Fermi National Accelerator Laboratory

FERMILAB-Pub-99/184-A

Constraints to Nucleon Source Distributions from the Highest Energy Cosmic Rays Spectrum

Maria Teresa Dova and Luis Epele

Universidad Nacional de La Plata
C.C. 67, 1900 La Plata, Argentina

Carlos Hojvat

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

June 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Distribution

Approved for public release; further dissemination unlimited.

Copyright Notification

This manuscript has been authored by Universities Research Association, Inc. under contract No. DE-AC02-76CH03000 with the U.S. Department of Energy. The United States Government and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government Purposes.

Constraints to nucleon source distributions from the highest energy cosmic rays spectrum

Maria Teresa Dova and Luis Epele

Departamento de Física, Universidad Nacional de La Plata, C.C. 67, 1900 La Plata, Argentina

and

Carlos Hojvat

Fermilab, P.O. Box 500, Batavia, IL 60510, USA

Received _____; accepted _____

ABSTRACT

The high energy cosmic ray spectrum as measured by the Fly's Eye and AGASA detectors, has been fitted for different hypothetical nucleon source distributions. In the analysis it is assumed an extragalactic component above $10^{17.6}$ eV where there is a feature of the spectrum, so-called second "knee", not usually mentioned. The modification of the shape of the spectrum above 10^{19} eV, the "ankle", is consequently only determined by the interaction of nucleons with the Microwave Background Radiation without changing the spectral index. It is also shown that the events observed above 10^{20} eV should have a different origin.

Subject headings: Cosmic rays

1. Introduction

One of the most important problems today in astrophysics is the question of the origin, acceleration and propagation of the highest energy cosmic rays. Several experimental groups, Volcano Ranch (Linsley 1963), Haverah Park (Lawrence, Reid and Watson 1991), Yakutsk (Efimov et al. 1991, Afnasiev 1996), Fly's Eye (Bird et al. 1993, 1995) and AGASA (Takeda et al. 1998) have established, althought with limited statistic, the existence of events well beyond the Greissen-Zatsepin Kuz'min cutoff (Greisen 1966, Zatsepin and Kuz'min 1966). This so called GZK cutoff is expected if the highest energy cosmic rays come from outside the Galaxy due to their interaction with photons of the microwave background radiation.

The Fly's Eye detector has measured the cosmic ray energy spectrum both in monocular and stereo modes and has reported the highest energy cosmic ray event ever recorded, of 3.2 10^{20} eV (Bird et al. 1993). The AGASA experiment has also reported events with energies higher than 10^{20} eV (Hayashida et al. 1994) that have been extensively analyzed (Yoshida et al.1995). More recently the same group (Takeda et al. 1998) has reported on the highest energy spectrum of cosmic rays with higher statistics, where it is shown a continuos spectrum between 10^{20} eV and 3×10^{20} eV, suggesting, however, a small deficit just below 10^{20} eV.

Around 10^{19} eV the spectrum changes shape and flattens, a feature referred to as the "ankle". The actual energy position of the "ankle" varies with the experiment. A combined spectrum of all experiments seems to indicate its position at $10^{18.9}$ eV (PDG 1998). In general, the spectrum can be fitted with simple exponentials over a wide range of energies. Fly's Eye reports a change of spectral index from -3.27 ± 0.02, between $10^{17.6}$ eV (second "knee") and $10^{18.5}$ eV, to -2.71 ± 0.1 between $10^{18.5}$ eV and $10^{19.6}$ eV together with a transition to a lighter composition (Bird et al. 1993). The change in the spectral slope

results in a dip at $\simeq 10^{18.5}\ eV$.

AGASA reports that the spectral index obtained above the "ankle" depends strongly on its position. They fit simultaneously for the energy position of the "ankle" and the slope of the spectrum above it. They obtain $E_{ankle} = 10^{19.01}\ eV$ for the "ankle" energy and the spectral index of $-2.78^{+0.25}_{-0.33}$ above it. If only events with energies below $10^{19}\ eV$ are considered, $\gamma = -3.23^{+0.10}_{-0.12}$ is obtained (Nagano et al. 1992).

