Limits on the molecular gas content of $z \sim 5$ LBGs

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ABSTRACT
We present limits on the molecular gas content of Lyman break galaxies (LBGs) at $z \sim 5$ from observations targeting redshifted CO(1–0) and CO(2–1) line emission. We observed a single field containing eight spectroscopically confirmed $z \sim 5$ LBGs, seven of which are contained within a narrow ($z = 4.95 \pm 0.08$) redshift range and the eighth is at $z = 5.2$. No source was individually detected. Assuming the CO to H$_2$ conversion factor for vigorous starbursts, we place upper limits on the molecular gas content of individual $z \sim 5$ LBGs of M(H$_2$) $\lesssim 10^{10}$ M$\odot$. From a stacking analysis combining all of the non-detections, the typical $z \sim 5$ LBG has an H$_2$ mass limit comparable to their stellar mass, $<3.1 \times 10^9$ M$\odot$. This limit implies that, given the star formation rates of these systems (measured from their UV emission), star formation could be sustained for at most $\sim$100 Myr, similar to the typical ages of their stellar populations. The lack of a substantially larger reservoir of cold gas argues against the LBGs being UV-luminous superstarbursts embedded in much larger UV-dark systems and as a result increases the likelihood that at least those LBGs with multiple components are starbursts triggered by mergers. The sources responsible for re-ionization are expected to be starbursts similar to these systems, but with lower luminosities, masses and consequently with star formation time-scales far shorter than the recombination time-scale. If so, the ionized bubbles expected in the IGM during the re-ionization era will only infrequently have UV-luminous sources at their centres.

Key words: galaxies: high-redshift – galaxies: starburst – galaxies: star formation – radio lines: galaxies.

1 INTRODUCTION
Detailed observations of the earliest galaxies are necessary if we are to form a complete picture of galaxy formation and evolution. While increasing numbers of spectroscopically confirmed galaxies are being discovered at $z \sim 5$ and above (within $\sim$1 Gyr of the big bang), almost all are discovered through rest-frame UV emission originating from strong ongoing star formation. Unfortunately, this tells us little about the (potentially dominant) UV-dark baryonic component of these galaxies and consequently limits our understanding of star formation in the high-$z$ Universe.

Lyman break galaxies (LBGs) form a substantial part of current samples of $z > 5$ galaxies (e.g. Douglas et al. 2009, 2010; Vanzella et al. 2009). They are identified via their UV-contuum emission longward of 1216 Å in the rest frame, which arises from hot young stars formed in unobscured starburst regions. While Spitzer-based follow-up observations have made some progress in exploring and placing limits on their older underlying stellar populations (e.g. Eyles et al. 2007; Verma et al. 2007), we know little about their gas content, which is a crucial diagnostic of the duration of the ongoing starburst and of the nature of the LBGs themselves. The galaxies have unobscured star formation rates of a few $\times 10^5$ M$\odot$ yr$^{-1}$ arising from regions with a typical surface area of $\sim$1 kpc$^2$. The strong wind generated by such a starburst can potentially limit the available fuel for continuing star formation. Clearly, the amount of gas available to the ongoing starburst is key to an understanding of the nature of the burst and the future of star formation activity within the system. HST imaging of $z \sim 5$ LBGs (e.g. Conselice & Arnold 2009; Douglas et al. 2010) shows that many systems have multiple UV components and extended, distorted morphologies on scales of a kpc or more. With the available optical and near-IR data, it is currently impossible to determine whether such structures imply that the LBGs originate in mergers, or are individual superstarburst regions embedded in much larger UV-dark systems, as found in low-redshift Lyman break analogues (Overzier et al. 2008, see Douglas et al. 2010 for a discussion). If the latter scenario is correct, then one would expect considerably cooler and cold gas present in the immediate environment of the LBGs than is present in the stellar mass produced by the ongoing starbursts.
In this Letter we probe the cool gas component of a sample of \( z \sim 5 \) LBGs drawn from the ESO Remote Galaxy Survey (ERGS\(^1\); Douglas et al. 2007, 2009, 2010). Out of 10, two of the 40–arcmin\(^2\) ERGS pointings display a large overdensity of spectroscopically confirmed UV-bright sources over narrow (\( \Delta z \sim 0.1 \)) redshift ranges. The first of these was the subject of a previous paper (Stanway et al. 2008) in which we discussed the identification of a UV-dark molecular line emitter at \( z \sim 5 \). Here, we target one field, J1054.4–1245, which contains many spectroscopically confirmed LBGs in a 2 arcmin diameter region. As in our previous work, we target the field using the Australia Telescope Compact Array (ATCA), but this time we use the new Compact Array Broad-band Backend (CABB) which probes a \( \Delta z \sim 0.6 \) redshift range in a single exposure (at 38 GHz). This is approximately 15 times broader than in our first work and easily encompasses the entire velocity range probed by the LBG overdensity.

