International Journal of Astronomy and Astrophysics, 2014, 4, 499-509
Published Online September 2014 in SciRes. http://www.scirp.org/journal/ijaa
http://dx.doi.org/10.4236/ijaa.2014.43046

TeV Blazars as the Sources of Ultra High Energy Cosmic Rays

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Received 26 June 2014; revised 25 July 2014; accepted 20 August 2014

Abstract

The origin of ultra high energy cosmic rays (UHECRs) is still an open question in astroparticle physics. TeV blazars are a small group of active galactic nuclei (AGNs). They all have been observed in TeV gamma ray band, and show violent variabilities in flux at all wavelengths. So it is believed that they have abilities to produce UHECRs. To judge whether the TeV blazars can be the candidates of the origin of UHECRs, we collect the information of emission region of 38 TeV blazars, and estimate the maximum energy that the charged particle can be accelerated there. The results show that TeV blazars have abilities to accelerate cosmic rays to the energy above 10^{18} eV, some even higher than 10^{20} eV, and they may be the sources of UHECRs.

Keywords

BL Lacertae Objects, TeV Blazars, UHECRs

1. Introduction

The earth's atmosphere is being constantly bombarded by elementary particles from outer space, historically called cosmic rays. Their discovery dates back to the beginning of the 20th century and they have been continuously studied by particle physicists and astrophysicists. The spectrum of cosmic rays extends smoothly over 11 orders of magnitude, from less than 10^9 eV to over 10^{20} eV. Over this large energy range the spectrum falls off approximately by an E^{-3} power law. Accurate measurement shows that the spectrum is structured with four noticeable features: the knee is around 3 - 5 × 10^{15} eV, the second knee is at 4 × 10^{18} eV [1]-[3], the ankle is near 3 × 10^{18} eV [3] [4], GZK cutoff is above 4 - 5 × 10^{19} eV [5] [6] which has been observed independently by HiRes and Auger experiments [4] [7]. At the lower energies this flux is high enough for direct satellite or bal-

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How to cite this paper: Zhang, B.K., Zhao, X.Y. and Cao, Z. (2014) TeV Blazars as the Sources of Ultra High Energy Cosmic Rays. *International Journal of Astronomy and Astrophysics*, **4**, 499-509. http://dx.doi.org/10.4236/ijaa.2014.43046

loon measurement. While at the highest energies, the flux is so low that an extremely large aperture must be used in the study of cosmic rays.

The sources of cosmic rays are still unknown. It is probable that for energies up to and possibly slightly beyond the knee, the observed flux can be accounted by acceleration in supernova remnants. The ankle in the spectrum may mean a change from galactic to extragalactic sources, especially as it occurs at certain energy where cosmic ray protons can no longer be confined in the galactic disk. It can be interpreted as the transition between the galactic and extragalactic components [8] or the result of pair production by extragalactic protons after the interaction with photons of the cosmic microwave background radiation (CMBR) during propagation [9] [10].

Ultra high energy cosmic rays (UHECRs) were defined as those cosmic rays with energies above 10^{18} eV [11]. Since the first evidence of a cosmic ray primary with energy of 10^{20} eV was reported [12], a succession of detectors, such as AGASA (the Akeno Giant Air Shower Array) [13], HiRes (the High Resolution Fly's Eye) [14], Auger (the Pierre Auger Observatory) [15], and TA (the Telescope Array) [16], have been constructed to try to determine the energy spectrum, the primary composition, and the arrival direction anisotropy of UHECRs. Now the origin of UHECRs is still an open question in astrophysics. As yet, no astronomical sources have been identified to be the sources of UHECRs. How and where these particles gain their remarkable energies have not been well understood. Linsley noted that nothing in our galaxy was thought to be capable of accelerating charged particles to such energies [12]. Given the strength of galactic magnetic fields and the lack of correlations with the galactic plane, the highest energy cosmic rays are likely to originate in extragalactic sources. Current observations show that the spectrum is consistent with an origin in extragalactic astrophysical sources.

