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HIGH COLUMN DENSITIES AND LOW EXTINCTIONS OF GAMMA-RAY BURSTS: EVIDENCE FOR HYPERNOVAE AND DUST DESTRUCTION

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ABSTRACT

We analyze a complete sample of γ -ray burst afterglows and find X-ray evidence for high column densities of gas around them. The column densities are in the range 10^{22} – 10^{23} cm⁻², which is right around the average column density of Galactic giant molecular clouds. We also estimate the cloud sizes to be 10–30 pc, implying masses $\geq 10^5 M_\odot$. This strongly suggests that γ -ray bursts lie within star-forming regions and therefore argues against neutron star mergers and for collapses of massive stars as their sources. The optical extinctions, however, are 10–100 times smaller than expected from the high column densities. This confirms theoretical findings that the early hard radiation from γ -ray bursts and their afterglows can destroy the dust in their environment, thus carving a path for the afterglow light out of the molecular cloud. Because of the self-created low extinction and location in star-forming regions, we expect γ -ray bursts to provide a relatively unbiased sample of high-redshift star formation. Thus, they may help resolve what is the typical environment of high-redshift star formation.

Subject headings: dust, extinction — early universe — gamma rays: bursts — stars: formation

1. INTRODUCTION

Gamma-ray bursts emit up to 10^{53} ergs in γ -rays and X-rays in a few seconds followed by an “afterglow” of X-ray (Costa et al. 1997), optical (van Paradijs et al. 1997), and radio (Frail et al. 1997) emission that generally lasts days to months (van Paradijs, Kouveliotou, & Wijers 2000). The arcsecond localizations of γ -ray bursts by the detection of these counterparts have made it possible to study the environments in which γ -ray bursts arise. This has provided a number of indications of their association with massive stars and star formation. First, most γ -ray bursts lie within the region of UV emission from massive stars in their host galaxy (e.g., Bloom, Djorgovski, & Kulkarni 2001). Second, the energies of γ -ray bursts are comparable to those of supernovae, further suggesting the deep gravitational collapse of a few solar masses as the source of energy for γ -ray bursts. Candidates satisfying these requirements include exploding very massive stars, also termed hypernovae or collapsars (Woosley 1993; Paczyński 1998), mergers of two neutron stars (Eichler et al. 1989), and the merger of a neutron star and a black hole (Mochkovitch et al. 1993). Mergers may be inconsistent with the small offsets between γ -ray bursts and their hosts (Bloom, Sigurdsson, & Pols 1999a; Bulik, Belczynski, & Zbijewski 1999). Further evidence for the relation between γ -ray bursts and star formation has been provided by the fact that the brightness distribution of γ -ray bursts agrees well with models in which the γ -ray burst rate tracks the star formation rate over the past 15 billion years of cosmic history (Totani 1997; Wijers et al. 1998; Komers et al. 2000). The most direct evidence relating γ -ray bursts to a specific type of progenitor has been the discovery of supernova 1998bw in the error box of GRB 980425 (Galama et al. 1998c) and the detection of supernova-like light curves underneath two afterglows, GRB 980326 (Bloom et al. 1999b) and GRB 970228 (Reichart 1999; Galama et al. 2000). Despite their unusually high luminosity, these supernovae would often go un-

noticed due to the much brighter γ -ray burst afterglow; therefore, we do not know whether most γ -ray bursts are associated with supernovae or just some of them. Also, the fact that GRB 980425 was very nearby and subluminal in γ -rays by a factor of 10^4 makes it hard to extrapolate its supernova association to normal γ -ray bursts without additional considerations.

To elucidate the γ -ray burst–supernova association further, we examine optical and X-ray extinctions of γ -ray burst afterglows (§ 2). Then we discuss the evidence these extinctions provide that the majority of long γ -ray bursts occur in molecular clouds, with dust destruction explaining the unusually low extinctions (§ 3). We thus infer that neutron star and black hole mergers are no longer plausible γ -ray burst progenitors, and we briefly mention some further implications of our results (§ 4).

