sim \frac{r_*}{\alpha c_{\rm s}}$, where $r_*$ is the disk radius. $c_{\rm s}$ can be estimated from $c_{\rm s}^2 \sim \frac{kT}{m_{\rm p}}$, where $k$ is the Boltzmann constant, $T$ the disk temperature and $m_{\rm p}$ the mass of the proton.

Since the radiation of afterglows is emitted from the disk, one can find (Frank, King & Raine 1992) $T \geq (\frac{L}{4\pi r_*^2 \sigma})^{1/4}$, where $L$ is the disk luminosity and also the afterglow luminosity, and $\sigma$ the Stefan-Boltzmann constant. Therefore, we reach an important result on the mass of black holes:

$$\frac{M}{M_\odot} \geq (\frac{L}{10^{23}\mathrm{erg\,s^{-1}}})^{1/10} t_{\mathrm{vis}}^{4/5} \equiv M_d, \tag{7}$$

where we have taken $\alpha \sim 1$, and $r_* \sim 3r_{\mathrm{g}}$.

To further test our model, we first calculate the isotropic $\gamma$-ray energy ($E_\gamma$) and optical (R band) peak luminosity ($L$) for 20 well-studied GRBs with known cosmological redshifts (Bloom, Kulkarni & Djorgovski 2000), and derive some intrinsic parameters of the GRBs; these are displayed in Table 1. In the calculation, we adopt the cosmological model with $H_0 = 65\mathrm{km\ s^{-1}Mpc^{-1}}, \Omega_{\mathrm{M}} = 0.3, \Omega_\Lambda = 0.7$, and take $t_{\mathrm{vis}} \sim t$, the timescale when the afterglow light curve falls from peak flux to one half. With these parameters and above equations, we estimate the ranges of the black hole mass and $z_{\mathrm{g}}$ in our model. The R band luminosity also gives a check on the BH mass using the Eddington luminosity limit:

$$\frac{M_L}{M_\odot} \sim \frac{L}{1.3 \times 10^{38}\mathrm{erg\,s^{-1}}}. \tag{8}$$

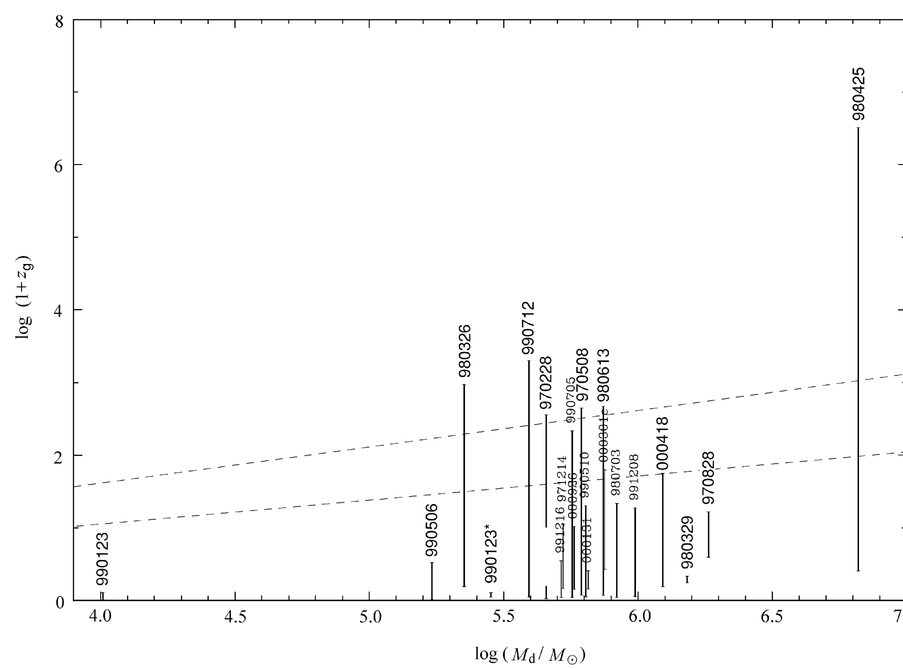


Fig. 1 Range of GRB gravitational redshift estimated from our model is plotted as a function of the lower limit of the BH masses. The upper and lower dashed lines describe the critical gravitational redshift of neutron stars disrupted by tidal force according to the Landau and pseudo-Newtonian potential, respectively. 20 GRBs with known cosmological redshifts are displayed, and we note most masses are distributed around $10^6\,M_\odot$ except GRB 980425 and 990123 (as noted in Table 1). If we cancel the optical flash and only take the second afterglow of 990123, then its representative point 990123* will be a normal one and similar to others. Refer to the text for details.

Our final results are presented in Table 1 and displayed in Figure 1. The two dashed lines have already been noted. From Figure 1, we may draw the following three conclusions. First, we have found the gravitational redshifts of some GRBs to be very large: seven have $z_{\rm g} > 0.5$, which strongly suggests that the central engines of these GRBs should be very good candidates of black holes. Second, the black hole masses are mostly distributed around $10^6\,M_\odot$, comparable to the mass of black holes in normal galaxies including our own. Third, the calculated range of $z_{\rm g}$ of GRBs is consistent with the range given by the two lines, so supporting our model.

