Region of Excessive Flux of PeV Cosmic Rays in the Direction Toward Pulsars PSR J1840+5640 and LAT PSR J1836+5925

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Abstract

An analysis of arrival directions of extensive air showers (EAS) registered with the EAS MSU and EAS–1000 prototype arrays has revealed a region of excessive flux of PeV cosmic rays in the direction toward pulsars PSR J1840+5640 and LAT PSR J1836+5925 at significance level up to 4.5σ. The first of the pulsars was discovered almost 30 years ago and is a well-studied old radio pulsar located at the distance of 1.7 pc from the Solar system. The second pulsar belongs to a new type of pulsars, discovered by the space gamma-ray observatory Fermi, pulsations of which are not observed in optical and radio wavelengths but only in the gamma-ray range of energies (gamma-ray-only pulsars). In our opinion, the existence of the region of excessive flux of cosmic rays registered with two different arrays provides a strong evidence that pulsars can give a noticeable contribution to the flux of Galactic cosmic rays in the PeV energy range.

PACS codes: 98.70.Sa Cosmic rays (including sources, origin, acceleration, and interactions), 96.50.sd Extensive air showers, 97.60.Gb Pulsars, 98.70.Rz gamma-ray sources

1 Introduction

The problem of the nature of the knee in the cosmic ray (CR) energy spectrum at 3 PeV and, in a more generic aspect, of the origin of CRs in the PeV energy range stays open for many years now. Attempts to collate arrival directions of CRs with
coordinates of their possible astrophysical sources is one of the routes of investigations on the subject. Another direction, which is being actively developed, is observation of gamma rays from such sources.

In both approaches, the main subject of investigation are Galactic supernova remnants (SNRs) since the model of diffusive shock acceleration at the outer front of expanding SNRs has become widely spread, see, e.g., a review by Hillas 2005. This does not imply though that there are no other astrophysical sources in the Galaxy that are able to accelerate hadrons to PeV and higher energies. In particular, the first results demonstrating that pulsars can act as effective CR accelerators appeared soon after the discovery of pulsars and their identification with neutron stars, see, e.g., Gunn & Ostriker 1969. After this, interest to pulsars as possible sources of CRs with energies \( \gtrsim 10^{14} \) eV up to the highest energies did not vanish, see, e.g., Blasi et al. 2000; Giller & Lipski 2002; Bhadra 2003; Erlykin & Wolfendale 2004; Bhadra 2006. Models considered included acceleration both in pulsar wind nebulae (e.g., the Crab nebula) and by isolated pulsars. It was demonstrated in particular that the Geminga pulsar is a possible candidate for being the single source of the knee at 3 PeV (Bhadra 2003).

In our previous works, we have already reported on the number of regions of excessive flux (REFs) found during an analysis of arrival directions of EAS registered with the EAS MSU array and the EAS–1000 prototype array (“PRO–1000”) and generated by CRs with energies of around PeV, (Kulikov & Zotov 2004; Zotov & Kulikov 2004, 2007, 2009). It was demonstrated that there are no Galactic SNRs in the vicinity of some of the REFs, though a considerable number of regions have isolated pulsars nearby. In Zotov & Kulikov 2009, we pointed out that there are two overlapping REFs in the vicinity of a point with equatorial coordinates \( \alpha = 285^\circ, \delta = 58^\circ \) in the EAS MSU and the PRO–1000 data sets. Taking into account possible errors in determining the boundaries of the REFs, one could consider them as one and the same region with the pulsar PSR J1840+5640 inside (coordinates of the pulsar \( \alpha \approx 280.19^\circ, \delta \approx 56.68^\circ \)). There are neither supernova remnants or SNR candidates inside or close to the region, nor open clusters or OB-associations, which are sometimes considered as possible sources of Galactic cosmic rays. PSR J1840+5640 was discovered back in 1980 (Shitov et al. 1980) and is a well-studied old radio pulsar of the age of \( 17.5 \times 10^6 \) years located at 1.7 kpc from the Solar system, see, e.g., Arzoumanian et al. 1994; Hobbs et al. 2004.