Cosmic rays in these energy regions (usually called ultra high energy cosmic rays, UHECR) are assumed to be of extra-galactic origin as their large magnetic rigidity would prevent them from being captured within our galaxy. From a simple dimensional argument, Hillas (Hillas 1984) has shown that only a few astrophysical sources are able to produce particles accelerated up to $10^{20}\ eV$. Radio-galaxies might be good candidates to be considered possible sources of ultra high extragalactic cosmic rays (Biermann 1995, 1997)

Recently, comparative analysis of the experimental UHECR spectra in different scenarios with several models of source distribution (Medina Tanco 1998, Sigl et al. 1998) has been considered.

In this article we analyze the energy spectrum of cosmic rays from the energy region of the second "knee" to the highest reported energies. We assume that any departure of the spectrum from an exponential law is a consequence of energy losses by extragalactic cosmic nucleons interacting with the microwave background radiation (MBR). We shall use analytical solutions for the expected spectrum which consider this effect (Anchordoqui et al. 1997) to fit for the spatial distribution of sources leading to the observed spectrum.

2. The model

A power law injection spectrum for the cosmic rays given by $Q(E) = \kappa\, E^{-\gamma}$ is assumed, where κ is the normalization factor and γ is the spectral index. The analytical solutions which take into account the modification due to the interaction with the MBR photons (Anchordoqui et al. 1997) are obtained by assuming two different hypothesis for the spatial distributions of sources.

For the case of a single source located at t_0 from the observer, the injection spectrum can be written as $Q(E,t) = \kappa\, E^{-\gamma}\, \delta(t - t_0)$ and, for simplicity, we consider the distance as measured from the source, that means $t_0 = 0$. The number of nucleons at a given distance from the source is

$$N(E,t) = \frac{\kappa}{b(E)} E_g^{-\gamma} b(E_g) \tag{1}$$

where $b(E)$ is the mean rate at which particles lose energy and E_g, the injection energy. t is the propagation time between the source and the observer, and therefore a free parameter describing the distance to the single source.

Another possibility considered in this paper is a gaussian spatial distribution of sources that can be assumed to model either a distribution of galaxies or an extended source. The injection spectrum is then given by the convolution of the exponential dependence on the energy and the gaussian spatial distribution. The number of nucleons as a function of energy is given by

$$N(E,t) = \frac{\kappa\, E_g^{-\gamma}\, b(E_g)}{b(E)} \left\{ 1 + \frac{\Delta^2 A^2 e^{-2B/E_g}}{2!} F_1(E_g) + \frac{\Delta^4 A^4 e^{-4B/E_g}}{4!} F_2(E_g) + \mathcal{O}(6) \right\} \tag{2}$$

where A and B ar the fitted constants in ref. (Anchordoqui et al. 1997) assuming an exponential behavior of the fractional energy loss,

$$F_1(E_g) = 2B^2 E_g^{-2} + (2 - 3\gamma) B E_g^{-1} + (1 - \gamma)^2$$

and

$$\begin{aligned} F_2(E_g) &= 24B^4E_g^{-4} + (4-50\gamma)B^3E_g^{-3} + (35\gamma^2 - 25\gamma + 8)B^2E_g^{-2} \\ &+ (-10\gamma^3 + 20\gamma^2 - 15\gamma + 4)BE_g^{-1} + (1-\gamma)^4 \end{aligned}$$

As in the case of the single source model above, a constraint in the injection energy E_g yields as free parameter t, in this case the distance to the center of the cluster and Δ, the width of the spatial distribution.

3. Results

The stereo spectrum of the Fly's Eye experiment shows three regions ($10^{17.3}$ eV – $10^{17.6}$ eV, $10^{17.6}$ eV – $10^{18.5}$ eV and $10^{18.5}$ eV – $10^{19.6}$ eV) that have been fitted with different exponential spectral indices by Bird et al. (Bird et al. 1993). The AGASA group examined the energy spectrum as broken in two regions above $10^{18.5}$ eV, with two different spectral indexes (Yoshida and Dai 1998).