2. EXTINCTION OF γ -RAY BURST AFTERGLOWS

2.1. Optical Extinction

A paradox in associating most γ -ray bursts with exploding very massive stars is that one expects the majority of these to lie amid highly absorbing molecular clouds. The lack of high rest-frame visual extinction has therefore led to considerable skepticism about the γ -ray burst–supernova connection. Here we reinvestigate the extinction for γ -ray bursts in a systematic way, by fitting an extinction model to all afterglows for which the required X-ray and optical data exist. The model function is

$$F_\nu = F_{\nu_0}(\nu/\nu_0)^{-\beta} \exp [-A_{\nu_r}(1+z)\nu/\nu_r], \quad (1)$$

where ν_ν and F_{ν_0} are the observer-frame V-band central frequency and extinction-corrected V-band flux, respectively, and A_{ν_r} is the rest-frame visual extinction; the extinction term is applied only to optical and infrared data. The results of the fits are given in Table 1. Note the low optical extinctions. (Some fitted A_{ν_r} are negative, as expected from a fit procedure if the values are less than the fit errors; we did not force $A_{\nu_r} > 0$.) We have used the simplest possible extinction law here, $A_\nu \propto \nu$. In metal-rich environments, the extinction can have features, such as the 2200 Å “bump.” We see no significant detection of this bump in any afterglow, despite its easy observability at redshifts 1–2, and therefore neglect it.

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TABLE 1
POWER-LAW FITS TO AFTERGLOW SPECTRAL ENERGY DISTRIBUTIONS

GRB	EPOCH (UT)	SINGLE POWER LAW PLUS DUST				BROKEN POWER LAW PLUS DUST							$N_{\rm H}$ ($\times 10^{21}$)	z
		$\log(F_{\nu_0})$ (Jy)	β	A_{ν_r}	χ^2/dof	$\log(F_{\nu_0})$ (Jy)	β	A_{ν_r}	$\log \nu_c$	χ^2/dof	β_x			
970228	0228.99	-5.2 ^{+0.4} _{-0.5}	0.63 ^{+0.13} _{-0.13}	-0.8 ^{+0.7} _{-0.7}	0.3/1	-5.1 ^{+0.5} _{-0.6}	0.46 ^{+0.29} _{-0.14}	-0.7 ^{+0.7} _{-0.8}	...	0.3/1	0.96 ^{+0.19} _{-0.19}	3 ⁺⁶ ₋₄	0.695	
970508	0510.98	-4.50 ^{+0.12} _{-0.11}	0.84 ^{+0.06} _{-0.05}	0.02 ^{+0.15} _{-0.14}	2.2/3	-4.38 ^{+0.14} _{-0.10}	0.50 ^{+0.35} _{-0.20}	0.16 ^{+0.16} _{-0.27}	...	2.1/3	0.99 ^{+0.29} _{-0.07}	6 ⁺¹⁰ ₋₅	0.835	
971214	1215.50	-4.72 ^{+0.14} _{-0.13}	0.90 ^{+0.05} _{-0.05}	0.38 ^{+0.11} _{-0.09}	0.2/1	-4.81 ^{+0.40} _{-0.08}	0.38 ^{+0.60} _{-0.03}	0.32 ^{+0.18} _{-0.03}	...	1.8/1	1.03 ^{+0.51} _{-0.22}	200 ⁺²⁹⁰ ₋₁₂₀	3.42	
980703	0704.40	-4.09 ^{+0.07} _{-0.06}	1.05 ^{+0.03} _{-0.03}	1.63 ^{+0.20} _{-0.20}	2.0/1	-4.06 ^{+0.23} _{-0.07}	1.01 ^{+0.06} _{-0.25}	1.68 ^{+0.40} _{-0.20}	...	2.1/1	18 ⁺² ₋₃	36 ⁺²² ₋₁₃	0.966	
990123	0124.65	-4.94 ^{+0.06} _{-0.06}	0.66 ^{+0.03} _{-0.03}	-0.20 ^{+0.17} _{-0.16}	2.0/5	-4.93 ^{+0.22} _{-0.06}	0.65 ^{+0.04} _{-0.15}	-0.07 ^{+0.14} _{-0.06}	18.8 ^{+0.6} _{-3.4}	1.9/5	0.97 ^{+0.04} _{-0.04}	5.4 ^{+9.4} _{-2.7}	1.60	
990510	0511.26	-4.20 ^{+0.08} _{-0.09}	0.86 ^{+0.04} _{-0.04}	-0.22 ^{+0.23} _{-0.23}	0.15/2	-4.09 ^{+0.11} _{-0.18}	0.60 ^{+0.25} _{-0.20}	0.01 ^{+0.11} _{-0.18}	16.7 ^{+3.2} _{-1.7}	0.0/3	1.12 ^{+0.12} _{-0.12}	10 ⁺⁹ ₋₉	1.62	
980329	0402.99	-5.70 ^{+0.17} _{-0.20}	0.91 ^{+0.10} _{-0.07}	2.9 ^{+1.1} _{-0.8}	0.0/0	-5.65 ^{+0.30} _{-0.22}	0.85 ^{+0.15} _{-0.20}	3.0 ^{+1.3} _{-0.9}	...	0.4/0	1.63 ^{+0.41} _{-0.36}	10 ⁺⁸ ₋₄	...	
980519	0520.34	-4.34 ^{+0.16} _{-0.15}	0.98 ^{+0.06} _{-0.06}	0.8 ^{+0.4} _{-0.4}	0.2/2	-4.31 ^{+0.26} _{-0.17}	0.92 ^{+0.11} _{-0.27}	0.9 ^{+0.6} _{-0.4}	...	0.4/2	1.52 ^{+0.70} _{-0.57}	4 ⁺¹⁰ ₋₅	...	