This region attracted our attention once again after there appeared a list of the brightest gamma-ray sources in the energy range from 100 MeV to 100 GeV registered during the first three month of operation of the Fermi Gamma-ray Space Telescope (Abdo et al. 2009a). It happened that there is a pulsar (coordinates \( \alpha \approx 279.06^\circ, \delta \approx 59.46^\circ \)) of a new type near the REF, a so called gamma-ray-only pulsar, i.e., a pulsar that only “blinks” in gamma rays. This pulsar as an intensive gamma-ray source was discovered by EGRET in 1991–1993 but the nature of the source remained unclear
(Nolan et al. 1994). It occurred to be the brightest unidentified gamma-ray source in the energy ranges $> 100$ MeV (significance level of $19.0\sigma$) and $> 1$ GeV ($14.2\sigma$) located far from the Galactic plane (Galactic latitude $b \approx 25^\circ$), see Hartman et al. 1999; Lamb et al. 1997.

Numerous attempts to elucidate the nature of the object named as 3EG J1835+5918 and to find a definite astrophysical counterpart did not succeed, see Mirabal et al. 2000; Reimer et al. 2001; Halpern et al. 2002; Fegan et al. 2005; Halpern et al. 2007, and references therein. After intensive studies of its error box in optical, X-ray, and radio wave bands it was identified as an isolated neutron star correlating with a faint X-ray source RX J1836.2+5925, discovered by ROSAT. It was suggested that the object is a Geminga-like pulsar, which is not observed in optical and radio wave bands, and an upper limit of the distance to the object was obtained ($\lesssim 800$ pc). All attempts to find pulsations in the X-ray and gamma-ray energy ranges failed. Pulsations of 3EG J1835+5918 were not observed during the first year of observations by the AGILE instrument either, though its gamma-ray emission was confirmed at $15.6\sigma$ significance level (Bulgarelli et al. 2008; Pittori et al. 2009). Only gamma-ray observations by the Fermi LAT lead to unequivocal identification of 3EG J1835+5918 as a pulsar, named LAT PSR J1836+5925.

Since the search for gamma-ray sources had become a natural part of the search for PeV cosmic ray sources (Rowell et al. 2005), we performed a more detailed analysis of the REF located in the direction to both pulsars.

### 2 Experimental Data

Similar to our previous studies of EAS arrival directions, the main data sets consist of 513 602 showers registered with the EAS MSU array in 1984–1990 and 1 342 340 showers of the PRO–1000 array registered in 1997–1999. Technical description of the arrays were given by Vernov et al. 1979, and Fomin et al. 1999, respectively. All EAS selected for the analysis satisfy a number of quality criteria and have zenith angles $\theta < 45.7^\circ$. Showers registered with the two arrays have different number of charged particles $N_e$ in a typical event. For the EAS MSU array, the median value of $N_e$ is of the order of $1.6 \times 10^5$, while that for the PRO–1000 array equals $3.7 \times 10^4$. Assuming that the majority of the EAS was generated by protons, one can estimate their energy as being at around 1 PeV. The EAS MSU array allowed one to determine arrival directions of EAS with a better accuracy than the PRO–1000 array but the mean error is estimated to be of the order of $3^\circ$ in both cases.
3 Method of the Investigation

The investigation is based on the method by Alexandreas et al. (Alexandreas et al. 1991), which has been used multiple times for the analysis of arrival directions of CRs by different research groups. The idea of the method is as follows. To every shower in the experimental data set, arrival time of another shower is assigned in a pseudo-random way. After this, new equatorial coordinates ($\alpha$, $\delta$) are calculated for the “mixed” data set thus providing a “mixed” map of arrival directions. The mixed map differs from the original one but has the same distribution in declination $\delta$. In order to compare both maps, one divides them into sufficiently small “basic” cells. A measure of difference between any two regions (cells) of the two maps located within the same boundaries is defined as

$$S = \frac{N_{\text{real}} - N_{\text{bg}}}{\sqrt{N_{\text{bg}}}},$$

where $N_{\text{real}}$ and $N_{\text{bg}}$ are the number of EAS inside a cell in the real and “mixed” (background) maps correspondingly. The mixing of the real map is performed multiple times, and the mixed maps are averaged then in order to reduce the dependence of the result on the choice of arrival times. The method is based on an assumption that the resulting mean “background” map has most of the properties of an isotropic background, and presents the distribution of arrival directions of cosmic rays that would be registered with the array in case there is no anisotropy. Thus, deviations of the real map from the background one may be assigned to a kind of anisotropy of arrival directions of EAS registered at the array. As a rule, selection of regions of excessive flux is performed basing on the condition $S > 3$.