As we have mentioned above, we assume that the modification of the spectrum above the "dip" energy is solely due to the interaction of extragalactic nucleons with the MBR without changing the spectral index obtained below that energy. In the case of Fly's Eye experiment we use the "stereo" data in the region immediately below the dip (those events viewed by both Fly's Eye I and II where the energy is determined by stereo reconstruction with a good energy resolution) to fit the spectral slope γ and the normalization κ assuming an exponential law. This assumption is valid since the corresponding energy is below the photopion production threshold and then there should be no modification of the spectrum. The monocular data extends to higher energies and will be use to fit for the distance to a single source, or for the center and width of a cluster of possible sources, keeping fix the γ value previously obtained. The same procedure has been used to analize the AGASA

experimental data.

The fit is performed constructing a likelihood function of the form,

$$\pounds = \prod_{i=1}^{N} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!} \tag{3}$$

where μ_i is the expected number of events in the energy bin i and n_i is the observed number of events. The probability of observing n_i events is assumed to be given by a Poisson distribution. The expected number of events μ_i, is obtained by integrating bin by bin, the differential distributions given by the analytical formula (1) above or the equivalent one for the finite size source model, equation (2).

The finite energy resolution is included by folding the theoretically calculated flux with a Gaussian whose width is given by the experimental resolution.

$$\frac{dj^*}{dE} = \int_{-\infty}^{\infty} \frac{e^{-\left(\frac{E'-E}{\sigma}\right)^2}}{\sqrt{2\pi\sigma}} \frac{dN(E',t)}{dE'} dE' \tag{4}$$

The array's exposure is included bin by bin.

$$\mu_i = \int_{E_i^{min}}^{E_i^{max}} \frac{dj^*}{dE} \mathcal{A}(E) dE \tag{5}$$

where $\frac{dj^*}{dE}$ is the calculated flux (equations (1) and (2)), $\mathcal{A}(E)$ is the exposure as function of energy and σ is the experimental energy resolution for each energy bin. The parameters of the theory are determined by maximizing the corresponding likelihood function.

First we examine the Fly's Eye data. Fitting the stereo data below the dip and assuming a power law spectrum, we obtain for the spectral index $\gamma = -3.27 \pm 0.02$ and for the normalization $\kappa = 29.3 \pm 0.45$, values in good agreement with those of Bird et al.

(Bird et al. 1993) for the same region of energy. With the published experimental energy resolution σ of $^{+28\%}_{-32\%}$ for $E \geq 2 \times 10^{19}$ we fit the parameters corresponding to different source models using the monocular spectrum data that extends to higher energies.

If the most energetic event is included, neither the single source nor the extended source hypothesis gives a good fit to the data. Once the highest energy point is excluded, the result of the fit, with the fix value of γ, corresponds to a single source distance of $D = (118 \pm 34)Mpc$ and the same value for the normalization factor indicated above. The hypothesis of a gaussian spatial distribution of sources improves the fit over the single source and gives $D = (119 \pm 33)Mpc$ for the mean cluster distance with a width of $\Delta = 35Mpc$. Although the analytical form resulting for these two models are different, it is clear that the result of the fits describes similar situations, as a consequence there is a strong correlation between the uncertainty in the location of a single source and the width of the gaussian distribution of a located cluster.

The expected number of events in each energy bin above $E = 10^{19}eV$, for the extended source model, is listed in Table 1 together with the number of observed ones. Figure 1 shows the energy spectrum observed by Fly's Eye, multiplied by E^3 and normalized to the value at $E = 10^{19}eV$. The solid line indicates the result of our fit.

EDITOR: PLACE TABLE 1 HERE.

EDITOR: PLACE FIGURE 1 HERE.

The expected number of events above $E = 10^{19.9}eV$ based on the fitted spectrum below that energy and taken into account the energy resolution indicates the existence of a sharp cut-off in the expected spectrum where one event is observed.

