OG 3.2.52

UHECR spectrum: the spatial distribution of the sources

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Abstract

The Ultra-high energy cosmic ray energy spectrum summarized by the AGASA collaboration indicates clearly that the cosmic ray spectrum extends well beyond the Greisen-Zatsepin-Kuzmin (GZK) cut-off at $\approx 5 \times 10^{19}$ eV. Furthermore, despite the small number statistics involved, some structure in the spectrum may be emerging. Using numerical simulations, it is demonstrated in the present work that these features are consistent with a spatial distribution of sources that follows the distribution of luminous matter in the local Universe. Therefore, from this point of view, there is no need for a second high-energy component of cosmic rays dominating the spectrum beyond the GZK cut-off.

1 Introduction:

In general, the distribution of sources of UHECR particles in bottom-up mechanisms should be related to the distribution of luminous matter in the Universe. In contrast, for top-down mechanisms, an isotropic distribution of sources should be expected in most of the models (c.f., Hillas 1998, Dubovsky and Tinyakov 1998, Medina Tanco and Watson 1999). Hence the importance of distinguishing observationally between these two scenarios.

The clusters of events observed by AGASA (Hayashida et al 1996) are consistent with UHECR production regions at distances of the order of $\approx$ 30 Mpc, for an intervening IGMF $\approx 10^{-10}$ to 10^{-9} Gauss (Medina Tanco 1998). Local maxima in the galaxy density distribution are located at those positions. This can be viewed as a point in favor of the hypothesis that the UHECR sources are distributed in the same way as the luminous matter in the local Universe does. Furthermore, it could naturally explain the extension of the UHECR spectrum beyond the GZK cut-off hinted by extreme high energy events of Volcano Ranch (Linsley 1963, 1978), Haverah Park (Watson 1991, Lawrence, Reid and Watson 1991), Fly's Eye (Bird et al. 1995) and AGASA (Hayashida et al., 1994), and recently confirmed (AGASA, Takeda et al. 1998).

Numerical simulations are used to assess both, the statistical significance of the AGASA result (Takeda et al. 1998) at the very end of the energy spectrum, and the degree to which it is compatible with a non-homogeneous distribution of sources that follows closely the spatial distribution of luminous matter in the nearby Universe. The possibility of solving the puzzle in few years of integration with the soon to be built Southern site of the Auger observatory, Malargüe, is explored.

2 Calculations and results:

Energy losses due to photo-pion production in interactions with the cosmic microwave background, should lead to the formation of a bump in the spectrum beyond 5×10^{19} eV, followed by the GZK cut-off at higher energies. The existence and exact position of these spectral features depends on the spatial distribution of the sources, their cosmological evolution and injection spectrum at the sources (Berezinsky and Grigor'eva 1988). Nevertheless, both bump and cut-off tend to smooth away for predominantly nearby sources or strong cosmological evolution. The most natural way to avoid the GZK cut-off is by invoking either top-down mechanisms or the existence of relatively very near (compared with the UHECR mean free path) sources.

The spectrum calculated by Yoshida and Teshima (1993, YT93) for an isotropic, homogeneous distribution of cosmic ray sources, and shown superimposed on the observed AGASA spectrum in Takeda et al (1998), seems unable to explain the extension of the UHECR spectrum beyond 10^{20} eV. It is not clear, however, whether the available data (461 events for E > 10^{19} eV, and only 6 events for E > 10^{20} eV) is sufficient to support any conjecture about the actual shape of the spectrum above 10^{20} eV. Furthermore, it is the nearby sources that are expected to be responsible for this region of the spectrum and their distribution is far from isotropic or homogeneous. It is not clear either what is the influence that the differential exposure in declination, peculiar to the AGASA experiment, has on the deduced spectral shape at the highest energies.

The energy spectrum by YT93 was recalculated using a homogeneous distribution of sources from z=0 to z=0.1, including adiabatic energy losses due to redshift, and pair production and photo-pion production due to interactions with the cosmic microwave background in a Friedmann-Robertson-Walker metric. A fiducial intergalactic magnetic field (IGMF, ignored in the original work of YT93), of intensity $B_{IGMF} = 10^{-9}$ G and correlation length L_c = 1 Mpc (cf., Kronberg, 1994; Medina Tanco et al 1997), was also included. Individual sources were treated as standard candles in UHECR proton luminosity above 10^{19} eV. The injected spectrum was a power law, $dN/dE \propto E^{-\nu}$, with $\nu = 3$ above the latter threshold. From the $\approx 10^7$ particles output by the simulation and arriving isotropically in right ascension and declination, one hundred samples were extracted, with the same distribution in declination as the quoted exposure of AGASA (Uchihori et al. 1996). The determination of the arrival energy of protons was performed assuming an error of 20% (energy-independent Gaussian distribution), typical of AGASA (e.g., Yoshida and Dai 1998). Similarly, the same bin and number of events above 10^{19} eV (461 protons) as in the AGASA paper (Takeda et al, 1998) were used for the calculation of the individual spectra. The resulting spectrum is shown in Figure 1, where the different shades indicate 63% and 95% confidence levels, i.e., the region in the $E^3 \times dJ/dE$ vs. E space where 63% and 95% of the spectra fell respectively. The model is able to fit the observed AGASA spectrum quite well up to $\approx 10^{20}$ eV. At E > 10^{20} eV, however, AGASA observations seem unaccountable by the homogeneous approximation, even when the quoted errors are considered.

