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FRONTIERS IN COSMIC RAYS*

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This rapporteur review covers selected results presented in the Parallel Session HEA2 (High Energy Astrophysics 2) of the *10th Marcel Grossmann Meeting on General Relativity*, held in Rio de Janeiro, Brazil, July 2003. The subtopics are: ultra high energy cosmic ray anisotropies, the possible connection of these energetic particles with powerful gamma ray bursts, and new exciting scenarios with a strong neutrino-nucleon interaction in the atmosphere.

1. Introduction

Since the early 60's several ground-based experiments have observed extensive air showers, presumably triggered by ultra high energy cosmic rays (UHECRs) interacting in the upper atmosphere.[1] The highest primary energy measured thus far is $E \sim 10^{20.5}$ eV,[2] corresponding to a center-of-mass energy $\sqrt{s} = \sqrt{2m_pE} \sim$ 750 TeV, where m_p is the proton mass. The interest in the origin of these particles is twofold: there is not only the intellectual curiosity about unknown properties of powerful astrophysical scenarios, but also the possibility to probe new physics at energies beyond the reach of any foreseeable man-made experiments.

Theoretically, one expects the CR spectrum to fall off somewhat above 10^{20} eV, because the particle's energy gets degraded through interactions with the cosmic microwave background (CMB), a phenomenon known as the Greisen-Zatsepin-Kuzmin (GZK) cutoff.[3] Unfortunately, as one can see in Fig. 1, the most recent measurements by the HiRes[4] and AGASA[5] experiments are apparently in conflict, if only statistical errors are taken into account, and the source of the difference remains

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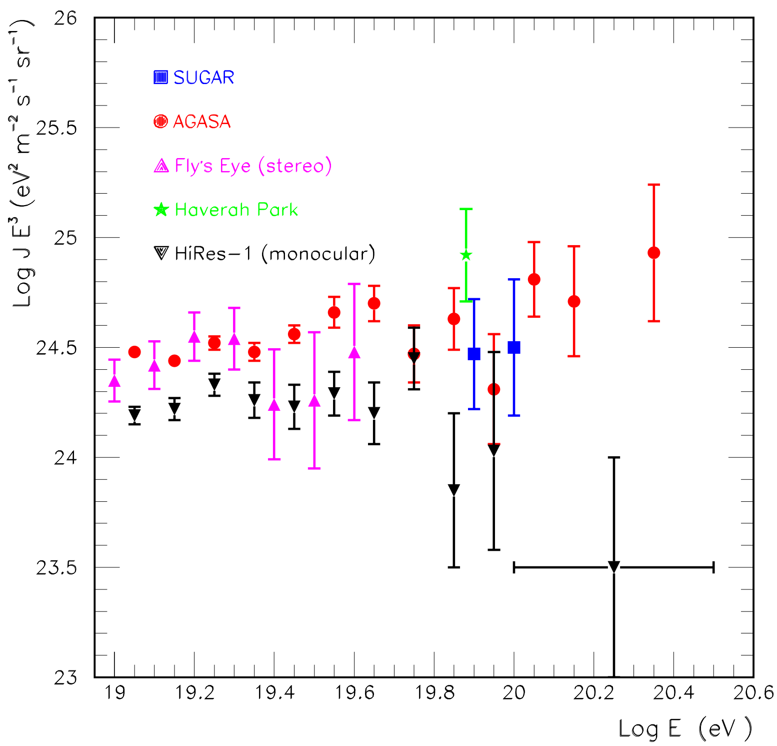

Figure 1. Data on the upper end of the cosmic ray energy spectrum with their statistical error bars. (HiRes,[4] AGASA,[5] Fly's Eye,[6] Haverah Park,[7] and SUGAR.[8])

unknown. However, if one takes the systematic uncertainties in the energy measurements into account, one finds that both data sets are mutually compatible on the $2\,\sigma$ level.[9] Attempts to explain the AGASA data with a homogeneuos population of astrophysical sources that injects power-law distributions of CRs give unacceptable χ^2 (see, e.g., Refs. [[10,11,12]]). On the other hand, an analysis[13] of the combined data reported by the HiRes, the Fly's Eye, and the Yakutsk collaborations is supportive of the existence of the GZK cutoff at the $> 5\,\sigma$ ($> 3.7\,\sigma$, depending upon the extrapolated energy spectrum) level.[a] The deviation from GZK depends on the set of data used as a basis for power law extrapolation from lower energies. One caveat is a recent claim[15] that there may be technical problems with the Yakutsk data collection. In view of the low statistics at the end of the spectrum and the wide variety of uncertainties in these experiments, perhaps the rational thing to do is to wait for more data, conservatively arguing that the jury is still out.