A comparison of the spectra from Fly's Eye (Bird et al. 1993) and that from AGASA (Takeda et al. 1998) shows some discrepancies that could be due to the corresponding experimental energy resolutions and systematic errors, nevertheless the general shape is similar. To carry out the fit of the AGASA data we have considered the published number of observed events and the exposures in each energy bin (Yoshida et al.1995). In the region below the threshold for the photopion production process we obtain a value of $\gamma = -3.26 \pm 0.06$, in good agreement with the one determined by the AGASA group.

As the AGASA data extends above the "ankle" and beyond the expected GZK cut-off, we have analized both, single and extended source models but we present here only results for the last one being the most realistic. The energy resolution is estimated to be $\sigma \simeq 25\%$ on average for events with $E \geq 10^{19}$ (Yoshida et al.1995). A fit including all the data published by AGASA does not provide a meaningful source distance, consequently the most energetic events are incompatible with the source models been considered here. We have made successive fits excluding each time the remaining highest energy bin. The best fit is obtained when we remove all bins above the energy of $10^{19.85} eV$. Keeping γ fixed in its value $\gamma = -3.26$ as discussed above, the result of the fit gives $D = (178 \pm 30) Mpc$ for the distance of the center of a cluster extended on a width of $\Delta = 30 Mpc$. The normalization factor is obtained to be the same as for $E < 10^{19} eV$. In Figure 2, the AGASA experimental data (points with error bars) together with the best fit considering a model of cluster of galaxies (solid line) are shown.

EDITOR: PLACE TABLE 2 HERE.

EDITOR: PLACE FIGURE 2 HERE.

Considering that the source of these events is of extragalactic origin and that the particles are nucleons, the GZK cut-off should be present. The calculated expected spectrum

above $E = 10^{19.85} eV$ agrees well with a cutoff. Nevertheless, the spectrum observed extends with 8 events well beyond the GZK expected cutoff provided by our model and taking into account the energy resolution. Table 2 contains the expected and observed number of events above $10^{19} eV$.

4. Conclusions

The most straightforward interpretation of the observed energy spectra is generally given in terms of a power law behaviour over a wide range of energies, with changes in the slopes at the so-called "knee" ($\simeq 10^{15} eV$), the second "knee" ($\simeq 10^{17.6} eV$) and the "ankle" ($\simeq 10^{19} eV$). The common accepted scenario is a superposition of a galactic component below the "ankle" and an extragalactic one above that. In this paper we propose a different interpretation: The modifications of the shape of the spectrum around the "ankle" are only due to the influence of the cosmic microwave background on extragalactic nucleons that have as a likely origin, a single source or an extended cluster of galaxies at a given distance. The events above the second "knee" and around the "ankle" are from the same extragalactic component but with an unmodified spectrum since the energy is not high enough to reach the photopion production threshold. As a direct consequence of this hypothesis, the spectral index must remain the same along the energy range under study.

The results obtained by fitting the Fly's Eye data, considering the energy resolution of the experiment, between $E = 10^{17.6} eV$ and $E = 10^{20} eV$ yields to a value of $\gamma = -3.27 \pm 0.02$ for the spectral index and $D = (119 \pm 33) Mpc$ for the distance to the center of a cluster of galaxies spatially extended over 70 Mpc. The highest energy event must be excluded of the fit to obtain the result indicated above.

Using the same assumptions, the parameters obtained from the best fit to the AGASA

data (which results excluding the events above $E = 10^{19.9} eV$), taking into account the resolution of the experiment, corresponds to $\gamma = -3.26 \pm 0.06$ and $D = (178 \pm 30) Mpc$ for the spectral index and the position of a cluster of galaxies spatially distributed over 60 Mpc, respectively.

The expected number of events above $E = 10^{19.9} eV$ was calculated from the models assumed with their parameters fitted from the observed spectra. There are indications of a cut-off in the expected spectrum which is based on pion photo-production from the cosmic microwave background, while there are observed cosmic rays that largely exceeds the cut-off.