It is generally believed that astrophysical sites such as neutron stars (or magnetars), gamma-ray bursts and active galactic nuclei may be reasonable candidates for UHECR sources (see [17] [18] and references therein). Active galactic nuclei (AGNs) are one of the best candidates for UHECR sources, as far as acceleration and energetics is concerned [19]. TeV blazars (see next section) are a subclass of AGNs characterized by rapid and large variability at all frequencies. Thus, TeV blazars are more likely to be the origin of UHECRs. However, it is difficult to directly connect UHECRs to blazars due to the sparse UHECR events and the changes of the arrival direction of UHECRs by intergalactic magnetic field. To judge whether TeV blazars can be candidates of UHECRs, the key is to judge whether the charged particles in the sources can be accelerated to ultra high energy. The most straightforward mechanism for accelerating a charged particle is placing it in an electromagnetic field. The interaction of a charged particle with the electric field will boost the particle's energy while the interaction with the magnetic field will confine the particle. The gyroradius of the particle is dependent on its charge and energy, so at some point the particle will get enough energy to escape the acceleration region. The purpose of this paper is to estimate the maximum energy that the charged particles can be accelerated according to the size of the emission region and the strength of the magnetic field, and then determine whether TeV blazars can be the candidates of UHECR source. The paper is organized as following: in Section 2 TeV, blazars are introduced, in Section 3 the maximum energies are estimated, then in Section 4 the discussion is given and in Section 5 conclusions are drawn.

2. TeV Blazars

Blazars are a subclass of AGNs with a relativistic jet pointed close to the line of sight of the observer [20]. They have been observed at all wavelengths from radio to high energy gamma rays, and they show variability in flux at all wavelengths as well as spectral shape on time scales ranging from months to a few minutes. Blazars are divided into flat spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs). Since the first detection of TeV gamma rays from Mkn 421 with the Whipple imaging atmospheric Cherenkov telescopes [21], blazars have become one of the most interesting class of object for VHE gamma-ray astronomy. For the TeV emission is the most prominent feature in those sources, they are called TeV blazars, which constitutes a relatively small group of sources within the blazar family. The gamma-ray emission of most blazars peaks in the MeV-GeV range. Moreover, TeV gamma rays are efficiently absorbed by the extragalactic background light (EBL). This in addition limits the number of observed TeV blazars. Nowadays, about 50 blazars have been detected in the TeV gamma-ray band. These sources locate both in the northern and in the southern hemisphere.

The electromagnetic (EM) radiation from blazar is predominantly non-thermal, and the spectral energy distributions (SEDs) of blazars are characterized by two broad peaks. The low energy peak in the SED is located between infrared to X-ray energies, and the mechanism is almost certainly synchrotron emission from a relativistic distribution of electrons. According to the frequency of the low energy peak, BL Lacertae objects are further subdivided into low-, intermediate- and high-frequency peaked BL Lac objects, and they are abbreviated as LBL, IBL and HBL, respectively. The high energy peak is located gamma-ray energies. However, the origin of the high energy peak is still a matter of debate. There are several models to explain the high energy emission based on either leptonic or hadronic interactions. Under the assumption of leptonic models, high energy emission is explained via inverse Compton scattering of soft target photons. The target photons may come from synchrotron emission by the same population of electrons which produce the low energy bump in synchrotron self Compton (SSC) model or from the external photons to the jet in external Compton (EC) models. These external photons can be the accretion disk photons or the accretion disk photons reprocessed by broad line region (BLR) clouds or the infrared radiation from the dusty torus. The hadronic models explain the high energy emission as an outcome of the synchrotron proton emission and proton-photon interactions with the synchrotron photons (see [22] and references therein).

Simultaneous observations of blazars across multiple wavelengths have been made to construct the spectral energy distributions (SEDs). Some authors shed light on the VHE emission mechanisms of these TeV sources according to their SEDs and get some information of emission regions. We collect the magnetic field B, linear size *R* and Doppler factor Γ of 38 TeV blazars. Since different models or different SED data give different values of these parameters, we calculate their mean values and list them in **Table 1**. The first column is for the object name, the second is for the red shift, the third is for the type, the fourth is for the magnetic field B, the fifth is for the emission size *R*, the sixth is for the Doppler factor Γ and the last is for the reference.

