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A possible cosmic ray source in TeV and EeV from the direction around the Cygnus Loop

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With the Akeno Giant Air Shower Array (AGASA), we published the small-scale anisotropy of cosmic rays with energies above 10^{19}eV. Among them, a broad cluster – BC1 around (20^h 50^m, 32°) – has interesting characteristics: The time distribution of members of the BC1 cluster is burst-like around MJD50000 , and this cluster locates near the famous supernova remnant: the Cygnus Loop. From this BC1 direction, two observations from the Tibet and Milagro experiments have been reported. In this report, we summarize the results from the whole observation time of AGASA and the Akeno 1km^2 array experiment, and the relation with the observations from the Tibet and Milagro experiments is discussed.

1. Introduction

In M.Takeda et al. [1], we reported the search result for the point like sources above $10^{19.6}$eV with AGASA. Five clusters (C1–C5), whose clustering are within experimental arrival direction uncertainty, are presented. In addition we have reported that two broad clusters (BC1–BC2) within a 4.0° radius are shown for the cosmic rays above 10^{19}eV. After this publication no supporting evidence for these directions has been reported from other observations. Recently, two interesting observations from Tibet[3] and Milagro[4] have been reported from this BC1 direction, though their energies are in TeV.

Eight events above 10^{19}eV were observed within a 4.0° radius from this direction for 8 years from 1990 to August 1998. The deviation from the random distribution can be estimated as a significance of 2.7σ, which is in the tail of random fluctuation of an isotropic distribution. Among eight events, however, five are observed within 1 year around MJD50000 ($> 7\sigma$). The highest energy is 2.3$\times 10^{19}$eV. We have noted that the direction of BC1 is coincident with that of a famous supernova remnant: the Cygnus Loop, which extends about 3° around (312.2°, 32.5°). We can not expect that particles are accelerated up to 10^{19}eV in such super nova remnants with conventional theories. However, around this BC1 direction we do not see any other potential sources, like BL Lac or EGRET sources.

2. Observational results

The analysis method of AGASA is described in [1]. Cumulative excess with threshold energies above $10^{17.5}$eV and 10^{19}eV are shown in Fig.1 as a function of MJD for 5000 days till the end of AGASA operation (January 2004, MJD53009). It is seen that the excess increases steadily with MJD and a rapid increase is observed for 10^{19}eV around MJD49950. The number of events within a 6° radius as BC1 at the center per 0.1 in logarithmic scale is shown in Fig.2.

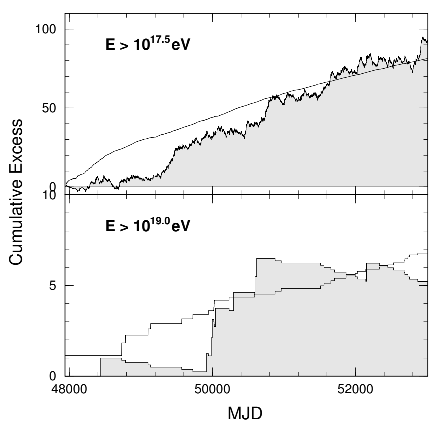

Figure 1. Cumulative excess of cosmic rays above $10^{17.5}$eV and 10^{19}eV from the direction of BC1. The solid curve is a 3σ level.

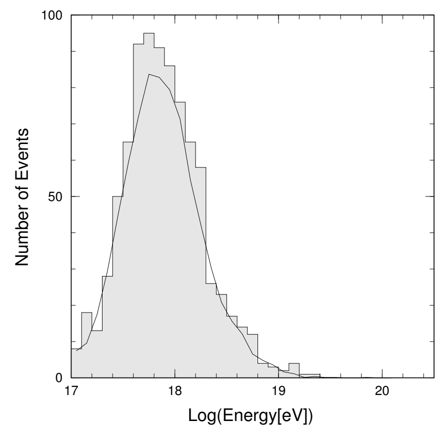

Figure 2. Energy distribution of cosmic rays from the direction of BC1. A solid curve is an expected distribution if cosmic rays are arriving isotropically from any direction.

Akeno 1km^2 array data accumulated from October 1981 to June 1992 was analyzed with the same method with AGASA. The details of the detectors and the analysis method is described in [2]. The triggering efficiency is almost uniform over 5.0$\times 10^5$m^2 for EASs whose electron shower size N_e are above 10^7. No significant excess with N_e above 10^7, whose energy is approximately $10^{16.5}$eV, has been observed.

3. Brief review of other studies

Tibet The results of the survey of point sources by the Tibet air shower array are described in [3]. Observations for 780 days from February 1997 to September 1999 with 5,175m^2 detection area (Tibet-HD) and for 173 days from November 1999 to June 2000 with 22,000m^2 area (Tibet-III) are included. Nineteen excess regions were selected with the significance of 4.0σ or more. Though these numbers are found to be consistent with the statistical fluctuation, the direction of BC1 is included in their list.

They found two flare type sources which show the rapid rise of events within several ten days. One is from the direction of BC1 with a significance of 6.03σ in 90 days from MJD50820 to 50910, just before the 3σ rise observed by AGASA (MJD50720–50820) as shown in Table 2.