Throughout this Letter, unless otherwise stated, all magnitudes are on the AB scale, and the cosmology used is \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_\Lambda = 0.7 \) and \( \Omega_M = 0.3 \).

2 OBSERVATIONS

Observations were carried out with the ATCA over two separate runs, one in 2009 May as part of project C1954 and another in 2010 March as part of project C2297. The primary goal of the project was to search for UV-dark molecular line emitters across our target field and the results of that study will be presented in a future paper. The array was in the compact H168 configuration, using both north–south and east–west baselines. We utilized the new CABB correlator with two intermediate frequency (IF) bands, each with 2 GHz/2048 channel configurations. We targeted CO(2–1) and CO(1–0) transitions at the LBG overdensity redshift. For CO(2–1) transitions we tuned the IF bands to 36.70 and 38.72 GHz to allow a simultaneous survey range of 4.81 \( \leq z \leq 5.44 \). We bin six adjacent 1-MHz channels to increase the signal-to-noise ratio, and we obtain a spectral resolution of \( \sim 47 \text{ km s}^{-1} \). During the first run, observations were taken in six 8-h periods between 2009 May 1 and 7. Three pointings were observed in order to target the maximum possible number of LBGs in the field. During the second run, two additional pointings were observed in four 8-h periods between 2010 March 21 and 23 (see Fig. 1). A nearby bright source, PKS1054–188, was observed every 15 min to determine the phase stability and the pointing accuracy was checked every hour. Primary flux calibration was carried out on the standard ATCA calibration source, PKS1934–638, each night. The half-power beamwidth (HPBW) of the ATCA at \( \sim 37 \) GHz is 74 arcsec and the restoring beam, for natural weighting and this configuration, is \( 7.3 \times 4.8 \) arcsec\(^2\). For CO(1–0) transitions we tuned the IF bands to 19.12 and 21.12 GHz giving redshift coverage of 4.23 \( \leq z \leq 5.34 \). We observed a single pointing for two nights on 2009 May 8 and 9, encompassing all five \( \sim 37 \) GHz pointings (see Fig. 1). As before, we bin three adjacent 1-MHz channels to increase the signal-to-noise ratio which gives a resolution of \( \sim 47 \text{ km s}^{-1} \) (matching the velocity resolution of our high-frequency data), and use the nearby source 1054–188 for secondary flux calibration and PKS1934–638 for primary flux calibration. The HPBW at \( \sim 20 \) GHz is 2.5 arcmin and the restoring beam is 15.9 \( \times \) 10.9 arcsec\(^2\). At \( z \sim 5 \) this corresponds to a beam size of \( > 50 \text{ kpc} \).

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Figure 1. The spatial position of spectroscopically confirmed LBGs in our target field. Red diamonds indicate LBGs in the narrowest redshift overdensity, while the black cross shows the eighth LBG in this region at slightly higher redshift. Our ATCA pointings are indicated by the 7-mm (solid circles for 2009 observations and dot–dashed blue circles for 2010 observations) and 12-mm (dashed circle) HPBWs. These encompass all eight LBGs.

We expect any detectable line emission from our sources to have a velocity width of \( \sim 150 \text{ km s}^{-1} \) (the only two known high-redshift, non-AGN, CO line-emitting galaxies at \( z \sim 5 \) have linewidths of \( \sim 160 \text{ km s}^{-1} \), Coppen et al. 2010, and \( \sim 110 \text{ km s}^{-1} \), Stanway et al. 2008), and we require detections to be statistically significant (\( > 2\sigma \)) in each of the three adjacent channels. Therefore by binning our data to 3 and 6 MHz at the lower and higher frequency settings, a detection in three adjacent bins will correspond to an \( \sim 150 \text{ km s}^{-1} \) wide line.