NOTE.—The table presents the results of fitting a single power law plus dust absorption (eq. [1]) and the results of fitting a broken power law plus dust absorption (eq. [2]) to the X-ray to optical/infrared spectral flux distributions at the given epoch of γ -ray burst afterglows (see text for fits and parameter and sample definitions); ν_c , A_V , and N_H are in the rest frame if z is known; β_x and N_H are from Owens et al. 1998, unless stated otherwise; 970228: Galama et al. 2000; Djorgovski et al. 1999; 970508: Galama et al. 1998a, 1998b; Bloom et al. 1998; 971214: Ramaprakash et al. 1998; Halpern et al. 1998; Wijers & Galama 1999; Kulkarni et al. 1998—in the fit we excluded the infrared data because of the observed spectral bump (Ramaprakash et al. 1998); 980329: Reichart et al. 1999; in 't Zand et al. 1998; 980519: Halpern et al. 1999; 980703: Vreeswijk et al. 1999b (β_x , N_H); Djorgovski et al. 1998; 990123: Piro 2001 (Fig. 6, β_x); Galama et al. 1999; J. Heise et al. 2001, in preparation (N_H); 990510: Harrison et al. 1999; Stanek et al. 1999; Kuulkers et al. 2000; Vreeswijk et al. 1999a.

The prompt and afterglow X-rays are not significantly attenuated, and there is only one γ -ray burst in which the search for an optical afterglow resulted in upper limits well below the expected optical flux (GRB 970828; Groot et al. 1998).⁴ Most optical nondetections are adequately explained by adverse observing conditions and consistent with the presence of a normal afterglow. Hence, there is no evidence from nondetections for a significant population of highly extinguished γ -ray bursts or for significant skewing of the extinction distribution due to the selection effect that γ -ray bursts with higher extinction are simply not found.

In the above analysis, we have assumed that the intrinsic spectrum of the afterglow is a pure power law. The theory of afterglows allows a so-called cooling break in the spectrum between X-rays and optical, where the power-law slope steepens by one-half. A comparison of the mean optical to X-ray slope β_{ox} and the X-ray spectral slope β_x shows that they are indeed different, indicating that such a break may be present: $\langle \beta_x - \beta_{\text{ox}} \rangle = 0.31 \pm 0.05$. Therefore, we redo our fits with an extra break. The fit function is

$$F_\nu = F_{\nu_0}(\nu/\nu_0)^{-(\beta+1/2)} \exp[-A_V(1+z)\nu/\nu_c] \times \left\{ \frac{[\nu(1+z)/\nu_c]^{-n/2} + 1}{[\nu_c(1+z)/\nu_c]^{-n/2} + 1} \right\}^{-1/n}. \quad (2)$$

The index n controls the sharpness of the break. We use $n = 2$, which provides a smooth transition over 2 dex in frequency, and find little change in the fits if we vary the width in the range 1–3 dex. The extra datum needed to constrain this fit is β_x . To treat this uniformly with the other data, we add an artificial data point with 10 times greater frequency than the first X-ray point and give it a value and error so that a fit to the two X-ray points gives the correct values and errors of the X-ray flux and spectral slope. The results of the new fits are also given in Table 1, showing hardly any change in the extinctions.