3. Estimation of Maximum Energy

There exist several theories describing mechanisms capable of producing particles above 10^{18} eV. These theories may be divided into two major classes: top-down decay scenario and bottom-up acceleration scenario [23]. Bottom-up acceleration describes processes that take a particle, such as a proton, and accelerate it to a very high energy. The model is the more conventional hypothesis but struggles to reach the highest energies observed. For bottom-up acceleration to work, the source must provide either a very large acceleration gradient or provide acceleration over a very large distance. Top-down mechanisms produce the particles locally using the decay or interaction of exotic particles such as the decay of a super heavy relic particle from the big bang or the interaction of a magnetic monopole and anti-monopole. In this model cosmic rays begin at energies at and preferably well above those observed, so top-down models can explain the existence of UHECR, while they have a more difficult time explaining the flux. Additionally, the models require the production of existence of very exotic particles. At present, no theory has yet to produce a conclusive mechanism nor has experiment been able to trace these particles to any conclusive source.

In the bottom-up models, irrespective of the details of the acceleration mechanism, the basic requirement that cosmic ray accelerators must meet was summarized by Hillas [24]. Charged particles will escape from an acceleration region when their gyroradii increase beyond the size of the acceleration region. Thus the size and magnetic field strength associated with an astrophysical acceleration site determine the maximum theoretical acceleration energy Emax for a charged particle. There are indications that jets, powered by super-massive black holes at the center of active galaxies, are cosmic ray accelerators. The cosmic ray acceleration process is assumed to occur within a relativistic blob of plasma moving along the jet with Lorentz factor $\Gamma \sim 10^{1.5}$ [25]. They produce photons of TeV energy, possibly higher, and may be the enigmatic source of the highest energy cosmic rays [26]. As acceleration site of charged particles, jets of AGN have the advantage that acceleration on the jet frame could have maximum energy smaller that these of the observed by $1/\Gamma$ [27]. Thus, one can calculate the maximum theoretical acceleration energy [24] [28], that does not include any efficiency factor,

$$\frac{E_{\max}}{10^{15}\ \text{eV}} \le \Gamma Z e \left(\frac{B}{\mu\text{G}}\right)\left(\frac{B}{\text{pc}}\right) \tag{1}$$

where Γ is the Lorentz factor of the shock matter, Z is the charge of the nucleus, B is the strength of magnetic field, and R is the radius of the emission region.

In the jets of TeV blazars, the maximum energy of a particle with charge Z is calculated within a given emission region with radius *R* and magnetic field strength B. We locate the TeV blazars on a plot of B vs. ΓR (see **Figure 1**). Three diagonal short dot lines, from top to bottom, indicate the size and magnetic field

Table 1. The information of emission region of TeV blazars.