With the extremely poor statistic at the end of the spectrum it is not possible to make a reliable fit considering different possibilities for the sources of events above $E = 10^{19.9} eV$. The shape of the spectrum in this energy region is an amazing puzzle. It seems to indicate the presence of a new component, whose origin, acceleration mechanism and propagation properties are still open questions, strongly constrained by statistic. The next generation of observatories, such as the High Resolution Fly's Eye (Corbató 1992), the telescope Array (Teshima 1992) and most notable the Pierre Auger Observatory (Auger Design Report 1996) will be expected to provide new insights to what today is a mystery. The Pierre Auger Observatory will certainly improve the situation since it will be the only operating observatory in the Southern hemisphere and a novel observatory to study the Northern part of the sky.

This work was partially supported by CONICET, Argentina. One of us, C.H., was the recipient of a Fulbright Commission fellowship for part of this work.

REFERENCES

Afnasiev B.N., 1996 Proc.International Symposium on Extremely High Energy Cosmic rays: Astrophysics and Future Observatories, ed. M.Nagano, Tokyo, p.32

Anchordoqui L. A. , Dova M. T., Epele L. N. and Swain J. D., 1997 Phys. Rev.D, 55, 7356.

Biermann P.L. , 1995, Nucl. Phys. B, Proc. Supl. 43, 221.

Biermann P.L., 1997, J. Phys. G: Nucl. Part.,23, 1

Bird D. J. et al., 1993, Phys. Rev. Lett.,71, 3401,

Bird D. J. et al., 1995, Ap. J.441, 144.

Corbató, S.C. et al. 1992, Nucl. Phys. B, (Proc. Supl.) 28, 36.

Efimov N.N. et al. 1991, Proc. International Symposium on Astrophysical Aspects of the most Energetic Cosmic rays, eds. M.Nagano and F.Takahara (World Scientific, Singapore), p.20

Greisen K., 1966, Phys. Rev. Lett.,16,748

Hayashida N. et al., 1994, Phys. Rev. Lett.,73, 3491.

Hillas A.M, 1984, Ann.Rev. Astron. Astrophys, 22, 425

Lawrence M.A. , Reid R.J.O., and Watson A.A., 1991,J. Phys. G:Nucl. Phys.,17,653.

Linsley J, 1963, Phys. Rev. Lett., 10, 146.

Medina Tanco G. , 1998, astro-ph/9810366.

Nagano M.et al., 1992, J. Phys. G: Nucl. Phys.,18, 423.

Review of Particle Physics, 1998, Eur. Phys. J. C,3, 136.

Sigl G. , Lemoine M. and Biermann P., 1998, astro-ph/9806283.

Takeda M.et al., 1998, Phys. Rev. Lett.,81, 1163.

Teshima et al. , 1992 Nucl. Phys. B, (Proc. Supl.) 28, 169.

The Auger Collaboration, 1996, Pierre Auger Project Design Report, Fermi National Accelerator Laboratory (unpublished).

Yoshida S.et al., 1995, Astropart. Phys.,3,105.

Yoshida S. and Dai H., 1998, J.Phys.G: Nucl. Phys., 24, 905.

Zatsepin G. T. and Kuz'min V. A., 1966, Pis'ma Zh. Eksp. Teor. Fiz.,4,114.

This manuscript was prepared with the AAS LaTeX macros v4.0.

$Log(E_{min})eV$	$Log(E^{max})eV$	Events Observed	Events Expected
19.0	19.1	65	72.4
19.1	19.2	51	51.8
19.2	19.3	39	29
19.3	19.4	23	21.2
19.4	19.5	10	12.7
19.5	19.6	11	8.5
19.6	19.7	5	6.3
19.8	19.8	3	4.9
19.9	19.9	1	1.3
≥ 20.0		1	$< 10^{-5}$

Table 1: Number of observed and expected events from the best fit to the Fly's Eye data with the extended source model.