⁴ If due to extinction, the factor of 300 or more flux deficit requires $A_V > 3$ for this source, which has $z = 0.96$ (Djorgovski et al. 2001, in preparation).

2.2. X-Ray Absorption

Our results confirm in a more rigorous way the casual impression of low optical extinction in γ -ray bursts and therefore seem to contradict the notion of exploding massive stars being the progenitors of γ -ray bursts. However, the hydrogen column densities toward the γ -ray bursts reveal startlingly contrasting evidence. In Table 1, we collect from the literature values of the hydrogen column density toward γ -ray bursts as derived from soft X-ray absorption. To obtain these values, we subtracted the Galactic foreground column (Dickey & Lockman 1990) from the total measured value. Then we accounted for the fact that the soft X-ray optical depth is a strong function of energy, $\tau_x \propto E^{-2.6}$ (Morrison & McCammon 1983), which implies that we have to multiply the foreground-subtracted column by $(1+z)^{-2.6}$ for a source at redshift z to get the true column density in the rest frame of the γ -ray burst. (Note that while in principle the photoelectric absorption has richer structure due to absorption edges of individual atomic species, the presently available spectral resolution and signal-to-noise ratio does not allow this to be discerned.) This is a large correction, ranging from 4 to 50 among the sample, and the resulting rest-frame hydrogen column densities are in the range $10^{21.5} - 10^{23.3} \text{ cm}^{-2}$. To emphasize the contrast between the optical and X-ray results, we show in Figure 1 the correlation between optical and X-ray extinction. The solid curve indicates the relation between A_V and N_H for the Milky Way (Predehl & Schmitt 1995), so we see that the observed visual extinctions are 10–100 times smaller than expected for the observed X-ray absorption.

To investigate the significance of the X-ray columns, we note that all background-subtracted values are positive, whereas one would expect equal numbers of positive and negative values if the net excess were zero. First, we test the hypothesis that there is no excess above the Galactic foreground. For this, we may include the two cases without a known redshift. The χ^2 -value is then 24.6 for 8 degrees of freedom (dof), which has a chance probability of 0.002. Therefore, the hypothesis of no host column density is rejected with 99.8% confidence for the whole sample. If we omit the two individually most significant ones, we get $\chi^2/\text{dof} = 10.7/6$, so even for the weaker cases the no host column hypothesis is rejected with

Fig. 1.—Hydrogen column density N_{H} vs. the optical extinction at V-band A_V for a number of γ -ray burst afterglows; data are from Table 1; error bars are 68% confidence. The solid curve is the Galactic A_V - N_{H} relation (Predehl & Schmitt 1995). The dashed line shows the average column density of a giant molecular cloud of $170 M_{\odot} \text{ pc}^2$ (Solomon et al. 1987).

90% confidence. Now we test the sample against the hypothesis that the host column agrees with the value predicted by the Galactic A_V - N_{H} relation. This we can do for only the six sources with known redshift, and we find $\chi^2/\text{dof} = 15.1/6$ for this hypothesis, which means it is excluded at the 98% confidence level. Even without GRB 980703, the hypothesis is excluded with 92% confidence. We can summarize the present statistics as showing with high significance that there is a host column density in γ -ray bursts (see also Owens et al. 1998) and with good significance that this column density exceeds the value predicted from their A_V .

Both types of extinction are due to heavy elements, so metallicity differences cannot change the ratio. However, the optical/UV extinction is due to dust grains, whereas the X-ray extinction is due to K and L shell electrons of intermediate-mass elements (mostly C and O) and therefore does not depend on whether the atoms are in a gas or a solid. The X-ray extinction is therefore a better measure of the total column density. However, converting the X-ray absorption to a hydrogen column density, as is customary, *does* depend on metallicity. Since the high-redshift regions we are probing may have lower metallicities, the true column densities can only be larger than those we have derived. (Since the regions are very actively star-forming, their metallicity may not be much less than in the Milky Way, though.)