Similar to the paper Zotov & Kulikov 2009, basic cells are of the size $0.5^\circ \times 0.5^\circ$. The number of cycles of mixing was increased from 1000 to 10,000 in order to further improve the quality of the background map. Due to this, the difference between the basic cells of any two consecutive averaged maps obtained close to the end of the mixing reduced approximately by an order of magnitude and is $\sim 1-2\times10^{-3}$ for both data sets.

Cells of excessive flux (CEF) of CRs were searched for in the following way. Adjacent basic strips in $\delta$ (each $0.5^\circ$ wide) were joined into strips of width $\Delta \delta = 3^\circ \ldots 30^\circ$ with step equal to $0.5^\circ$. Each wide strip was then divided into adjacent cells of some fixed width $\Delta \alpha$. After this, we calculated the number of EAS inside each of these cells for both experimental ($N_{\text{real}}$) and background ($N_{\text{bg}}$) maps. For each pair of cells, $S$ was calculated. A cell was considered as a possible CEF if $S > 3$. Every wide strip was divided into cells with a shift of $0.5^\circ$ in $\alpha$ until all possible locations on the grid were covered.

\footnote{We use the word “cell” for regions selected during the initial analysis and preserve the term “region of excessive flux” for regions formed of multiple cells. Thus, contrary to cells, REFs are not necessarily quadrangles.}
Contrary to Zotov & Kulikov 2009, we did not restrict the search to cells such that \( \Delta \alpha = \Delta \delta / \cos \bar{\delta} \), where \( \bar{\delta} \) is the mean value of \( \delta \) for the current strip, and \( \Delta \alpha \) is rounded to the nearest half-integer number, but allowed \( \Delta \alpha \) to deviate from that value by \( \Delta \alpha / 6 \). As a result, additional cells were considered. For example, besides cells of the size \( \Delta \alpha \times \Delta \delta = 3^\circ \times 3^\circ \), we also considered cells of the sizes \( 2.5^\circ \times 3^\circ \) and \( 3.5^\circ \times 3^\circ \). Finally, only cells with more than 10 EAS inside were analyzed.

The method of Alexandreas et al. does not provide a direct answer to the question about the chance probability of appearance of a CEF. It is implicitly assumed that the deviation of \( N_{\text{real}} \) from \( N_{\text{bg}} \) has a Gaussian distribution, and thus one is expected to calculate the corresponding probability basing on the value of \( S \), which is an estimate of the standard deviation of a sample and thus acts as a significance level. Hence, it is assumed the chance probability of a CEF to appear is less than \( 1 - 0.9973 \) providing it was selected at significance level \( S > 3 \).

In order to estimate the chance probability of appearance of a CEF basing on the number of EAS inside, we introduced the following simple method based on the binomial distribution (Zotov & Kulikov 2009). Let a shower axis getting inside the CEF be a success. The number of trials equals the number of showers \( N \) in the data set under consideration, and an estimate of success (for a fixed region) equals \( \tilde{p} = N_{\text{bg}} / N \), where \( N_{\text{bg}} \) is the number of showers in the cell of the background map. The assumption is based on the fact that in the method of Alexandreas et al., \( N_{\text{bg}} \) is considered as an expected number of showers in a cell. Obviously, the chance probability of finding exactly \( N_{\text{real}} \) EAS in a cell (or region) equals

\[
P(\nu = N_{\text{real}}) = C(N, N_{\text{real}}) \tilde{p}^{N_{\text{real}}} (1 - \tilde{p})^{N - N_{\text{real}}},
\]

where \( \nu \) is a random variable equal to the number of successes in the binomial model, and \( C(N, N_{\text{real}}) \) is the corresponding binomial coefficient. Obviously, it is more interesting to consider a probability that there are at most \( N_{\text{real}} \) showers in the cell \( P_N = P(\nu \leq N_{\text{real}}) \), or its adjacent value \( 1 - P_N \). The analysis performed and the data presented below demonstrate that values of \( P_N \) correlate well with the values of chance probabilities calculated on the basis of significance level \( S \).