Total integration times were 16 h at each frequency giving a root mean square (rms) noise of \( 0.11 \text{ mJy beam}^{-1} \) at 19 GHz and \( 0.17 \text{ mJy beam}^{-1} \) at 37 GHz in each 47 km s\(^{-1}\) channel.

3 LIMITS ON LBG CO EMISSION

Our observations target eight spectroscopically confirmed \( z \sim 5 \) LBGs which are spatially distributed within the HPBWs of individual pointings at both \( \sim 37 \text{ and } \sim 19 \) GHz (properties given in Table 1). Seven lie in the three-dimensional overdensity (\( z \sim 4.95 \pm 0.08 \)) of LBGs in the larger ERGS field and the eighth is at a slightly higher redshift (\( z \sim 5.2 \)). None of these galaxies shows detectable line or continuum emission at either of the redshifted CO transitions targeted. For the line emission, each extracted one-dimensional spectrum was examined for emission at the frequency expected for redshifted CO emission (using the redshift determined from either Ly\( \alpha \) emission or the break at Ly\( \alpha \) detected in optical spectroscopy, Douglas et al. 2010). However, in a study of \( z \sim 3 \) star-forming galaxies, Steidel et al. (2010) show that the Ly\( \alpha \) redshift can differ from the systemic redshift derived from interstellar absorption lines and other emission lines by up to \( \sim 600 \text{ km s}^{-1} \), with the Ly\( \alpha \) redshift being systematically higher. Consequently,
we additionally determined limits to any line flux at frequencies corresponding to velocity offsets of up to 600 km s\(^{-1}\) shortward of the Ly\(\alpha\)-derived value (see Fig. 2).

To search for CO line emission, 47 km s\(^{-1}\) wide slices of the data cube were extracted and the rms variation was ascertained in each for a region of \(\sim 20 \times 20\) arcsec\(^2\) centred on the position of each LBG. Any real emission line is likely to be broader than 50 km s\(^{-1}\) as noted above. Consequently, we define a detection as three consecutive 47 km s\(^{-1}\) spectral bins at least 2\(\sigma\) above zero flux in the region between 0 and 600 km s\(^{-1}\) shortward of the Ly\(\alpha\) redshift. Using these criteria, no individual source was detected. To determine a characteristic line limit for each source, 11 values of the rms over three consecutive bins in the same 0–600 km s\(^{-1}\) region were obtained. As the variation between these was small, we took the average value of these as characteristic of a given source. This results in a typical rms flux limit of \(<60\) mJy km s\(^{-1}\) for the CO(2–1) lines and \(<40\) mJy km s\(^{-1}\) for the CO(1–0) line. These correspond to luminosity limits in each line of typically \(1.1 \times 10^{10}\) K km s\(^{-1}\) pc\(^2\) at \(z \sim 1.95\) for CO(2–1) and \(2.6 \times 10^{10}\) K km s\(^{-1}\) pc\(^2\) for CO(1–0) (Solomon et al. 1997).

Converting this to a limit on the molecular gas mass requires an appropriate conversion factor. In the absence of a directly measured value at the highest redshifts, we use the commonly used conversion factor derived from local strongly star-forming galaxies (Solomon & Vanden Bout 2005) of \(M_{\text{gas}}/L_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}\) given the strength of the starbursts in these LBGs. Assuming that the emitting medium is optically thick and thermalized, the line luminosity is independent of transition [i.e. \(L_{\text{CO(2–1)}} = L_{\text{CO(1–0)}}\); Solomon & Vanden Bout 2005]. The typical CO(2–1) limit places a constraint on the gas mass of \(M_{\text{H}_2} \lesssim 8.9 \times 10^8 M_{\odot}\). This is comparable to the stellar mass content of LBGs at this redshift (e.g. Verma et al. 2007; Stark et al. 2009). The constraint placed by the CO(1–0) line is a factor of 2–4 higher depending upon the source.

