The energy spectrum observed by the AGASA experiment and the spatial distribution of the sources of ultra-high energy cosmic rays

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ABSTRACT

Seven and a half years of continuous monitoring of giant air showers triggered by ultra high-energy cosmic rays have been recently summarized by the AGASA collaboration. The resulting energy spectrum indicates clearly that the cosmic ray spectrum extends well beyond the Greisen-Zatsepin-Kuzmin (GZK) cut-off at $\sim 5 \times 10^{19}$ 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.

Subject headings: Cosmic Rays — large-scale structure — magnetic fields

1. Introduction

Several mechanisms have been proposed for the acceleration of UHECR. At the most general level, they can be classified into two large groups: bottom-up and top-down mechanisms. Bottom-up mechanisms, although more conservative, imply the stretching of rather well known acceleration processes to their theoretical limits (and sometimes beyond). They involve particle acceleration in the accretion flows of cosmological structures (e.g., Norman, Melrose and Atcherberg 1995, Kang, Ryu and Jones 1996), galaxy collisions (Cesarsky and Ptuskin 1993, Al-Dargazelli et al. 1997, but see Jones 1998), galactic wind shocks (Jokipii and Morfill 1987), pulsars (Hillas 1984, Shemi 1995), active galactic nuclei (Biermann and Strittmatter 1987), powerful radio galaxies (Rawlings and Saunders 1991, Biermann 1998), gamma ray bursts (Vietri 1995, 1998, Waxmann 1995, but see Stanev, Schaefer and Watson 1996), etc.. Top-down mechanisms, on the other hand, escape from the acceleration problems at the expense of exoticism. They already form the particles at high energies and involve the most interesting Physics, for example: the decay of topological defects into superheavy gauge and Higgs bosons, which then decay into high energy neutrinos, gamma rays and nucleons with energies up to the GUT scale ($\sim 10^{25}$ eV) (e.g., Bhattacharge, Hill and Schramm 1992, Sigl, Schramm and Bhattacharge 1994, Berezinsky, Kachelrie and Vilenkin 1997, Berezinsky 1998, Birkel and Sarkar 1998), high energy neutrino annihilation on relic neutrinos (Waxmann 1998), etc..

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). Hence the importance of distinguishing observationally between these two scenarios.

A possible correlation between compact radio quasars and the five most energetic

UHECR has already been proposed by Farrar and Biermann (1998). Furthermore, the clusters of events observed by AGASA (Hayashida et al 1996) are consistent with UHECR production regions at distances of the order of ~ 30 Mpc, for an intervening IGMF $\sim 10^{-10}$ to 10^{-9} Gauss (Medina Tanco 1998a). 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 by the latter experiment (Takeda et al. 1998, Nagano 1998).

In the following sections we use numerical simulations 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 next generation of large area (10^3 km^2) experiments is exemplified through the Southern site of the Auger observatory.

2. Numerical approach and discussion of 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 (Greisen 1966, Zatsepin and Kuzmin 1966) 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) 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. Therefore, 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.

To analyze the effects of the previously mentioned factors on the observed energy spectrum, two different sets of simulations are discussed here.

As a check on the simulations, the energy spectrum by Yoshida and Teshima (1993) was reproduced 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 radiation (CMBR) in a Friedmann-Robertson-Walker metric. Furthermore, a fiducial intergalactic magnetic field (IGMF), characterized by an intensity $B_{IGMF} = 10^{-9}$ G and a correlation length $L_c = 1$ Mpc (cf., Kronberg, 1994), was also included. The IGMF was assumed uniform inside cells of size L_c and randomly oriented with respect to adjacent cells (Medina Tanco et al 1997). The IGMF component was neglected in the original work of Yoshida and Teshima

(1993). Individual sources were treated as standard candles supplying the same luminosity in UHECR protons 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 $\sim 10^7$ 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 here for the calculation of the spectra.

The resulting predicted 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. It can be seen that, as predicted by Yoshida and Teshima (1993), the model is able to fit the observed AGASA spectrum quite well up to $\sim 10^{20}$ eV. The introduction of the IGMF does not make appreciable changes. At higher energies, however, AGASA observations seem unaccountable by the homogeneous approximation, even when the quoted errors are considered.