Object	z	Type	B (G)	R (10^{16}cm)	Γ	Refs.
KUV 00311−1938	-	HBL	0.40	0.65	26	[48]
RGB J0152+017	0.08	HBL	0.14 ± 0.13	0.58 ± 0.55	18.3 ± 11.5	[48]-[50]
3C66A	0.41	IBL	0.44 ± 0.48	3.47 ± 3.28	27.8 ± 4.7	[48] [50] [51]
1ES 0229+220	0.14	HBL	0.24 ± 0.34	2.70 ± 1.12	24.2 ± 22.3	[48] [50]
PKS 0301−243	-	HBL	0.33	1	2	[48]
RBS 0413	0.19	HBL	10.11 ± 17.23	1.07 ± 0.55	18.3 ± 2.9	[52]
1ES 0347−121	0.188	HBL	0.25 ± 0.39	3.47 ± 2.41	26.7 ± 16.6	[48] [50] [53]
1ES 0414+009	0.287	HBL	0.01	10	50	[54]
PKS 0447−439	-	HBL	0.24 ± 0.23	0.98 ± 0.66	29.5 ± 13.4	[48] [55]
1ES 0502+675	0.341	HBL	0.40 ± 0.49	1.0	16.5 ± 4.9	[48] [56]
PKS 0548−322	0.069	HBL	0.27 ± 0.29	1.24 ± 0.79	13.7 ± 10.0	[48] [50] [57]
RX J0648.7+1516	0.179	HBL	3.41 ± 5.70	1.06 ± 0.90	18.3 ± 2.9	[58]
RGB J0710+591	0.125	HBL	0.10 ± 0.05	1.86 ± 1.34	18.0 ± 9.5	[48] [50] [56] [59]
S5 0716+714	0.31	IBL	0.33 ± 0.25	0.78 ± 0.06	34.8 ± 8.2	[48] [50] [60]
1ES 0806+524	0.138	HBL	0.40 ± 0.07	1.08 ± 1.11	18.0 ± 4.0	[48] [50] [61]
1RXS J101015.9−311909	0.143	HBL	0.09 ± 0.10	3.62 ± 4.78	30.0 ± 0.0	[62]
1ES 1011+496	0.212	HBL	0.30 ± 0.21	1.20 ± 0.78	29.3 ± 12.3	[48] [50] [63] [64]
1ES 1101−232	0.186	HBL	0.33 ± 0.46	2.15 ± 2.26	23.3 ± 9.9	[48] [50] [65] [66]
Mkn 421	0.031	HBL	0.10 ± 0.08	2.64 ± 2.49	31.3 ± 19.4	[48] [50] [67]-[69]
Mkn 180	0.045	HBL	0.18 ± 0.12	0.45 ± 0.52	27.5 ± 18.1	[48] [50] [64]
1ES 1215+303	0.13	HBL	0.05 ± 0.04	1.26 ± 1.42	45.2 ± 24.4	[48] [70]
1ES 1218+304	0.182	HBL	0.15 ± 0.04	0.86 ± 1.15	33.0 ± 12.1	[48] [50] [71]
W Comae	0.102	IBL	0.20 ± 0.11	1.92 ± 2.08	19.7 ± 4.2	[48] [50] [72] [73]
4C+21.35	0.432	FSRQ	0.28	0.09	75	[74]
3C279	0.536	FSRQ	0.48 ± 0.62	18.47 ± 26.28	19.8 ± 3.8	[22] [75]-[77]
PKS 1424+240	-	IBL	0.28 ± 0.12	3.42 ± 1.70	32.9 ± 13.7	[48] [50] [78]
H 1426+428	0.129	HBL	0.07 ± 0.05	1.92 ± 1.05	19.5 ± 7.2	[48] [50] [79] [80]
PKS 1510−089	0.36	FSRQ	0.23 ± 0.09	6.29 ± 2.03	15.8 ± 4.9	[81]
AP Lib	0.049	LBL	0.01	1	40	[48]
PG 1553+113	0.5	HBL	0.76+0.84	2.26 ± 2.75	27.5 ± 7.1	[48] [50] [82]
Mkn 501	0.034	HBL	0.25 ± 0.22	1.31 ± 2.99	17.6 ± 5.1	[48] [50] [83]-[90]
1ES 1959+650	0.048	HBL	0.30 ± 0.38	0.84 ± 0.45	17 ± 3.87	[48] [50] [91] [92]
PKS 2005−489	0.071	HBL	0.26 ± 0.31	11.61 ± 18.98	23.3 ± 13.0	[48] [50] [93]
PKS 2155−304	0.116	HBL	8.24 ± 25.21	1.31 ± 1.70	37.9 ± 27.3	[48] [50] [68] [77] [94] [95]
BL Lacertae	0.069	IBL	0.62 ± 0.54	0.53 ± 0.23	16.5 ± 3.7	[48] [50] [96]
B3 2247+381	0.119	HBL	0.07 ± 0.01	0.60 ± 0.28	32.5 ± 3.5	[97]
1ES 2344+514	0.044	HBL	0.09 ± 0.02	0.75 ± 0.39	19.0 ± 6.2	[48] [50] [64] [98]-[100]
H 2356−309	0.165	HBL	0.18 ± 0.15	0.74 ± 0.46	24.8 ± 17.1	[48] [50] [77] [101]