3. IMPLICATIONS FOR γ -RAY BURST ENVIRONMENTS

The values of the X-ray column densities are very high and typical of the column densities through giant molecular clouds (Fig. 1; Solomon et al. 1987). This strongly suggests that most γ -ray bursts are located in molecular clouds. We now attempt to constrain the size of the clouds and thereby their mass.

First, the surprisingly low extinctions may be explained by recently proposed dust destruction: dust is sensitive to the UV and X-radiation from the γ -ray burst and its afterglow. UV and X-ray light heats the grains and out to about 20 pc can evaporate them (Waxman & Draine 2000; Fruchter, Krolik, & Rhoads

2001). Waxman & Draine find that a prompt flash like that seen only in GRB 990123 is needed to muster enough UV light; however, Fruchter et al. show that the X-ray flux is at least as efficient in heating the grains. Since this comes mostly from the prompt burst emission, the uncertain UV flashes are not needed in their model. They find that average γ -ray bursts can evaporate all dust out to 20 pc. Beyond this, dust may be shattered by strong grain charging. Since the effect of this on dust extinction properties is unclear, we shall not consider it here. From our low optical extinctions, we conclude that dust destruction must be taking place. This limits the bulk of the cloud to lie within about 20 pc of the γ -ray burst.

A definite lower limit to the size of the absorbing region follows from the fact that the afterglow radius after a day is about 0.1 pc (e.g., Wijers & Galama 1999). This firmly excludes any remains of the exploded star as the source of X-ray or optical absorption. The size of the absorbing cloud can also be bounded from below using absorption lines of Mg I in the spectra of many optical transients (e.g., Vreeswijk et al. 2001; Metzger et al. 1997). Afterglows tend to have strong Mg I lines, especially relative to Mg II, indicating they originate in denser regions than the normal diffuse interstellar medium. We therefore suppose they originate in the same region that causes the large X-ray columns. The fact that this Mg I is still visible after a day means it has not all been ionized away. Mg I has an ionization energy of 7.84 eV, and photons above 13.6 eV are stopped by H very near the γ -ray burst. Averaging the ionization cross section over this energy range, weighted by the afterglow fluence spectrum, we find an optical depth to Mg I ionizing photons of $0.7N_{\text{H}22.5}$ (assuming the solar value of $[\text{Mg}/\text{H}]$). This means that for most of the column density range, the optically thin limit is adequate for judging the survival of Mg I at the edge of the cloud. Recombination times are much too long to play a role.

Integrating the γ -ray burst flux over time and over the same energy range, weighted by the energy-dependent cross section, we find that an average Mg atom would intercept $2.1 \times 10^4 E_{52}^{4/3} n^{1/2} \epsilon_{B,-2}^{5/6} \epsilon_{e,-1}^{4/3} (d/1 \text{ pc})^{-2}$ ionizing photons (for a typical afterglow with $\beta = 0.75$, where $\epsilon_B = 0.01 \epsilon_{B,-2}$ and $\epsilon_e = 0.1 \epsilon_{e,-1}$ are the equipartition fractions in the notation of Wijers & Galama 1999). Therefore, some of the Mg must be many parsecs from the γ -ray burst in order to survive. The Mg lines are usually rather saturated, so we can get only a lower limit to the Mg I column density. For the case of GRB 990510 (Vreeswijk et al. 2001), this limit is $10^{13.3} \text{ cm}^{-2}$, which for normal Mg abundance is contained in less than 10^{21} cm^{-2} of total N_{H} , accounting for depletion. This is less than the total observed X-ray column, so only a fraction of Mg need remain neutral. To set a conservative lower limit, we shall tolerate 10 ionizations for the average Mg atom at the edge, implying survival of less than $e^{-10} = 5 \times 10^{-5}$ of Mg anywhere in the cloud. Then the lower limit to the cloud size becomes $45 E_{52}^{2/3} n^{1/4} \epsilon_{B,-2}^{5/12} \epsilon_{e,-1}^{2/3} \text{ pc}$. This is quite sensitive to burst parameters and often above the upper limit from dust destruction. Therefore, Mg lines need not occur in every burst, and their presence should be correlated with burst strength (see also Perna & Loeb 1998).