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, given the relatively small mean free path of protons above 10^{20} eV, 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.

The second set of simulations is intended to address the latter problem. 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 latest release (version of Jul 27, 1998) of the CfA Redshift Catalogue (Huchra et al 1992). Also shown in the same figure is a homogeneous, isotropic distribution of sources. The normalization of the latter is such that both distribution enclose the same number of galaxies inside $r_0 = 100$ Mpc. The observed distribution of galaxies shows an excess for $r < 60$ Mpc compared to the homogeneous distribution. Between $r \sim 60$ and $r \sim 100$ Mpc both distributions increase with the same slope. This suggests that the approximation of homogeneity begins to be valid beyond $r \sim 60$ Mpc and that the actual distribution of galaxies is reasonably well sampled (even if obviously incomplete) up to $r \sim 100$ Mpc $= r_0$. Farther away the slope of the observed distribution changes abruptly, very likely due to the predominance of bias effects.

The approximation adopted here is, therefore, 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. Additionally, in the latter case, the same procedure as in Medina Tanco (1997, 1998a) is used in the description of the IGMF: a cell-like spatial structure, with cell size given by the correlation length, $L_c \propto B_{IGMF}^{-2}(r)$. The intensity of the IGMF, in turn, scales with luminous matter density, ρ_{gal} as $B_{IGMF} \propto \rho_{gal}^{0.3}(r)$ (e.g., Vallée 1997) and the observed IGMF value at the Virgo cluster ($\sim 10^{-7}$ G, Arp 1988) is used as the normalization condition.

The resultant spectrum is obtained by combining both contributions, from nearby and distant sources respectively, after taking into account the complicating fact that our knowledge of the distribution of galaxies is not uniform over the celestial sphere (e.g., obscuring by dust over the galactic plane). 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.

There is hope, however, for a solution in the relatively near future. The same calculations have been performed for the first three years of operation of the future 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, i.e., 9075 (Auger Design Report, 1997). The results are given in figure 4, superimposed with the present AGASA spectrum and its previously calculated uncertainty.

Finally, a word of caution should be given regarding the possibility of large scale structuring of the IGMF (Ryu, Kang and Biermann 1998). The effects that this could have on UHECR propagation have been discussed extensively in Medina Tanco (1998b). Unfortunately, it is not possible to state undoubtedly in which direction this would influence the resulting particle spectrum without knowing the exact topology of the IGMF and location of nearby sources with respect to the field.

3. Conclusions

From the previous analysis it can be concluded that, 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. In the latter approach a single power-law injection energy-spectrum is assumed, extending up to the highest observed energies beyond the GZK cut-off. 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.

Three years of integration by the future Southern site of the Auger observatory should suffice to decide whether the spatial distribution of UHECR sources is the same of the nearby luminous matter or not.

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Figure Captions

Figure 1: : Spectrum from a uniform distribution of sources superimposed on the observed AGASA spectrum (adapted from Takeda et al. 1998). The same total number of events, energy determination error and exposure as a function of declination as AGASA's are used. Error bars in the AGASA spectrum represent the Poisson upper and lower limits at 68% and arrows are 98% confidence upper limits.

Figure 2: Number of galaxies inside shells of constant thickness $\Delta z = 0.001$ as a function of redshift z for the CfA redshift catalog (July 1998) and a uniform distribution of sources. Both distribution were normalized to give the same number of sources inside $r_0 = 100$ Mpc. Note the observed excess of galaxies at short distances relative to the uniform distribution. Moreover, both curves have the same slope between 60 and 100 Mpc. This suggests that beyond 60 Mpc the observed distribution behaves approximately as a uniform distribution and that the catalog maps correctly the actual distribution of galaxies as far as 100 Mpc. At larger distances the undersampling is apparent. (Quoted distances are for $h = 0.5$.)

Figure 3: Major result of this work. Calculated observable spectrum for the same experimental conditions of AGASA, under the assumption that the UHECR sources are distributed spatially in the same way as the luminous matter in the nearby universe.

Figure 4: The future. The same calculations as in figure 4 are reproduced for the Southern site of the future Auger experiment. The result corresponds to the first three years of observation and is compared with the results for the present data of the AGASA experiment. Only 95% confidence spectra are shown.