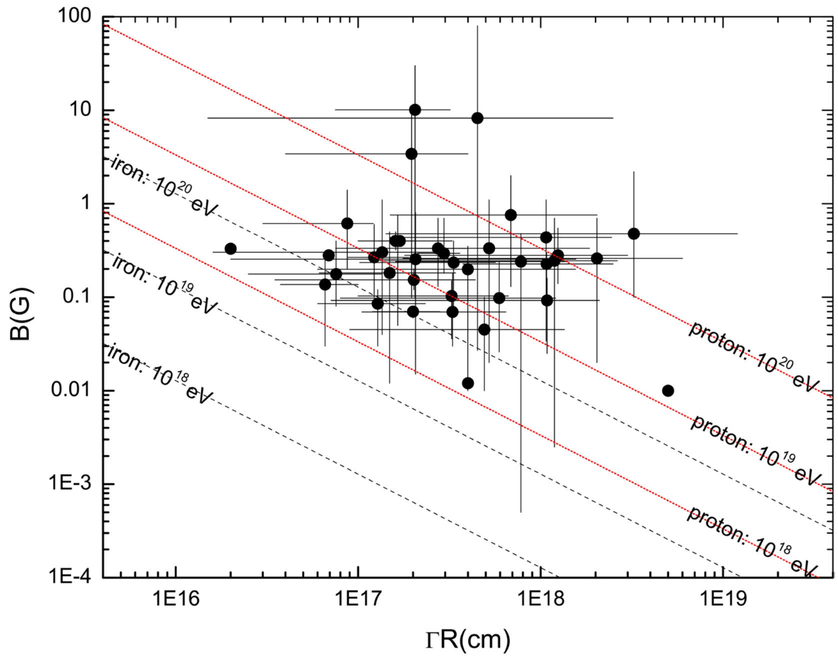

Figure 1. The magnetic field strength vs. the size multiplied by the doppler factor of the emission region for 38 TeV blazars.

strength required of an object to accelerate protons to 10^{20} eV, 10^{19} eV and 10^{18} eV, respectively. Objects below the lines are not up to the corresponding task. The dash lines represent that the object can accelerate irons to 10^{20} eV, 10^{19} eV and 10^{18} eV, respectively. From the figure, one can see that most of the TeV blazars can accelerate the protons to 10^{18} eV, but less of them can accelerate protons to 10^{20} eV. One can also see that most of the TeV blazars are above the dash lines. This means that they have abilities to accelerate heavy nuclei irons above 10^{20} eV. So, TeV blazars can be taken as the candidate for UHECR origin. It should be noted that the acceleration efficiency and the possible energy loss mechanisms when particles are accelerating are not taken into account. It is expected that cosmic ray energy will be degraded by protonpion production on the intense nearby radiation and by synchrotron losses in the associated magnetic fields [24] [29].

4. Discussion

As can be seen from **Figure 1**, most of the TeV blazars can accelerate protons and irons to the energies above 10^{18} eV. So, the TeV blazars meet the basic requirement of UHECR sources and can be taken as the sources of UHECRs. Dermer and Razzaque [18] used Fermi data to constrain the maximum energies of cosmic rays accelerated in colliding shells of gamma-ray bursts and blazars. Their results show that irons rather than protons are more likely to be accelerated to ultra high energies in AGNs, and BL Lac objects radiate a volume- and time-averaged emissivity of 10^{45} - 10^{46} erg $\text{Mpc}^{-3}\cdot\text{yr}^{-1}$ innonthermal gamma rays. So, BLLac objects have sufficient emissivity to power UHECRs, which require ~10^{44} erg $\text{Mpc}^{-3}\cdot\text{yr}^{-1}$ [30].

The direct way to identify the sources of ultra high energy cosmic rays is to observe their arrival directions, pointing back toward their sources. So, the search for anisotropies in the arrival direction of cosmic rays on different angular scales can contribute to the understanding of the cosmic ray origin, in particular the identification of source regions or individual sources. The correlation between the UHECR arrival directions and the astrophysical objects has been studied by several authors [31]-[38]. However, the claimed correlations between ultra high energy cosmic ray arrival directions and AGNs are controversial.

The largest experiment of Pierre Auger Observatory claimed correlations of UHECRs with the nearby AGNs (redshift $z \le 0.018$) [39] [40] which were not confirmed by HiRes experiment in the Northern hemisphere [41]. The Auger collaboration updated the analysis and found that a smaller fraction of the UHECR events correlate with the same set of AGNs in the latest UHECR data set [42] than in the original one. Using the same parameters reported by the Auger collaboration, Abu-Zayyad *et al*. searched for the correlation of UHECRs detected by the Telescope Array experiment with nearby active galactic nuclei, and found no statistically significant correlation [43].