**Table 1** The Intrinsic Parameters of 20 GRBs

| Name | $T_\gamma$ (s) | $\log E_\gamma$ (erg) | $\log t$ (s) | $\log L$ (erg s$^{-1}$) | $\log M$ ($M_\odot$) | $z_{\rm g}$ | $z$ |
|---|---|---|---|---|---|---|---|
| 970228 | 47 | 51.9 | 4.5 | 43.2 | 5.7–9.2 (5.1) | 0.05–358 | 0.695 |
| 970508 | 18.7 | 51.8 | 4.5 | 45.1 | 5.9–8.9 (7.0) | 0.16–443 | 0.875 |
| 970828 | 5 | 53.2 | 5.0 | 45.6 | 6.3–6.9 (7.4) | 3.0–15.5 | 0.935 |
| 971214 | 6.8 | 53.4 | 4.3 | 45.8 | 5.8–6.9 (7.7) | 0.6–10.2 | 3.42 |
| 980326 | 2.5 | 51.5 | 4.0 | 44.5 | 5.4–8.3 (6.4) | 0.6–1000 | 1 |
| 980329 | 13 | 54.2 | 4.9 | 45.6 | 6.2–6.3 (7.4) | 0.8–1.1 | 3.5 |
| 980425 | 31 | 47.9 | 6.0 | 45.2 | 6.8–13.0 (5.1) | 1.4–$3\times10^6$ | 0.0085 |
| 980613 | 24 | 51.8 | 4.7 | 44.1 | 5.9–9.1 (6.0) | 0.16–466 | 1.096 |
| 980703 | 46 | 53.1 | 4.7 | 44.6 | 6.0–8.0 (6.4) | 0.1–20.5 | 0.966 |
| 990123 | 15 | 54.3 | 1.6 | 50.2 | 4.1–6.0 (12) | 0.01–0.3 | 1.61 |
| 990123* | | | 3.5 | 46.3 | 5.4–6.0 (8.0) | 0.15–0.3 | |
| 990506 | 65 | 53.9 | 3.7 | 45.7 | 5.7–7.3 (7.6) | 0.05–2.3 | 1.310 |
| 990510 | 28.6 | 53.1 | 4.3 | 46.6 | 5.6–7.5 (7.5) | 0.1–19 | 1.62 |
| 990705 | 36 | 52.1 | 4.7 | 43.0 | 5.7–8.9 (4.8) | 0.1–214 | 0.25 |
| 990712 | 21 | 51.1 | 4.3 | 45.7 | 5.6–9.6 (6.4) | 0.1–2000 | 0.434 |
| 991208 | 41 | 53.2 | 4.7 | 45.3 | 6.0–7.9 (7.2) | 0.15–17.7 | 0.7055 |
| 991216 | 30 | 53.9 | 4.3 | 45.7 | 5.7–7.0 (7.6) | 0.1–2.5 | 1.02 |
| 000131 | 9 | 54.1 | 4.5 | 45.3 | 5.8–6.2 (7.2) | 0.4–1.5 | 4.5 |
| 000301c | 3.3 | 52.6 | 4.5 | 45.9 | 5.9–7.3 (7.8) | 1.9–61 | 2.0 |
| 000418 | 14 | 52.7 | 4.9 | 44.7 | 6.1–7.9 (7.6) | 0.6–55 | 1.11854 |
| 000926 | 8.2 | 53.4 | 4.3 | 46.2 | 5.8–7.0 (8.1) | 0.4–9 | 2.066 |

Notes: Timescales $T_\gamma$ and $t$ have been divided by a factor $(1+z)$ correction to the GRB intrinsic timescales. Since a particular prompt optical flash (Akerlof et al. 1999) was observed 15 seconds after GRB 990123 stated, we take two cases of the afterglow: the flash ($m_R \sim 9$) as a peak and the second afterglow ($m_R \sim 17$) as the peak where $m_R$ is the visual magnitude of optical peak in R band. Because of the possible association between GRB 980425 and SN1998sw (Galama et al. 1998b), $z$ is very small making the $\gamma$-ray energy too low, and $t$ is very long probably due to the effect of the light curve of SN1998sw. $M_L$ is shown in the brackets, in many cases, it shows a super-Eddington accretion, but some are the sub-Eddington ones.

Because short bursts (with the duration $T_\gamma < 2\,$s) correspond to relatively small masses of black holes, radiation from the disk around low-mass black holes will be so faint that it cannot be observed by our optical telescopes. Therefore, our model for GRBs and afterglows may provide a credible explanation as to why afterglows are not observed in most detected GRBs but only in a small fraction with longer durations. Because in galaxies the number of isolated neutron stars is larger than the number of neutron stars in binary systems according to the observations of pulsars (Taylor, Manchester & Lyne 1993), the possibility of the former being captured by black holes will be correspondingly larger, implying that the afterglows of GRBs are intrinsically rare, even as they are observed to be (Lamb 2000). The different behaviors between long-duration GRBs and AGNs may result from the circumstance of black holes: AGNs are in a dirty environment while GRBs are in a clean one with an occasional capture of a neutron star or binary. We think that our unified model as a possible mechanism of GRBs and afterglows can successfully explain the different occurring rates of bursts and afterglows, and the formation of the recently discovered iron lines.