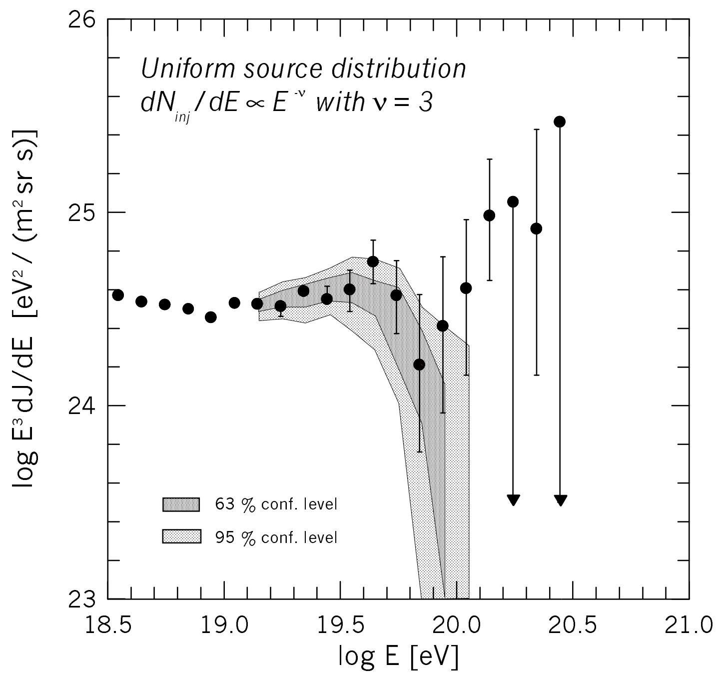

Figure 1: homogeneous distribution of sources

The distribution of luminous matter in scales comparable with a few mean free paths of UHECR protons in the CMBR (i.e., tens of Mpc) is, nevertheless, far from homogeneous. Therefore, it should be expected that the local distribution galaxies plays a key role in determining the shape of the UHECR spectrum if the sources of the particles have the same spatial distribution as the luminous matter.

In figure 2, the number of galaxies inside shells of constant thickness in redshift, $\Delta z = 0.001$, are shown as a function of z for the July 1998 release of the CfA Redshift Catalogue (Huchra et al 1992).

Also shown in the same figure is a homogeneous, isotropic distribution of sources (as used in the previous calculation). The normalization of the latter is such that both distributions enclose the same number of galaxies for $r_0 \leq 100$ Mpc. The observed distribution of galaxies shows an excess for r < 60 Mpc compared to the homogeneous distribution. Between r ≈ 60 and r ≈ 100 Mpc both distributions increase with the same slope. This suggests that the approximation of homogeneity begins to be valid beyond r ≈ 60 Mpc and that the actual distribution of galaxies is reasonably well sampled (even if obviously incomplete) up to r ≈ 100 Mpc = r_0. For r > 100 Mpc bias effects dominante the observations. Therefore, we assume that the distribution of luminous matter at $r < r_0 = 100$ Mpc is well described by the CfA catalog, while the homogeneous approximation holds outside that volume. The previously described simulation scheme is used for the distant sources in the homogeneous region, while the actual distribution of galaxies is used for the UHECR sources nearer than 100 Mpc. The IGMF (Medina Tanco 1997, 1998a) is modeled as a cell-like spatial structure, with cell size given by the correlation length, $L_c \propto B^2_{IGM}(r)$. The intensity of the IGMF, in turn, scales with luminous matter density, ρ_{gal} as $B_{IGM} \propto \rho^{0.3}_{gal}(r)$ (e.g., Medina Tanco 1999) and the observed IGMF value at the Virgo cluster (≈ 10^{-7} G, Arp 1988) is used as the normalization condition.

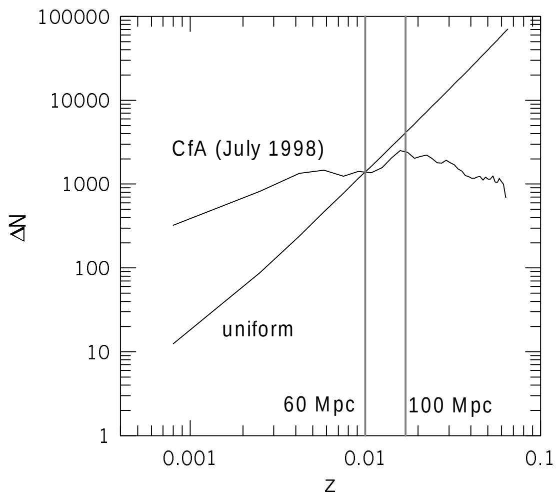

Figure 2: Actual distribution of galaxies with known redshift and a homogeneous distribution