Of course, if the linewidth is much narrower than we assumed, we may have missed emission using these criteria. However, we note that the above flux and luminosity limits are appropriate for a \(\sigma\) non-detection of any emission confined to a single channel. In fact, no channel in the 600 km s\(^{-1}\) range in any of the spectra deviates from zero by more than 2.5\(\sigma\), so the limit quoted above is robust.

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Table 1. Properties of LBGs in target field (positions given in J2000).

<table>
<thead>
<tr>
<th>RA (°)</th>
<th>Dec. (°)</th>
<th>Redshift</th>
<th>I (mag)</th>
<th>R – I (mag)</th>
<th>I – z (mag)</th>
<th>rms(_{\text{rms}}) (CO(2–1)) (mJy beam(^{-1}))</th>
<th>(L_{\text{CO(2–1)}}^a) (x10(^{10}) K km s(^{-1}))</th>
<th>(M_{\text{H}<em>2}^b) [CO(2–1)] (^c) (x10(^{10}) (M</em>{\odot}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>163.654</td>
<td>−12.7144</td>
<td>4.975 ± 0.001</td>
<td>26.0 ± 0.3</td>
<td>1.2 ± 0.4</td>
<td>&lt;−0.1</td>
<td>0.580</td>
<td>&lt;1.28</td>
<td>&lt;1.03</td>
</tr>
<tr>
<td>163.640</td>
<td>−12.7181</td>
<td>4.975 ± 0.001</td>
<td>25.8 ± 0.2</td>
<td>1.4 ± 0.4</td>
<td>&lt;−0.3</td>
<td>0.595</td>
<td>&lt;1.31</td>
<td>&lt;1.05</td>
</tr>
<tr>
<td>163.662</td>
<td>−12.7240</td>
<td>4.930 ± 0.001</td>
<td>25.7 ± 0.2</td>
<td>1.5 ± 0.4</td>
<td>0.5 ± 0.3</td>
<td>0.530</td>
<td>&lt;1.17</td>
<td>&lt;0.94</td>
</tr>
<tr>
<td>163.655</td>
<td>−12.7243</td>
<td>5.014 ± 0.001</td>
<td>25.7 ± 0.2</td>
<td>&gt;2.3</td>
<td>0.6 ± 0.3</td>
<td>0.409</td>
<td>&lt;0.90</td>
<td>&lt;0.72</td>
</tr>
<tr>
<td>163.635</td>
<td>−12.7265</td>
<td>5.201 ± 0.001</td>
<td>26.1 ± 0.3</td>
<td>&gt;1.8</td>
<td>&lt;0.0</td>
<td>0.583</td>
<td>&lt;1.28</td>
<td>&lt;1.02</td>
</tr>
<tr>
<td>163.633</td>
<td>−12.7316</td>
<td>4.879 ± 0.001</td>
<td>25.8 ± 0.2</td>
<td>1.3 ± 0.4</td>
<td>&lt;−0.3</td>
<td>0.584</td>
<td>&lt;1.29</td>
<td>&lt;1.03</td>
</tr>
<tr>
<td>163.649</td>
<td>−12.7349</td>
<td>5.028 ± 0.001</td>
<td>26.2 ± 0.3</td>
<td>&gt;1.8</td>
<td>&lt;0.1</td>
<td>0.334</td>
<td>&lt;0.74</td>
<td>&lt;0.59</td>
</tr>
<tr>
<td>163.654</td>
<td>−12.7366</td>
<td>5.000 ± 0.001</td>
<td>26.1 ± 0.3</td>
<td>1.3 ± 0.5</td>
<td>&lt;−0.0</td>
<td>0.348</td>
<td>&lt;0.77</td>
<td>&lt;0.61</td>
</tr>
</tbody>
</table>

\(^a\)Average of the total of the 2\(\sigma\) rms errors in three adjacent bins (total in 150 km s\(^{-1}\) width) for all bins, 600 km s\(^{-1}\) blueward of the CO(2–1) line position if optical redshifts are correct.

\(^b\)Limit of CO luminosities derived from rms errors for an unresolved \(\sim 150\) km s\(^{-1}\) line (three channels at 2\(\sigma\) rms limit).