The fact that \( S > 3 \) for a given cell does not imply it is valid for its sub-cells. More than this, since the method of Alexandreas et al. does not anyhow restrict sizes and shapes of regions to be considered, the non-uniformity of the distribution of data w.r.t. declination \( \delta \) can result in a selection of a CEF such that a great value of \( S \) is obtained due to an excess of EAS in just one of its sub-cells. A situation such that \( S < 3 \) for a number of adjacent cells but \( S > 3 \) for a cell (region) combined of them is possible. In order to improve the robustness of selection of CEFs, we have tried a number of additional quantities. One of the most efficient of them is the probability \( P_{\text{bc}} = P(\xi < N_{\text{bc}}^{+}) \), calculated from the following binomial model. Let \( \xi \) be a random
variable equal to the number of basic cells of the given cell with an excess of EAS over the background values, and $N_{bc}^+$ is the corresponding experimental value. The number of trials equals the number of basic cells in the CEF. It is natural to assume the probability of success to be equal to 1/2. In the results presented below, all CEFs satisfy a condition $P_{bc} > 0.9545$, which corresponds to the significance level of $2\sigma$ for the Gaussian distribution. We thus reduced the chance that a CEF is selected solely due to the non-uniformity of the EAS distribution w.r.t. $\delta$.

4 Results

The region of excessive flux of CRs in the direction toward pulsars PSR J1840+5640 and LAT PSR J1836+5925 found by the analysis of the main EAS MSU data set is shown in the upper panel of Figure 1. The REF consists of 99 CEFs with $S > 3.0$ located within the boundaries $\alpha = 277.5^\circ \ldots 289^\circ$, $\delta = 55.5^\circ \ldots 61^\circ$. Some parameters of the CEFs the region consists of are presented in Table 1. $P_{bc} = 0.989308$ for a CEF with the highest value of $S$. For this CEF, an excess of the experimental flux over the background one takes place in 53 of 84 basic cells that form the CEF. The set of showers within the REF has a slightly greater median value of $N_e$ than the whole data set. For example, median $N_e \approx 1.7 \times 10^5$ for 1508 EAS with $\alpha = 277.5^\circ \ldots 289^\circ$, $\delta = 56^\circ \ldots 60^\circ$, and median $N_e \approx 1.8 \times 10^5$ for 856 EAS within the region covered by CEFs with $S > 4.3$.

The result obtained for the whole EAS MSU data set is confirmed in the case one selects subsets with an improved accuracy of determination of arrival directions.

Table 1: Parameters of cells of excessive flux that form the REF found in the EAS MSU data set (see Figure 1). Notation: $S$ is the significance level for selecting CEFs, $N_{CEF}$ is the number of CEFs selected for a given value of $S$, $\alpha$ and $\delta$ are the ranges of the corresponding equatorial coordinates, $N_{EAS}$ is the range of the number of EAS registered in selected CEFs, $N_{bg}$ is the corresponding range background events, $\min P_N$ is the minimum value of $P_N$ for the CEFs selected.

| $S$  | $N_{CEF}$ | $\alpha$, $^\circ$ | $\delta$, $^\circ$ | $N_{EAS}$ | $N_{bg}$ | $\min P_N$ |
|------|-----------|---------------------|---------------------|-----------|---------|------------|
| $> 3.0$ | 99        | 277.5...289         | 55.5...61           | 518...1146| 449.6...1025.2| 0.998584   |
| $> 3.5$ | 48        | 278...289           | 56...60             | 528...1146| 449.6...1025.1| 0.999735   |
| $> 4.0$ | 21        | 280...287.5         | 56...60             | 537...1029| 451.5...904.3| 0.999958   |
| $> 4.3$ | 5         | 280...287           | 56...59.5           | 594...856 | 496.6...736.8| 0.999989   |
| 4.478 | 1         | 280...286           | 56...59.5           | 744       | 631.5   | 0.999994   |
Figure 1: Upper panel: the region of excessive flux of CRs found in the main data set of the EAS MSU array. Lower panel: the region of excessive flux of CRs found in the PRO–1000 data set for showers with $N_e > 3 \times 10^4$.