In this Parallel Session we saw many thorough reviews covering all the most

[a] This evidence disappears, however, if one assumes that UHECRs are protons and excludes nearby ($\lesssim$ 50 Mpc) sources from the otherwise homogeneous distribution.[14] In this case even the HiRes-1 data are incompatible with the GZK cutoff on the $3\,\sigma$ level.[10,11]

interesting and timely topics in CR physics. In this rapporteur summary we cannot do justice to all the presentations.[b] Priority will be given to two intriguing scenarios, which pose possible explanations of the data.

2. Anisotropies in UHECRs

At the highest energies, the arrival directions of CRs are expected to begin to reveal their origins. If the CR intensity were isotropic, then one should expect a time-independent flux from each direction in local detector coordinates, i.e., declination and hour angle. In that case, a shower detected with local coordinates could have arrived with equal probability at any other time of a shower detection. For any point of the celestial sphere, the expected shower density can be estimated if the exposure in each direction can be obtained. This implies that celestial anisotropies can be easily discerned by comparing the observed and expected event frequencies at each region.

For experiments with 100 % duty cycle, continuous operation in solar time for several years leads to a uniform observation in right ascension. Therefore, one of the conventional methods to search for any global anisotropy is to apply the Linsley's[17] harmonic analysis to the full sky cosmic ray distribution, i.e., determine the amplitude and phase of the $m^{\rm th}$ harmonic by fitting the right ascension distribution of events to a sine wave with period $2\pi/m$.

There is a remarkable agreement among several experiments favoring a significant anisotropy (encoded in the first harmonic amplitude) around 10^{18} eV from the general direction of the Galactic Plane (GP). Specifically, the AGASA experiment has revealed a correlation between the arrival direction of CRs (with energy $\sim 10^{18}$ eV) and the GP at the $4\,\sigma$ level.[18] The GP excess, which is roughly 4% of the diffuse flux, is mostly concentrated in the direction of the Cygnus region, with a second spot towards the Galactic Center (GC).[19] Evidence at the $3.2\,\sigma$ level for GP enhancement in a similar energy range has also been reported by the Fly's Eye Collaboration.[20] Interestingly, the full Fly's Eye data include a directional signal from the Cygnus region which was somewhat lost in an unsuccessful attempt to relate it to γ-ray emission from Cygnus X-3.[21] Finally, the existence of a point-like excess in the direction of the GC has been confirmed via independent analysis of data collected with the SUGAR experiment.[22]

For the ultra high energy ($> 10^{19.6}$ eV) regime, all experiments to date have reported no departure from isotropy in the first harmonic amplitude.[23][c] This does not imply an isotropic distribution, but it merely means that available data are too

[b] A scenario in which UHECRs are able to break the GZK barrier was presented by She-Sheng Xue.[16]

[c] For the Fly's Eye data-sample the first harmonic amplitude is computed using weighted showers, because it has had a nonuniform exposure in sideral time. A shower's weight depends on the hour of its sideral arrival time, and the 24 different weights are such that every time bin has the same weighted number of showers.

sparse to claim a statistically significant measurement of anisotropy. In other words, there may exist anisotropies at a level too low to discern given existing statistics.[24]

The right ascension harmonic analyses are completely blind to intensity variations which depend only on declination. Combining anisotropy searches in right ascension over a range of declinations could dilute the results, since significant but out of phase "Rayleigh vectors" from different declination bands can cancel each other out. Moreover, the analysis methods that consider distributions in one celestial coordinate, while integrating away the second, have proved to be potentially misleading.[25] An unambiguous interpretation of anisotropy data requires two ingredients: *exposure to the full celestial sphere and analysis in terms of both celestial coordinates.*[26]

The first full sky search for large scale anisotropies in the distribution of arrival directions of CRs with energy $> 10^{19.6}$ eV was reported in this Parallel Session by John Swain.[27] Data from the SUGAR and AGASA experiments, taken during a 10 yr period with nearly uniform exposure to the entire sky, show no departures from either homogeneity nor isotropy on angular scale greater than $10°$.

