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Hints from Extremely High Energy Cosmic-Ray Observations

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Abstract. Two of the most fascinating research programs carried out over the last few decades are the search for primary antimatter and the identification and source location of the highest energy particles in cosmic rays.

The fact that there has been no detection of primary antimatter in the Milky Way up to about hundred GV/c does not disprove the existence of superclusters of antigalaxies in the Universe.

In this paper we show the conditions under which the supra-10^{20} eV AGASA data might consist of extragalactic particles, with a possible component of antimatter.

The AGASA experiment results have been also compared to the predictions of different theoretical models.

1 Introduction

The existence of primary antimatter in the Universe and the origin of Extremely High Energy Cosmic Rays (EHECR) are two of the most intriguing mysteries in modern physics.

Particle physics shows a symmetry between matter and antimatter, while in the known Universe, matter overwhelms antimatter. Gamma-ray measurements indicate no presence of major domains of antimatter up to distances of superclusters of galaxies, tipically 100 Mpc (Omnes, 1969; 1970). Accurate, recent cosmic-ray observations as well show no evidence of primary antimatter up to energies of about hundred GV/c (Hof et al., 1996; Barwick et al., 1998).

EHECR observations up to energies of 4 10^{19} eV suggest that there is a correlation between their arrival direction and the pulsar location in the Local arm (Mikhailov, 1999). Conversely, experimental evidence indicates that above this energy EHECR (most probably protons) show an approximately isotropic distribution of their arrival directions (see for example Biermann, 1997). Stanev and Hillas (1999) have also suggested that a correspondence might exist between particle arrival directions and the supergalactic plane.

In case of extragalactic origin for EHECR, particle interactions during propagation are supposed to limit the distance of sources of 10^{20} - 10^{21} eV cosmic rays from the Milky Way to a maximum of 50 Mpc. Consequently, an abrupt cut-off (GZK cut-off) is expected (Greisen, 1966; Zatsepin and Kuzmin, 1966) in the EHECR flux above 5 10^{19} eV.

Many models have been suggested to explain the observed absence of the GZK cut-off and the origin of EHECR.

In this paper it has been shown under what circumstances the AGASA data (Akeno Giant Air Shower Array) might consist of extragalactic particles with a possible contribution of antimatter. For the data above 0.8 10^{20} eV, we attempt a flux-binning different from that reported in Hayashida et al. (2000), in order to investigate if the data-interpretation results are biased by the binning process. The original measurements of the AGASA experiment above 10^{20} eV have been also compared to different models.

2 Cosmic-ray observations on antimatter and EHE particles

Antinuclei have never been detected in cosmic rays up to the present time. The AMS satellite-borne experiment has recently allowed to set an upper limit of 1.1 10^{-6} to the $\overline{He}/He$ ratio up to rigidities of 140 GV/c (Alcaraz et al., 1999). Positron and antiproton measurements carried out in the late seventies and in the eighties (Golden et al., 1979; Muller and Tang, 1987) seemed to show an excess of these particles compared to the expected secondary production due to primary cosmic-ray propagation in the interstellar medium.

The improved capabilities of detectors used during this last decade have lead to different results (Grimani, 1996; Basini et al., 1999).

The fact that there has not yet been any evidence of the existence of primary antimatter might only mean that primary antiparticles reach the Milky Way at much higher energies.

By studying the diffusion coefficient of cosmic rays in clusters of galaxies and in the intracluster medium, it has

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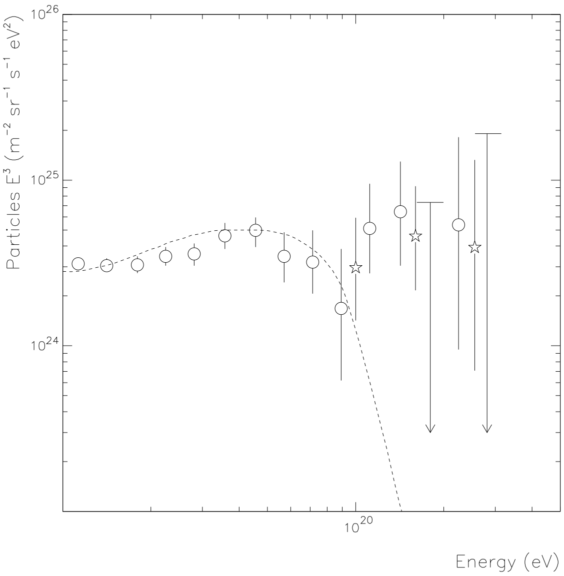

Fig. 1. EHECR flux measurements according to the AGASA experiment (open dots).The dashed curve represents the expected contribution of sources uniformly distributed in space. A binning different from that reported in Hayashida et al. (2000) has been accomplished above 0.8 10^{20} eV (open stars).

been shown (Grimani, 1999 and references therein) that particles with energies greater than 10^{19} eV are favoured to leak out of their source cluster, therefore (if they have enough energy at the source) they *can* reach the Milky Way from distances of hundred Mpc during a Hubble time. If this is the case, a some of these particles might be primary antimatter.