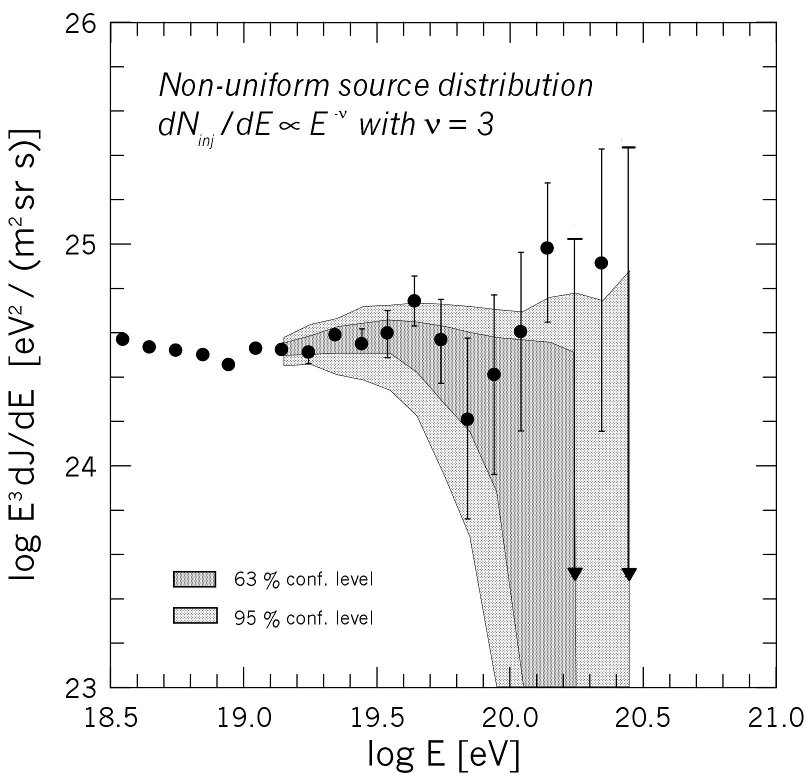

Figure 3: UHECR energy spectrum from sources following the distribution of luminous matter

The resultant spectrum is obtained by combining both contributions, from nearby and distant sources respectively. The results, particularized for the AGASA experiment (i.e., same declination exposure and energy error, as well as number of events and bin size), are shown in Figure 3. It can be seen that, when the actual distribution of galaxies is taken into account, the 63% confidence spectrum is able to fit all the data if the corresponding experimental errors are considered. Consequently, the UHECR spectrum observed by the AGASA experiment is, given the available data, compatible with a distribution of cosmic ray sources that follows the distribution of luminous matter in the Universe. The latter is true up to the highest energies observed so far. Clearly, more data is needed before the hypothesis can be falsified.

However, an answer can be expected in the next few years. The same calculations have been performed for the first three years of operation of the soon to be built Southern site of the Auger experiment. The appropriate dependence of exposure on declination was used (A. Watson, private communication), and the expected number of events (Auger Design Report, 1997). The results are given in figure 4, superimposed with the present AGASA spectrum and its previously calculated uncertainty.

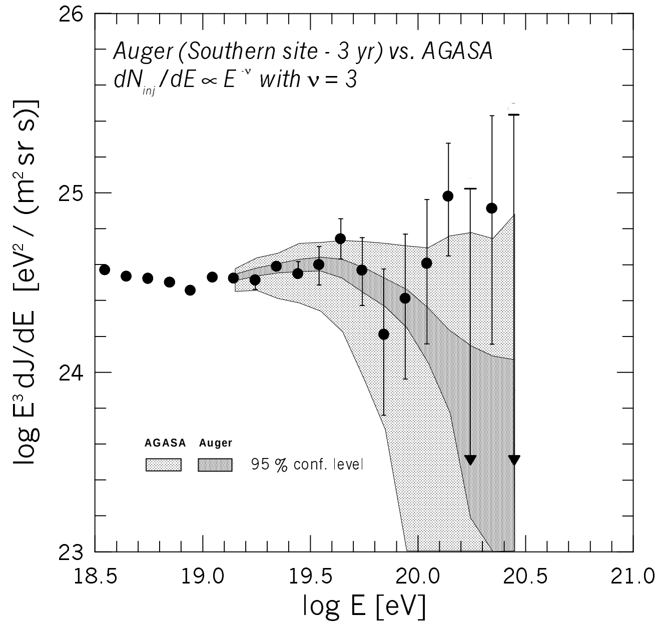

Figure 4: projected Southern Auger results after 3 years of operation vs. present AGASA uncertainties.

3 Conclusions:

Given the low number of events detected by the AGASA experiment so far with E > 10^{19} eV, the observed UHECR spectrum is consistent with a spatial distribution of sources that follows the luminous matter distribution in the nearby Universe. Therefore, based on the observational uncertainties at present, there is no need for a second UHECR component responsible for the events observed above the nominal GZK cut-off. Few years of operation of the Southern portion of the Auger experiment (Malargüe, Argentina) should be enough to distinguish whether the GZK cut-off feature is present or not in the UHECR spectrum.

GAMT acknowledges the partial support from the Brazilian agencies FAPESP, CNPq and CAPES

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