\(^c\)Inferred gas mass derived from conversion factor for local infrared-luminous galaxies (Solomon & Vanden Bout 2005).

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Figure 2. One-dimensional spectrum of a typical LBG in our target region centered on the redshifted CO(2–1) line with redshifts assuming the Ly\(\alpha\) redshift. The blue solid line is the target spectrum (binned to 6-MHz channels) with errors displaying the 1\(\sigma\) rms error in a 20 \(\times\) 20-arcsec\(^2\) region around the LBG position. The red dashed line shows the target spectrum convolved with a 150 km s\(^{-1}\) (FWHM) Gaussian. The shading highlights the region in which CO lines will be found, given the typical offsets between Ly\(\alpha\) and systematic redshifts. The most significant positive peak in the above spectrum at +650 km s\(^{-1}\) is still no more than 2\(\sigma\) away from zero and consequently, given the number of independent bins displayed, is entirely consistent with noise.
true redshifts for the sources may not exactly match the Lyα features contained within a single bin as would be the case for ex-100 and −600 to 0 km s−1.

Figure 3. Histogram of the distribution of flux limits from 823 43 possible iterations of stacking LBG spectra. Eight LBG spectra were combined varying the relative offset in redshift between seven of the spectra in six steps, +150, +100, +50, 0, −50, −100 and −150 km s−1 relative to the eighth spectrum. The dashed line shows the flux limit for the eight spectra stacked at the optically derived redshifts. The distribution of flux limits is Gaussian distributed as expected given the noise characteristics of individual velocity channels.

In addition to determining limits on individual sources, we can derive deeper limits on the ‘typical’ z ∼ 5 LBG by creating an average stack from the spectra of the eight individual sources, having shifted each spectrum to the same effective redshift. Concentrating on the CO(2−1) data and using the same criteria as for an individual spectrum, no line was detected in the averaged spectrum. The limits on the flux, line luminosity and H2 mass of a ‘typical’ LBG are tightened to SCOΔν < 17.5 mJy km s−1, L′(CO(2−1)) < 3.9 × 109 K km s−1 pc2 and MHI < 3.1 × 1010 M⊙ at z = 4.95 (2σ).

However, this process is not completely straightforward as the true redshifts for the sources may not exactly match the Lyα-derived values, as noted above. The offsets between the Lyα and true values may vary by ∼300 km s−1 between objects. Consequently, any combination of weak lines may be averaged in such a way that they are smeared out in frequency and do not reinforce each other to become a detection in the average spectrum. To explore this we made multiple average spectra, varying the relative offset in redshift between each spectrum in seven steps, +150, +100, +50, 0, −50, −100 and −150 km s−1, in total 77 or 823 543 average spectra. We then take the 10 flux limits in the −600 to 0 km s−1 region from each spectrum. The distribution of flux limits for these spectra are shown in Fig. 3. As can be seen, using the Lyα redshifts does not significantly underestimate the true value of the limit.

For completeness, we carried out the same procedure, but looking at features contained within a single bin as would be the case for extremely narrow lines. The highest flux in one of the −600 to 0 km s−1 bins in the average spectra was 12.6 mJy km s−1 (consistent with the noise characteristics given the 823 543 different realizations), considerably less than the above limit of SCOΔν < 17.5 mJy km s−1 and so we consider that limit to be robust even for a very narrow line.

4 DISCUSSION

Assuming that the conversion between CO luminosity and H2 mass determined by Solomon & Vanden Bout (2005) is applicable (the intensity of the starbursts in these LBG indicates that it is), the non-detection of CO emission from these LBGs places interesting constraints on their nature. The similarity between the typical stellar masses of such systems as determined from multiband photometry of z ∼ 5 LBGs (Verma et al. 2007), and the limit to their typical H2 mass (a few times larger) would indicate that the systems are observed about halfway through the ongoing burst of star formation assuming that the current star formation rate is maintained and the conversions from gas to stars approaches ∼100 per cent efficiency. However, the efficiency with which gas is converted into stars is typically no more than 10 per cent, and potentially only 1 or 2 per cent (Lehnert et al. 2009), thus suggesting that these sources are much more than halfway through their life cycle. This is unsurprising as time-scales of ∼10 Myr will be required to produce and sustain the observed UV-continuum fluxes from a population of O and B stars. Dividing the limiting gas mass by the typical star formation rate from Verma et al. (2007) gives a time-scale of ∼100 Myr, with the typical age of a stellar population determined by Verma et al. (2007) being a few tens of Myr. As this implicitly assumes an unrealistic complete transformation of gas into stars, even if the CO luminosity to H2 conversion factor is higher than the Solomon & Vanden Bout value, this is a robust upper limit to the star formation time-scale at this level of activity.