The most highly pronounced CEF for a set of showers with $N_e > 10^5$ (343 141 EAS) has $S = 3.951$, $P_N = 0.999947$, $P_{bc} = 0.993082$ and contains 620 EAS within the boundaries $\alpha = 280.5^\circ \ldots 287^\circ$, $\delta = 54.5^\circ \ldots 58.5^\circ$ with the background level equal to 529.1 EAS. For this CEF, an excess of the experimental flux over the background one
takes place in 65 of 104 basic cells that form the CEF.

A similar result is obtained if one excludes showers that have arrival directions close to the vertical. In the set of showers with the zenith angle $\theta > 6^\circ$ (492 853 EAS), we found a CEF with $S = 3.985$, $P_N = 0.999952$, $P_{bc} = 0.961815$ within the boundaries $\alpha = 280^\circ \ldots 286^\circ$, $\delta = 56^\circ \ldots 59^\circ$. For the CEF, an excess of the experimental flux over the background one takes place in 44 of 72 basic cells. Thus, in all these cases we observe regions of excessive flux with the probability to appear by chance that can be estimated as $7.8 \times 10^{-5}$–$7.5 \times 10^{-6}$ if one uses the maximum values of $S$, or as $5.3 \times 10^{-5}$–$6 \times 10^{-6}$ in case one uses the corresponding values of $P_N$.

A region of excessive flux of CRs in the direction toward pulsars PSR J1840+5640 and LAT PSR J1836+5925 was also found in the full data set of the PRO–1000 array (with the significance level up to $S = 3.573$ and $P_N = 0.999800$) and in its subsets similar to those described above. Namely, we found a CEF with $S = 3.785$, $P_N = 0.999908$ in a subset with $\theta > 6^\circ$ (1 267 089 EAS), and a CEF with $S = 3.603$ for a subset with $N_e > 3 \times 10^4$ (471 554 EAS). A REF found in the latter case is shown in the lower panel of Figure 1. Some parameters of CEFs that form the REF are presented in Table 2. The median value of $N_e$ for the CEF selected at the highest significance level equals $6.9 \times 10^4$. This is slightly less than the corresponding value for the whole set of showers with $N_e > 3 \times 10^4$ equal to $7.2 \times 10^4$.

Table 2: Parameters of CEFs that form a region of excessive flux of CRs in the subset of the PRO–1000 data with $N_e > 3 \times 10^4$. See notation in Table 2.

| $S$     | $N_{CEF}$ | $\alpha, ^\circ$ | $\delta, ^\circ$ | $N_{EAS}$   | $N_{bg}$       | $\min P_N$   |
|---------|-----------|-------------------|-------------------|-------------|----------------|--------------|
| $> 3.0$ | 57        | 280.0...291.5     | 58...62.5         | 544...1510  | 476.9...1392.5 | 0.998526     |
| $> 3.3$ | 10        | 280.5...288.5     | 58...62.5         | 695...1170  | 612.3...1060.5 | 0.999472     |
| $> 3.5$ | 3         | 280.5...288.5     | 59...62.5         | 810...917   | 714.4...816.4  | 0.999748     |
| 3.603   | 1         | 280.5...288.0     | 59...62.5         | 865         | 765.3          | 0.999811     |

Thus, we have found cells of excessive flux in the experimental data of the PRO–1000 array with the probabilities of appearing by chance that can be estimated as $1.5–3.5 \times 10^{-4}$ if we use the maximum values of the significance level $S$, or as $1–2 \times 10^{-4}$ in case estimates are based on the corresponding values of $P_N$.

5 Discussion

In spite of the fact that the boundaries of the regions of excessive flux found in the data sets obtained with two different experimental arrays are shifted with respect to
each other, we think they point to one and the same region. Making this conclusion, we take into account the discreetness of the grid and possible errors in determination of arrival directions of EAS.

As we have already mentioned in the introduction, there are no other Galactic objects usually considered as possible sources of PeV cosmic rays in the vicinity of the REF described above. The list of objects checked includes supernova remnants (Green 2009), including pulsar wind nebulae (Roberts 2004), open clusters (Dias et al. 2002), OB-associations, and SNR candidates (SIMBAD database). Hence, a natural question is whether pulsars PSR J1840+5640 and LAT PSR J1836+5925 are able to accelerate protons and/or heavier nuclei up to energies of the order of PeV.