In this full-sky anisotropy search, the intensity distribution of the set of $N = 99$ arrival directions

$$I(\mathbf{n}) = \frac{1}{\mathcal{N}} \sum_{j=1}^{N} \frac{1}{\omega_j}\, \delta(\mathbf{n}, \mathbf{n}_j) \ , \tag{1}$$

was conviniently expanded in spherical harmonics ($Y_{\ell m}$)

$$I(\mathbf{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}\, Y_{\ell m}(\mathbf{n}) \ , \tag{2}$$

going into the multipole expansion out to $\ell = 5$. Here, ω_j is the relative exposure at arrival direction $\mathbf{n}_j$ and $\mathcal{N}$ is the sum of the weights ω_j^{-1}. The coordinate independent total power spectrum of fluctuations,

$$C(\ell) = \frac{1}{(2\ell+1)} \sum_{m=-\ell}^{\ell} a_{\ell m}^2 \ , \tag{3}$$

is consistent with that expected from a random distribution for all (analyzed) multipoles, though there is a small (2σ) excess in the data for $\ell = 3$.[28] To give a visual impression of the level of homogeneity and isotropy in existing data, in Fig. 2 we show the intensity distribution as seen by AGASA and SUGAR experiments.

3. UHECRs from GRBs

In this section, arguments for the origin of UHECRs from gamma ray bursts (GRBs) are reviewed. This line of enquiry has led to a complete model for CRs originating from supernovae (SNe) and GRBs in our Galaxy and throughout the universe,[29,12] which is summarized here.

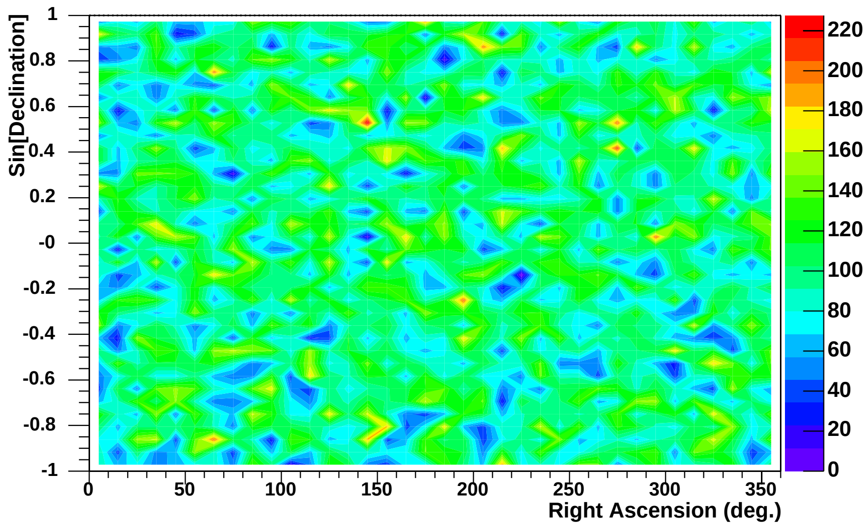

Figure 2. UHECR intensity in arbitrary units (equatorial coordinates) as seen by the AGASA and SUGAR experiments.

The connection betweeen GRBs and UHECRs was first made on the basis of an intriguing coincidence[30,31] beween the power required to sustain the measured flux of super-GZK ($\gtrsim 10^{20}$ eV) CRs against photohadronic energy losses and the local time- and space-averaged hard X-rays/soft γ-ray luminosity of GRBs. This luminosity density is estimated to be $\approx 10^{44}$ ergs Mpc^{-3} yr^{-1}. Thus GRBs have, in principle, sufficient energy to power the UHECRs and post-GZK CRs. Moreover, many GRB sources are found within the GZK radius, and CRs with energies $\gtrsim 10^{20}$ eV can be accelerated by the relativistic shocks formed in GRB explosions.[32] The hypothesis of a GRB/UHECR association points to a closer connection between SNe and CRs that could provide a complete solution to the problem of CR origin.

3.1. *CRs from Supernovae*

Even though the controversy surrounding the origin of the UHECRs has generated much interest, it should be noted that the much older problem of the origin of the CRs is itself not solved. Cosmic rays with energies from GeV/nucleon up to hundreds of TeV are widely thought to be accelerated by supernova remnant (SNR) shocks. Yet the prediction that SNRs should be luminous γ-ray sources and display the characteristic 70 MeV π^0 decay emission feature from hadronic interactions was not confirmed by the EGRET instrument on the *Compton Observatory*. Nevertheless, there is statistical evidence that SNRs are associated with unidentified γ-ray sources.[33] There is also clear evidence for a π^0 decay feature in the diffuse galactic γ-ray background, even if the spectrum is harder than would be expected if CRs throughout the Galaxy have the same spectrum as those observed locally.[34]