Milagro R. Atkins et al. [4] reported the search results for steady point sources of TeV gamma-rays using the Milagro Observatory. They listed 11 locations of all regions with an excess of more than 4σ from December 2000 to November 2003. The direction BC1 is also included in their list as shown in Table 1.

Correlation study of Tibet and Milagro point sources G.Walker et al. [5] examined the directional cross-correlation of unidentified candidate sources of both observations. Three directions are within an angular separation of 1.5°, and they estimated the chance probability for the occurrence of three correlated sources is approximately 10^{-4} by simulation. One of three is BC1 direction.

4. Discussion

In Table 1, the results of three experiments are summarized and compared. It should be noted that the excesses seem to be not steady, but flare like as observed by AGASA and the Tibet experiment. Duration of the flare are listed in Table 2. Though the probability of accidental coincidence of three independent observations is quite low, the AGASA energy is 10^6 times higher than the Tibet and Milagro energy.

Table 1. Summary of observations from BC1 direction

Experiment	E_{th}	Observation	R.A.	Decl.	Excess	Sigma
AGASA	100 PeV	May. 1990 – Dec. 2003	312.50	32.00	102	3.4
	1 EeV	May. 1990 – Dec. 2003	312.50	32.00	43	2.4
Tibet	3 TeV	Feb. 1997 – Sep. 1999	313.50	32.40	4244	4.52
		Nov. 1999 – Jun. 2000				
Milagro	1 TeV	Dec. 2000 – Nov. 2003	313.00	32.20	8320	4.5

Table 2. Summary of flare analysis from BC1 direction

Experiment	E_{th}	Duration	N_{on}	N_{off}	N_{exp}	N_{excess}	Sigma
AGASA	10 EeV	MJD49950 – 50300	6	11	1.39	4.61	2.61
	1 EeV	MJD50720 – 50820	12	35	4.41	7.59	3.08
	0.1 EeV	MJD50720 – 50820	28	113	14.2	13.8	2.99
Tibet	3 TeV	MJD50820 – 50910				$\sim$1000	6.03

The integral flux at 1 TeV is given by the Milagro as 1.49×10^{-7} $m^{-2}s^{-1}$ (0.85 Crab) [4]. The flux above 3 TeV is given by the Tibet flare observation as about twice larger than that of the Crab nebula [3]. This is the flare flux averaged over 90 days. Since the excess events of the flare seem to be nearly the same as those of the remaining 690 days, the average flux for the steady time may be 2/(690/90)=0.26 Crab. Therefore, the average flux over the entire observation time may be $\frac{2\times90+0.26\times690}{780}$=0.46 Crab.

Recently Crocker et al. [8] proposed that the AGASA small scale anisotropy for the energy range $10^{17.9}$–$10^{18.5}$

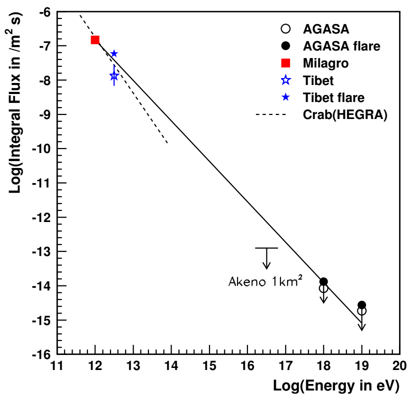

Figure 3. Integral energy spectrum from BC1 direction from four observations.

These fluxes are plotted in Fig.3 relative to the Crab energy spectrum [6] shown by a dashed line. The average flux value of the flare observed at Tibet is also plotted. Approximate fluxes of flare time and steady one of AGASA are plotted as upper limits. The upper limit by the Akeno 1km^2 array is also plotted. If we assume the power law energy spectrum $I = CE^{-\gamma}$ between 1 TeV and 1 EeV, the integral slope parameter γ is about 1.18 as shown by the solid line.

The BC1 locates in the direction of the Cygnus Loop (NGC6960-92-95). It is a shell type supernova remnant, and one of the strong X-Ray sources (3×10^{-8}erg/cm^{2}s). The coordinate is (312.2°, 32.1°) and the distance is about 1470 light years. From the Hillas confinement condition (magnetic field times its size – MS) for cosmic-ray acceleration [7], the MS in the shock of the Cygnus Loop is too small to accelerate cosmic rays up to 10^{19}eV. The coincidence of its direction with BC1 might be accidental and the BC1 source may be behind the Cygnus Loop.

eV from the direction of Galactic Center [9] could be consistently explained with the gamma-ray observations in GeV by EGRET (3EG J1746-2851) [10] and in TeV by HESS[11]. According to their model, particles in EeV are neutrons through charge-exchange in p-p collisions, where the incident, high energy protons obey an $\sim E^{-2}$ (differential) power law associated with acceleration at a strong shock, and the gamma-ray signals in GeV and TeV are ascribed to p-p induced neutral pion decay. It should be noted that the present integral spectral index of 1.18 is similar to the obtained one from the GC direction as 1.2 by Crocker et al.

Though the probability of an accidental coincidence of three independent observations is quite low, further observation of this BC1 direction around 0.1–1EeV is required. We expect for the next generation experiments to reveal whether this region is a point source with statistics of more than ten.

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