The apparent lack of a comparatively large reservoir of molecular gas in and around the UV-luminous system strongly argues against the LBGs being unobscured superstarbursts embedded in much more massive and extended underlying systems. Any such system should contain sufficiently large amounts of enriched molecular gas to be detectable here. Consequently, it provides support for the alternative hypothesis of a merger origin for at least those systems with multiple spatially distributed UV-luminous components. If all z ∼ 5 LBGs are triggered by mergers with other galaxies, our lack of a single detection implies that few involve comparatively massive systems with substantial obscured star formation or large amounts of processed molecular gas. Additionally, the most active phases of a merger occur when the gas has been consumed and is concentrated in the central regions of the systems. If LBGs are triggered by mergers, and given the need to build UV-continuum fluxes through star formation, this may take substantial time. Therefore in this model LBGs may only be detectable (in the rest-frame UV) towards the end of their starbursts. Observed luminous starburst galaxies at high z typically have short gas depletion times relative to their ages, similar to that seen in these sources. The lack of detectable 850-μm continuum flux in APEX/LABOCA observations of different but essentially similar LBGs (Stanway et al. 2010) gives further support to this model. As noted in Stanway et al. (2010) the conversions from continuum flux limits to star formation rates are currently ambiguous. However, the lack of detectable dust emission from these similar sources lends support to the idea that they do not have large reservoirs of cool and cold material, thus strengthening the idea that these sources are not embedded in more massive obscured systems.

There has been recent discussion (Gnedin & Kravtsov 2010; Papadopoulos & Pelupessy 2010) on whether there should be deviation away from the low-redshift Schmidt–Kennicutt (SK) relation (Schmidt 1959; Kennicutt 1998) at high redshift. Here we note that for unobscured star formation rates of a few tens of solar masses per year arising from regions of ∼1 kpc (e.g. Bouwens et al. 2004; 2010 RAS, MNRAS 408, L31–L35 © 2010 The Authors. Journal compilation © 2010 RAS, MNRAS 408, L31–L35
Bremer et al. 2004; Verma et al. 2007), a limit of $M_{\text{H}_2} \lesssim 3.1 \times 10^{9} \, M_\odot$ in the same area is consistent with the low-redshift SK relation. The synthesized ATCA beam at 38 GHz probes an area of well over 100 kpc$^2$ centred on each LBG and so if there was an underlying larger UV-dark galaxy within which each LBG was embedded, any significant obscured star formation in that galaxy would lead to deviation from the nearby SK relation. As simulations imply that the relation gets steeper with redshift (more gas per unit star formation, e.g. Gnedin & Kravtsov 2010), the deviation from the SK relation would only increase if the nearby relation is inappropriate.

Given the comparatively brief elapsed time between the end of re-ionization and the redshift explored here, the limited gas reservoirs available for star formation in these systems and their relatively short star formation time-scales have an important consequence for the re-ionization process. Re-ionization is likely to be dominated by as-yet undetected faint, low-mass UV-luminous starbursts (e.g. Lehnert & Bremer 2003; Salvaterra, Ferrara & Dayal 2010). As a consequence of their lower mass, these sources will have even shorter star formation lifetimes than the LBGs observed here. At all redshifts the recombination time for the IGM is longer than the Hubble time and hence also much longer than the UV-luminous lifetime of a low-mass starburst. Consequently, most of the ionized bubbles expected to exist in the otherwise neutral IGM during re-ionization will only occasionally have UV-luminous sources at their centres, and most starbursts giving rise to the ionizing flux will have long since ceased to actively form stars and therefore have faded in the UV.

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