## 3 SEARCHING FOR FIRM EVIDENCE OF BLACK HOLES

In the above section, we have applied our model to some GRBs with known cosmological redshifts. In Table 1, we note that some of the GRBs have very large gravitational redshifts such as GRB 970828 ($z_{\rm g} > 3.0$), 980425 ($z_{\rm g} > 1.4$), 000301c ($z_{\rm g} > 1.9$). Therefore, according to our model, these GRB central engines should be good candidates of black holes. However, to further probe the central body of a gamma-ray burst, we expect that high spectral resolution detectors can find reliable emission lines in the spectra of GRBs and we also suggest that the pair annihilation line (511 keV line) may be the best approach. Hitherto, the emission lines have been detected and identified in the energy spectrum of GRBs by Venera 11 and 12 (Mazets et al. 1981) before 1980 and BASTE (Briggs et al. 1997, 1999) in 1990's. The centroid energies of emission lines are distributed in two different ranges: 330–460 keV and 40–50 keV.

The lines in the broad range of 330–460 keV were interpreted as the strongly redshifted 511 keV annihilation lines, but the emission lines at 40–50 keV were thought to be formed in another process. For instance, GRB 790526 revealed a emission line at 45 keV which was previously thought to be reliable evidence of emission at the cyclotron frequency in the surface of a nearby magnetized neutron star (Mazets et al. 1981). However, since the measurement of the redshift of GRB 970508 (Metzger et al. 1997), the evidence for a cosmological distance scale for most or all bursts is confirmed, then GRBs cannot be a local phenomena on the surface of neutron stars. Hence, we need a new physical mechanism to explain the emission lines observed. In this Letter, we interpret the emission lines as strongly redshifted 511 keV annihilation lines in the gravitational field of black holes. Supposing the cosmological redshift of GRBs, $z \sim 1$, we calculate the gravitational redshifts of the lines whose centroids are around 50 keV, $z_{\rm g} \sim 4$ in accordance with our model expectation. Because the gravitational redshift produced by the known compact objects including neutron stars or even possible strange stars cannot be greater than 0.5, we may make the judgement that the central bodies of these bursts are the best candidates of black holes. In fact, the other lines at 330–460 keV observed have the gravitational redshifts in the range 0.1–0.5, which would also be very hard to realize on the surface of neutron stars. Therefore, GRBs may really originate in the region of very strong gravitational field, where the central progenitors are black holes with captured neutron stars.

## 4 DISCUSSION AND SUMMARY

Because the iron lines discovered in the X-ray afterglows of some bursts imply similarity between AGNs and GRBs, a model of GRBs and afterglows is proposed. In our model, we can determine the range of gravitational redshift of $\gamma$-ray radiation from intrinsic parameters of the GRBs and afterglows, and we note some of the values obtained to be very large ($z_{\rm g} > 0.5$), suggesting that GRBs can serve as probes of ultra-strong gravity of black holes. However, very firm evidence could come from the identification of GRB line emissions. Through the determination of very strong gravitational redshifts of the emission lines, one can identify the central bodies as black holes. Thus, the spectral line observation of GRBs may provide a very powerful evidence for the existence of black holes. Because of the limitations on present missions, we need more advanced detectors with higher spectral resolutions in the future. Here, we expect that recently launched HETE-II and Swift (in 2003) will contribute valuably to the search for GRB emission lines.

The model of GRB afterglows in this Letter is also used to explain the X-ray flares recently detected in several nearby normal galaxies with the ROSAT database. Assuming the number of massive stars which can produce NSs through supernova explosion is about 10% of total star number and one supernova event occurs per 100 years, we simply estimate the density ratio of stars to NSs in a normal galaxy as $n_{\rm star}/n_{\rm NS} \sim 1000$. From the observations, we have the GRB rate, $R_{\rm GRB} \sim 10^{-6} - 10^{-7}\,{\rm yr}^{-1}\,{\rm gal}^{-1}$, so we approximately obtain a flare event rate, $R_{\rm flare} \sim 10^{-3} - 10^{-4}\ {\rm yr}^{-1}\,{\rm gal}^{-1}$, and this is consistent with the tidal disruption rate theoretically expected (Rees 1988, 1990), and the search results given by the ROSAT all-sky survey (Komossa & Dahlem 2001). With the above flare event rate and assume that one solar mass is swallowed by a black hole in an event, we find that the central black hole masses in normal galaxies can increase at least up to $10^6 - 10^7\,M_\odot$ (e.g. the massive black holes in the center of our Galaxy and M31) through the tidal disruption of stars within the Hubble time scale ($\sim 10^{10}\,$yr). This conclusion is also important to the formation and evolution of normal galaxies and massive black holes.

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