Out of the complete sample of about 20 events observed with energies larger than 10^{20} eV (see for example Olinto, 2000a and references therein) eight have been detected by the AGASA experiment.

In order to avoid introducing possible energy-rescaling biases among different experiments, we investigate herein if any possible hint on EHECR can be obtained from the Akeno data sample alone.

In fig. 1 we show the AGASA energy spectrum, as originally reported (open dots).

The dashed curve represents the expected contribution of cosmic-ray sources uniformly distributed in space. Data and theoretical curve are reported in Hayashida et al. (2000). Below 10^{20} eV there is a very good agreement between the data and the model, while at higher energies there is an evident disagreement increasing with energy. With the purpose of further investigating the compatibility of the data with the theoretical models, it is interesting to rebin the AGASA data above 0.8 10^{20} eV in only three bins in energy (open stars in fig. 1). The flux re-binning has been accomplished on the basis of the data reported in Hayashida et al. (2000). The new binning seems to indicate a more constant slope for the flux above 7 10^{19} eV.

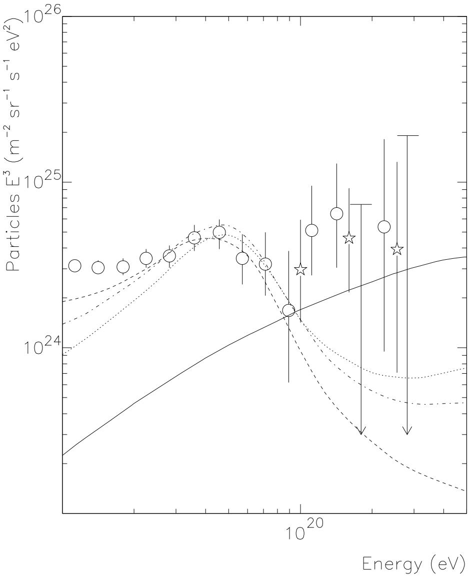

Fig. 2. The Akeno data are compared to theoretical predictions of topological defects (necklaces) producing gauge bosons of 10^{14} GeV (dashed line), 10^{15} GeV (dot-dashed line), 10^{16} GeV (dotted line). The solid line represents the possible contribution of super-heavy particles (m=10^{14} GeV) belonging to the Milky Way halo to the EHECR flux. The theoretical curves are reported in Berezinsky (1999).

3 Possibilities for the EHECR origin

Many models have been proposed for the origin of EHECR. Not one of these models can be considered fully plausible if it doesn't predict correctly (1) the particle arrival direction, (2) the absence of the GZK cut-off and (3) the observed energy spectrum. Galactic models comply with the absence of the GZK cut-off, but only heavy ions can be confined in the Galaxy at energies larger than 10^{20} eV. Conversely, extragalactic models can account for the observations if large scale structures will be found compatible with particle arrival directions.

Among galactic models it has been suggested that iron nuclei can be accelerated by a relativistic magnetohydrodynamic wind-up to 3 10^{20} eV in high magnetic fields found near young pulsars (Olinto et al., 1999). This model is characterized by a heavy composition at EHE and a very flat spectrum (proportional to E^{-1}). Conversely, (see fig. 2) a light composition might indicate a process of annihilation and/or collapse of topological defects (TD) or decay of super-heavy (SH) primordial particles belonging to the halo of the Milky Way (Berezinsky, 1999). It must be stressed that the low observed photon flux and the approximately isotropic particle distribution of EHECR leave doubts about these last possibilities.

Gamma-ray bursts (Vietri, 1995; Waxman, 1995), Active Galactic Nuclei, and in particular, radiogalaxies (Biermann et al., 2000) have been proposed as possible sources of EHE extragalactic cosmic rays.

In any case, since particles with energies higher than 10^{19} eV are favoured to escape from their source cluster, regardless of their acceleration process, it is possible that EHECR generated in distant clusters of galaxies are able to re-enter other galaxies. EHECR produced in our Virgo cluster would be privileged in reaching the Milky Way, but an extra-cluster component cannot be excluded, as it will be shown in the next Section.