$Log(E_{min})eV$	$Log(E^{max})eV$	Events Observed	Events Expected
18.95	19.05	168	180.2
19.05	19.15	103	113.2
19.15	19.25	62	64.4
19.25	19.35	48	40.3
19.35	19.45	27	22.5
19.45	19.55	19	13.8
19.55	19.65	17	9.5
19.65	19.75	7	7.5
19.75	19.85	2	1.6
19.85	19.95	2	$< 10^{-5}$

Table 2: Number of observed and expected events from the best fit to the AGASA data with the extended source models.

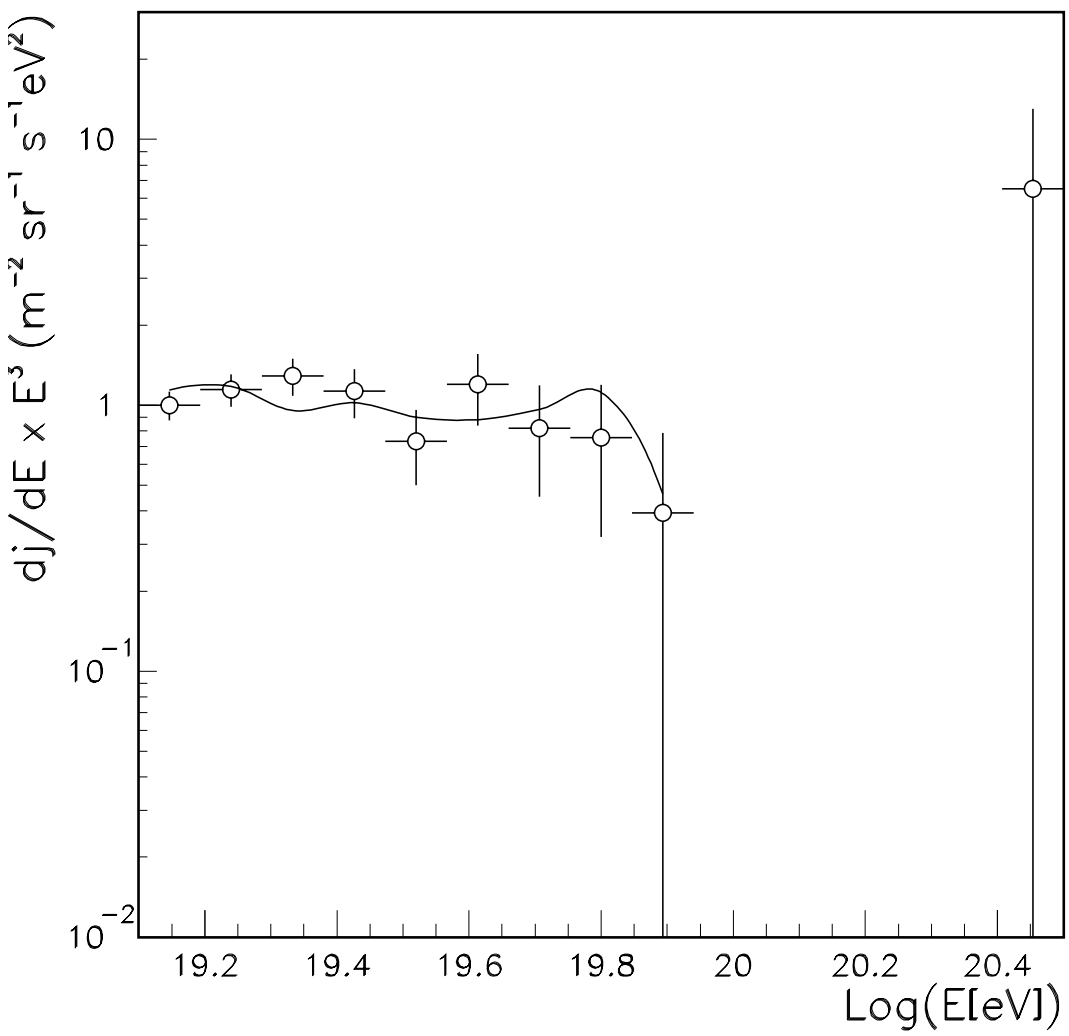

Fig. 1.— Best fit of extended source model to the Fly's Eye monocular data . The solid line indicates the fit described in the text. The flux is normalize to the $E = 10^{19.05} eV$ data.