Together, dust destruction and Mg I survival constrain the size of the cloud to be tens of parsecs. The cloud therefore has a density of $500 N_{\text{H}22.5} / R_{20} \text{ cm}^{-3}$ and a mass of $4 \times 10^5 N_{\text{H}22.5} R_{20}^2 M_{\odot}$ (where $N_{\text{H}22.5} = N_{\text{H}} / 10^{22.5} \text{ cm}^{-2}$ and $R_{20} = R / 20 \text{ pc}$). These parameters are very much like those of giant molecular clouds (Solomon & Edmunds 1980; Solomon et al. 1987). We therefore consider our findings strong evidence that

almost all (long) γ -ray bursts are associated with giant molecular clouds and therefore with star-forming regions. This, in turn, speaks in favor of massive stars rather than compact object mergers as the progenitors of γ -ray bursts.

Further predictions of the location of γ -ray bursts in molecular clouds are associated with absorption/scattering processes of the γ -ray burst emission in the cloud. (1) Absorption and reradiation by sublimating dust in the infrared may produce a reradiation echo with a thermal spectrum that peaks in rest-frame infrared on a timescale of several tens of days (Waxman & Draine 2000). (2) Scattering of the afterglow's light by dust outside the dust-vacated region may produce a scattering echo on timescales of tens to hundreds of days (Esin & Blandford 2000). This echo has a spectrum similar to that of the afterglow. Each echo can emit 10^{41} – 10^{42} ergs s $^{-1}$. (3) The far-UV radiation will be absorbed by H $_2$, causing a strong drop in the UV at 1650 and 1300 Å, and fluorescence will result in rest-frame UV emission on timescales of days to months (Draine 2000). (4) If burst radiation is collimated, it is likely that the later, softer emission is less collimated, enabling us to see more afterglows than γ -ray bursts (e.g., Rhoads 1997). However, because dust is destroyed only along the collimated path of the initial hard radiation, such “ γ -ray burst-less afterglows” would not be visible in optical and near-IR from embedded sources. Only in far-IR, millimeter, and radio could the frequency of afterglows be significantly greater than that of γ -ray bursts.

Our findings may also have some indirect bearing on the issue of the cosmic star formation history in the following sense: there has been much recent debate on the relative importance of UV and far-IR radiation in counting the star formation rate at high redshift (e.g., Madau, Pozzetti, & Dickinson 1998; Barger, Cowie, & Sanders 1999). In both cases, one counts the location of massive, UV-producing stars, but in the far-IR case it is found/assumed that the majority of these are deeply shrouded in dust, concentrated in ultraluminous IR galaxies (ULIGs; e.g., Sanders & Mirabel 1996). Since γ -ray burst radiation escapes fairly well even from ULIGs, γ -ray burst locations might provide an unbiased sample of massive-star

locations at redshifts 1–4. This means that a far-IR study of γ -ray burst host galaxies should help resolve the issue of what type of host, ULIGs or UV-emitting smaller galaxies, are the dominant source of massive-star production at these redshifts.

4. CONCLUSIONS

We have examined a complete sample of γ -ray burst afterglows, namely, those with known redshift and X-ray column density, for which optical to X-ray data allow a determination of reddening. As a sample, they provide strong evidence for high X-ray column densities, without a single good exception. However, the individual measurements in a given source are very significant only for GRB 980703 and GRB 980329. Therefore, good X-ray spectra are required for more sources in order to confirm our findings and pin down the parameters of the clouds better. The size and origin of the absorbing matter are constrained by the low extinction, the blast wave size, and the survival of Mg I. High-resolution measurements of the Mg absorption lines to better determine the location and column density of the Mg absorber are needed to strengthen the lower limits on cloud size and mass.

In short, we find high X-ray column densities and low optical extinctions for γ -ray burst afterglows, from which we infer that (1) most γ -ray bursts are embedded in large molecular clouds; (2) γ -ray bursts are therefore likely produced by dying massive stars and not by mergers of neutron stars and/or black holes; (3) the low optical extinctions of γ -ray bursts confirm theoretically predicted dust destruction by their hard radiation, which “paves the way” for the optical afterglow to escape even large clouds; and (4) γ -ray burst host studies may help identify the dominant sources of high-redshift star formation.

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