4 Statistical compatibility of data with models

In case of an extragalactic origin of EHECR, their source spectrum results modified by the propagation process before reaching the Milky Way. The characteristics of the intergalactic medium are uncertain therefore calculations of extragalactic cosmic-ray fluxes are affected by large uncertainties (see for example, Olinto, 2000b). In particular, to estimate the component of antimatter included in the overall energy spectrum of EHECR near the Earth might result meaningless but it is important to determine under which conditions EHE particles might reach the Earth from distant clusters of (anti)galaxies.

It will be assumed here that (anti)protons constitute primary EHECR and that the characteristics of the intergalactic medium are those reported in Grimani, 1999. Energy losses due to photo-pion production will limit the diffusion process of EHECR. Primary antiprotons might reach our galaxy only after propagation through the intergalactic medium for distances of at least 100 Mpc.

In fig. 3 it has been shown how the propagation process through the intergalactic medium modifies the (anti)proton integral spectrum per bin by assuming a spectral index of 2 at the source. The source spectrum has been normalized to 1 in the energy bin 0.1E - E. Poisson fluctuations have been considered in proton energy losses by assuming a mean free path of 30 Mpc for an energy loss of a factor of 10 (see Biermann, 1997; Grimani, 1999).

The white histogram in fig. 3 represents the flux at the source, the gray-shaded histogram corresponds to the spectrum propagated through 90 Mpc of intergalactic medium (3 mean free paths), the hatched histogram relates to a propagation through 120 Mpc of intergalactic medium (4 mean free paths).

It must be stressed that the propagation process causes only a different distribution of particles in energy but the total number of particles does not change. In particular, the propagated spectrum will present particle concentration in the energy bin just below the threshold for photo-pion production (5 10^{19} eV), and it will be depleted at the higher energies. As an example, an original differential flux with a spectral index of 2 up to 10^{22} eV propagated for 120 Mpc will appear with a spectral index of approximately 2.4 between 10^{20} eV and 10^{22} eV.

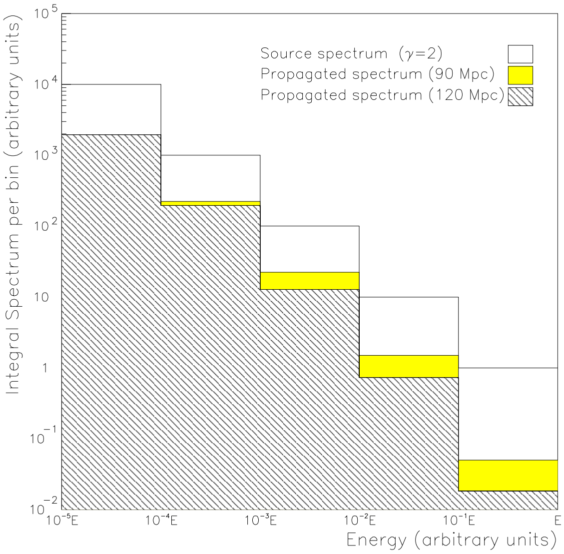

Fig. 3. Cosmic-ray differential flux (A E^{-2}) at the source (white histogram) and propagated through 90 Mpc (gray-shaded histogram) and 120 Mpc (hatched histogram) in the intergalactic medium. It is possible to notice that the propagation process steepens the flux mainly in the higher energy bins.

To investigate if, despite the large error bars, the AGASA data above 10^{20} eV hide any hint of the nature of the theoretical models, the original (3 data points above 10^{20} eV) and the rebinned (3 data points above 0.8 10^{20} eV) data have been fitted with different functions (Tables 1 and 2, respectively).

The re-binning process seems to show a regular slope for the flux above 7 10^{19} eV. Therefore the trend of the original AGASA data point at 7.1 10^{19} eV along with the 3 rebinned data points above 0.8 10^{20} eV has also been studied (4 data points - Table 3).

Finally, the original data above 10^{20} eV has been compared to theoretical models. In particular, the hypotheses of TD and SH particles populating the galactic halo have been considered (Table 4).

In this work, we follow these guidelines:

1) The free parameters for the fitting process are reported each time to evaluate the degrees of freedom.

2) The fitting process has been accomplished by averaging the asymmetric errors.

3) The values of the spectral index reported for the power-law best-fits are those generated by the fit.

It is easily observed from Table 1 and Table 2 that the Confidence Level (CL) values for all of the fits are quite high, making it somewhat difficult to choose one model over another. However, a power-law in energy with a spectral index between 2 and 3 seems to be preferred with respect to other values of the spectral index or to a constant value.

In Table 3 a power-law behaviour with a spectral index of 3 is definitely favoured (CL=0.98 to be compared, for example, to a constant value fit having a CL of 9%).

It can be concluded that the binning process actually plays some role in the data interpretation.

In Table 4 the CL values are equally high, but are smaller when compared to the power-law fits.