When searching for potential sources of cosmic rays, the basic obstacle is that charged particles will inevitably deflect as they travel through the magnetic fields that permeate galactic and extragalactic space. The information about their source direction is erased, and this results in their observed arrival directions being almost isotropically distributed. Subsequently, the cosmic ray arrival directions do not point back to any of their powerful candidate sources. After a charged particle travels over a distance d in an extragalactic magnetic field $B_{eg} \sim \text{nG}$ of coherence length $l_c \sim 1\ \text{Mpc}$, the deflection angle can be estimated as [25]

$$\theta \sim 1.3^{\circ} Z \left(\frac{E}{6\times10^{19}\ \text{eV}}\right)^{-1} \left(\frac{d}{10\ \text{Mpc}}\right)^{1/2} \left(\frac{l_c}{\text{Mpc}}\right)^{1/2} \left(\frac{B_{eg}}{\text{nG}}\right) \tag{2}$$

At sufficiently high energies, the deflection is small. This means, for example, that a 10^{20} eV proton propagating through a 1 nG field with a 1 Mpc coherence length (perhaps typical of the extra-galactic field), arriving from 100 Mpc, will be deflected by 2.5° on average. While for a proton with energy of 10^{19} eV, the deflection can reach 25°. If for irons, the deflection will be more serious. The galactic magnetic field, locally observed to be on the order of a few μG, is also sufficiently strong to induce deflections in the arrival directions of ultra high energy cosmic rays. For a particle traveling a distance S through a uniform magnetic field with perpendicular component B, the angular deflection δ, from its initial trajectory is [44]:

$$\delta = 0.5^{\circ} Z \left(\frac{S}{\text{kpc}}\right) \left(\frac{B}{\mu\text{G}}\right) \left(\frac{10^{20}\ \text{eV}}{E}\right) \tag{3}$$

the galactic magnetic field strength is μG, and the solar system is ~8 kpc from the galactic center. Therefore at energies of 10^{20} eV a proton will experience a deflection of 4° during propagation.

However, protons with energies of 10^{19} eV will experience larger deflections. This deflection can be sufficiently large as to make source identification difficult. Extragalactic and galactic magnetic fields certainly play an important role in UHECRs propagation. Yet the lack of knowledge concerning the distribution and strength of these fields, at both galactic and extragalactic scales, introduces a large degree of uncertainty in the subject of charged particle propagation [45].

Heavy nuclei have higher electric charge than protons and consequently suffer bigger deflections by magnetic fields. Determining the type of particles that are arriving at earth will also provide indications as to which astrophysical processes could have produced them. A satisfactory understanding of the origin of cosmic rays must deal with the issue of chemical composition. With existing observation techniques, UHECR composition cannot be determined on an event-by-even basis. Only the trends or changes in composition can be measured from the statistics of many events. However, chemical compositions of ultra high energy cosmic rays measured by two largest detectors, High Resolution Fly's Eye (HiRes) and Pierre Auger Observatory (PAO), particularly at the highest energies, are significantly differently. The HiRes data show pure proton composition [46]. On the contrary, the PAO data strongly favor the nuclei composition getting progressively heavier at $E \sim (4\text{ - }40)$ EeV [47].

5. Conclusion

The origin of UHECRs is one of the most puzzling problems in cosmic ray physics. Astrophysical extragalactic models for the observed UHECR must satisfy some constraints. A minimum requirement for astrophysical sources of UHECRs is the ability to magnetically confine particles of the requisite energies. The results show that TeV blazars meet this basic criterion, and they can accelerate protons and irons up to ultra high energies. So they can be the potential UHECR sources. However, the detail of the acceleration mechanism is poorly known. In addition, there are some great uncertainties in intervening magnetic fields and cosmic ray primary composition. These cause the lack of any confirmed anisotropy in arrival directions to date, and then hinder the development of theories of cosmic ray origins. Reduction of the uncertainties by large exposure observatories will be one way to unveil these extremely energetic sources. It should be noted that due to interactions between cosmic rays and the CMB protons, UHECR with energies above GZK energy can not be observed on earth when they traveled over distance larger than the GZK horizon (~100 Mpc). The other messengers, such as neutrinos and high energy gamma rays will also play an important role in identifying the sources of UHECRs.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant Nos. 11273008 and 11147134).

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