To estimate the maximum energy of a particle accelerated in the wind near the light cylinder of a pulsar, one can use the following expression (Blasi et al. 2000):

\[ E_{\text{max}} = 0.34 \cdot Z \cdot B \cdot \Omega^2 \cdot eV, \]

where \( Z \) is the charge number of the particle, \( B \) is the strength of the surface magnetic field, \( G \), \( \Omega \) is the angular velocity of a pulsar, \( \text{rad s}^{-1} \), and the radius of the pulsar equals \( 10^6 \) cm. The typical energy of the accelerated particle equals approximately a half of \( E_{\text{max}} \).

For PSR J1840+5640, \( B \approx 1.59 \times 10^{12} \) G, \( \Omega \approx 3.80 \) rad s\(^{-1}\) (barycentric period \( P \approx 1.653 \) s, see Manchester et al. 2005). Thus, the maximum energy of a proton accelerated by this pulsar equals approximately \( 7.8 \times 10^{12} \) eV. An iron nuclei can be accelerated up to \( 2 \times 10^{14} \) eV. It follows that PSR J1840+5640 can contribute to the formation of the REF only in case there is a considerable fraction of heavy nuclei in the flux of primary CRs from the corresponding direction.

For LAT PSR J1836+5925, \( B \approx 0.5 \times 10^{12} \) G, \( \Omega \approx 36.26 \) rad s\(^{-1}\) (Abdo et al. 2009b). Thus, the maximum energy of a proton accelerated by this pulsar is of the order of \( 2.2 \times 10^{14} \) eV. For an iron nuclei, \( E_{\text{max}} \approx 5.8 \times 10^{15} \) eV. Hence, LAT PSR J1836+5925 is a possible candidate for being an accelerator of charged particles in the PeV energy range.

Let us assume basing on the estimates of \( E_{\text{max}} \) that the REF described above was formed due to the contribution of one or both pulsars. Then there arises a question of how was the arrival direction of the corresponding EAS kept so close to the direction to these pulsars. It is difficult to give a definite answer. On the one hand, we cannot totally exclude a possibility that a part of showers that formed the REF was initiated by photons but not hadrons. The PRO–1000 array did not allow one to distinguish between gamma-ray and hadronic showers but the EAS MSU array provided such an opportunity because it had a muon detector. Since photonic showers contain very few muons in comparison with hadronic ones, their fraction in the whole data set could be estimated. It was shown by Kristiansen et al. 1975 that the fraction of photon-initiated showers in the data set obtained with the EAS MSU array in 1960s was of the order of \( 10^{-3} \). The same question applied to the REF can be studied separately.

Another possibility is a negligible influence of the Galactic magnetic field (GMF)
on particle trajectories, or even magnetic lensing. It is difficult to say anything definite about the transverse component of the GMF along the line of sight to the pulsars but provide the usual estimates of the mean values of the field in the vicinity of the Solar system. It is remarkable though that there exists a local magnetic field going toward the Galactic longitude \( l \approx 90^\circ \), close to that of both pulsars, with a strength about 2–3 \( \mu \)G (Manchester 1974). Known values of the rotation measure RM and the dispersion measure DM of the pulsar PSR J1840+5640 allow one to estimate the average value of the GMF along the line of site to the pulsar (see, e.g., Han et al. 2006): \( \langle B_\parallel \rangle = \frac{1.232 \text{ RM}}{\text{DM}} \mu \text{G} \). For PSR J1840+5640, \( \text{RM} = -3 \text{ rad m}^{-2} \), \( \text{DM} = 26.698 \text{ cm}^{-3} \text{ pc} \) (Manchester et al. 2005). Thus, \( \langle B_\parallel \rangle \approx -0.138 \mu \text{G} \).

To conclude, we cannot unequivocally claim that the region of excessive flux of PeV cosmic rays described above was formed due to the contribution of any or both of the pulsars PSR J1840+5640 and LAT PSR J1836+5925. Still, we think the existence of the REF in the direction toward these pulsars is worth paying attention as a possible sign that isolated pulsars provide a more noticeable contribution to the flux of Galactic cosmic rays than it is sometimes assumed. This point of view is supported by the fact that there are four more REFs in the EAS MSU data set selected with significance level \( S > 4 \) that can be associated with pulsars which do not have known SNRs nearby. These REFs will be the subject of a separate article.

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