Table 1. Interpolation of the original AGASA data above 10^{20} eV with different functions (3 data points)

Fit function	χ^2/dof	CL
Constant value (A)	1.105	0.33
Best Fit (A $E^{-\gamma}$;$\gamma = 2.80$)	0.0414	0.84
Power law (A E^{-1})	0.548	0.58
Power law (A E^{-2})	0.118	0.89
Power law (A E^{-3})	0.0251	0.98

Table 2. Interpolation of the rebinned AGASA data above 0.8 10^{20} eV with different functions (3 data points)

Fit function	χ^2/dof	CL
Constant value (A)	1.088	0.34
Best Fit (A $E^{-\gamma}$;$\gamma = 2.54$)	0.0665	0.80
Power law (A E^{-1})	0.592	0.55
Power law (A E^{-2})	0.112	0.89
Power law (A E^{-3})	0.0794	0.92

Table 3. Interpolation of an original and rebinned AGASA data above 0.7 10^{20} eV with different functions (4 data points)

Fit function	χ^2/dof	CL
Constant value (A)	2.174	0.089
Best Fit (A $E^{-\gamma}$;$\gamma = 2.72$)	0.0456	0.96
Power law (A E^{-1})	1.381	0.25
Power law (A E^{-2})	0.294	0.83
Power law (A E^{-3})	0.0577	0.98

Table 4. Comparison of the AGASA data above 10^{20} eV with theoretical models (3 data points)

Theoretical models	χ^2/dof	CL
Necklaces (10^{14} eV)	1.186	0.31
Necklaces (10^{15} eV)	1.023	0.38
Necklaces (10^{16} eV)	0.970	0.41
Super Heavy Particles	0.598	0.62

5 Conclusions

Current measurements from the AGASA experiment, affected by large statistical errors, do not lead to final conclusions about EHECR. However, the flux seems to indicate a power-law behaviour with a spectral index between 2 and 3 above 10^{20} eV. This trend is even more evident after re-binning the AGASA data above 0.8 10^{20} eV in only three data points. In this last case, a power-law fit with a spectral index close to 3 above 0.7 10^{20} eV is favoured. It has been shown that extragalactic sources located within 100-120 Mpc from the Earth might contribute to the observed EHECR flux only if cosmic-ray particles (assumed to be (anti)protons) present at the source energies of 10^{22} eV. Future experiments like AUGER and the OWL-Airwatch Projects will measure direction, mass composition and energy of EHECR. If a light composition as well as an extragalactic origin for EHECR will be confirmed by these experiments, a component of primary antimatter cannot be excluded.

References

Alcaraz, J. et al., Physics Lett. B, 461, 38, 1999.
Barwick, S. W. et al., Ap. J., 498, 779, 1998.
Basini, G. et al., Proc. of 26th International Cosmic Ray Conference (Salt Lake City), 3, 77, 1999.
Berezinsky, V., Nucl. Phys. B (Proc. Suppl.), 75A, 11, 1999.
Biermann, P. L., J. Phys. G.: Nucl. Part. Phys., 23, 1, 1997.
Biermann, P. L. et al., Nucl. Phys. Proc. Suppl., 87, 417, 2000.
Grimani, C., Astr. Sp. Sc., 241, 29, 1996.
Grimani, C., Astr. Sp. Sc., 268, 4, 1999.
Golden R. L. et al., Phys. Rev. Lett., 43, 1264, 1979.
Greisen, K., Phys. Rev. Lett., 16, 748, 1966.
Hayashida, N. et al., astr0-ph/0008101.
Hof, M. et al., Ap. J. Lett., 467, L33, 1996.
Mikhailov, A. A., Nucl. Phys. B (Proc. Suppl.), 75A, 359, 1999.
Muller, D. and Tang, K. K., Ap. J., 312, 183, 1987.
Olinto, A. V., Epstein, R. I., Blasi, P., Proc. of 26th International Cosmic Ray Conference (Salt Lake City), 4, 361, 1999.
Olinto, A. V., astro-ph/0002006, 2000a.
Olinto, A. V., astro-ph/0011106, 2000b.
Omnes, R. , Phys. Rev. Lett., 23, 38, 1969.
Omnes, R., Phys. Reps. C3, 1, 1970.
Stanev, T. and Hillas A. M., Proc. of 26th International Cosmic Ray Conference (Salt Lake City), 4, 365, 1999.
Stanev T. et al, Phys. Rev. D, 62, 093005, 2000.
Vietri, M., Ap. J., 453, 863, 1995.
Waxman, E., Phys. Rev. Lett., 75, 386, 1995.
Zatsepin, G. T. and Kuzmin, V. A., Zh. Eksp. Teor. Fiz, 4, 7, 1966.