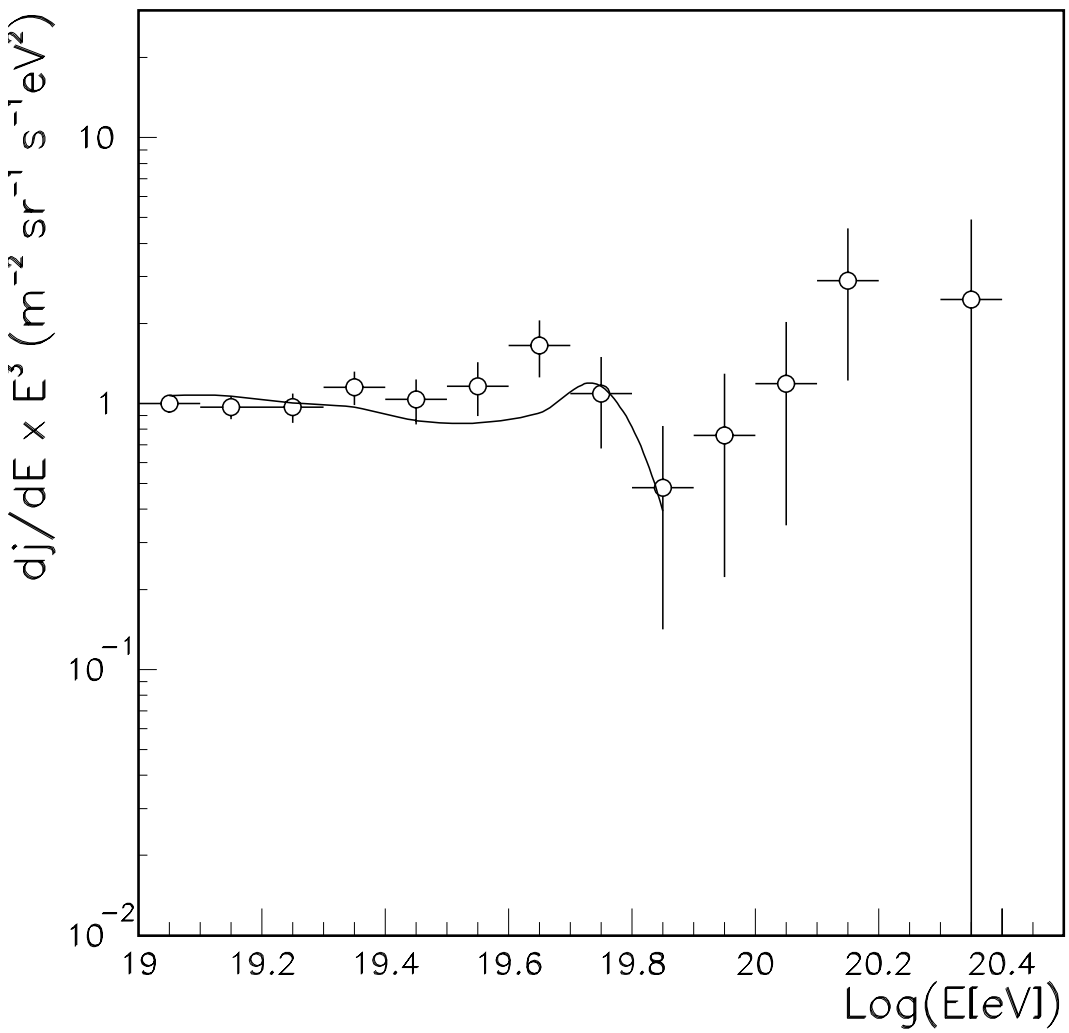

Fig. 2.— Best fit of the extended source model to the AGASA data. The solid line corresponds to the fit described in the text. The flux is normalize to the $E = 10^{19} eV$ data.