Sensitivity of JEM-EUSO to Ensemble Fluctuations in the Ultra-High Energy Cosmic Ray Flux

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Abstract: The flux of ultra-high energy (UHE) cosmic rays (CRs) depends on the cosmic distribution of their sources. Data from CR observatories are yet inconclusive about their exact location or distribution, but provide a measure for the average local density of these emitters. Due to the discreteness of the emitters the flux is expected to show ensemble fluctuations on top of the statistical variations, a reflection of the cosmic variance. This effect is strongest for the most energetic cosmic rays due to the limited propagation distance in the cosmic radiation background and is hence a local phenomenon. In this work we study the sensitivity of the JEM-EUSO space mission to ensemble fluctuations on the assumption of uniform distribution of sources, with local source density $\sim 10^{-5}$ Mpc$^{-3}$. We show that in 3 years of observation JEM-EUSO will be able to probe ensemble fluctuations if the nearest sources are at 3 Mpc, and that after 10 years orbiting the Earth, this pathfinder mission will become sensitive to ensemble fluctuations if the nearest sources are 10 Mpc away. The study of spectral fluctuations from the local source distributions are complementary to but independent of cosmic ray anisotropy studies.

Keywords: UHECRs, ensemble fluctuations, JEM-EUSO.

1 Introduction

Above about 10 GeV, the CR spectrum falls as an approximate power-law in energy, $dN/dE \propto E^{-\gamma}$. On a gross scale, this power law appears rather featureless, but closer examination reveals several breaks in the spectral index, $\gamma$. The small change from $\gamma \approx 2.8$ to $\gamma \approx 3.0$ at $E \approx 10^{6.5}$ GeV is known as the knee. The spectrum steepens further to $\gamma \approx 3.2$ above the dip ($E \approx 10^{6.7}$ GeV), and then flattens to $\gamma \approx 2.7$ at the ankle ($E \approx 10^{10}$ GeV). The most recently uncovered feature is a sharp and statistically very significant suppression of the flux reported first in 2007 by the HiRes collaboration [1], and later confirmed by the Auger collaboration [2], which reported $\gamma = 2.69 \pm 0.02$ (stat) $\pm 0.06$ (syst) and $\gamma = 4.2 \pm 0.4$ (stat) $\pm 0.06$ (syst) below and above and $E = 10^{10.6}$ GeV [2] respectively. In 2010, an updated Auger measurement of the energy spectrum was published [3]. The break corresponding to the suppression is located at $\log_{10}(E/\text{GeV}) = 10.46 \pm 0.03$. Compared to a power law extrapolation, the significance of the suppression is greater than 200$\sigma$.

This collection of spectral features clearly reflects physically interesting phenomena, including CR source distributions, emission properties, composition and propagation effects. Indeed, there is a large body of literature devoted to inferring such fundamental information from details of spectral features. A common approach involves developing some hypothesis about source properties and, using either analytic or Monte Carlo methods, deducing the mean spectrum one expects to observe at Earth. As our knowledge of source distributions and properties is limited, it is common practice to assume spatially homogeneous and isotropic CR emissions, and compute a mean spectrum based on this assumption. In reality, of course, this assumption cannot be correct, especially at the highest energies where the GZK effect severely limits the number of sources visible to us. We can, however, quantify the possible deviation from the mean prediction based on the knowledge we do have on the source density and the possible distance to the closest source populations. This next statistical moment beyond the mean prediction is referred to as the ensemble fluctuation [6]. It depends on, and thus provides information on, the distribution of discrete local sources, source composition, and energy losses during propagation. This ensemble fluctuation in the energy spectrum is one manifestation of the cosmic variance, which should also appear directly through eventual identification of nearby source populations. In fact, once statistics become sufficiently large, it will be interesting to try to identify the ensemble fluctuations in the energy spectrum in two ‘realizations’ of the universe; one could for instance try to detect spectral variations in the northern and southern skies which are consistent with ensemble fluctuations, or, if a dipole anisotropy eventually becomes evident, search for distinct ensemble fluctuations associated with this spatial anisotropy. (JEM-EUSO searches for CR anisotropy are discussed elsewhere in these proceedings [7].)

It was recently pointed out that next generation experiments may be sensitive enough to find evidence of this hitherto unexplored effect. The existence of this suppression is consistent with the predictions of Greisen, Zatsepin and Kuzmin (GZK) [4,5], in which CR interactions with the cosmic microwave background (CMB) photons rapidly degrade the CR energy, limiting the distance from which UHE CRs can travel to $\sim 100$ Mpc.
Characterizing ensemble fluctuations is an exceedingly difficult task owing to the rarity of the highest energy events. Space-based observatories with huge exposures will be critical to pursue this endeavor. The Extreme Universe Space Observatory on the Japanese Experiment Module (JEM-EUSO) will be placed into orbit aboard the International Space Station (ISS) [10]. For $E \geq 9 \times 10^{10}$ GeV, this instrument will observe some $6 \times 10^8$ km$^2$ sr y annually [11], about a factor of 9 greater than the Pierre Auger Observatory nominal annual exposure (for zenith angles up to 60°) [12]. In this work we quantify the sensitivity of JEM-EUSO to ensemble fluctuations.

2 Calculation of ensemble fluctuations

The calculation of ensemble fluctuations reflecting spatial variations that depend on the local source density is formally divergent, unless we introduce a regulator: $r_{\min}$. This mathematical regularization has a physical interpretation as the distance to the closest source (or source population), and it is these potential close by sources that introduce the largest contribution to variations from the mean spectrum prediction.

As described in the Introduction, ensemble fluctuations are influenced by various UHECR source and propagation characteristics, including the distribution of discrete local sources, the nuclear composition, and energy losses during propagation. If the primary CRs are protons, the dramatic energy degradation proceeds via resonant photopion production in the CMB. If the primary CRs are heavy nuclei, successive photoevaporation of one or two nucleons through the giant dipole resonance is mainly responsible for the UHECR energy loss [4, 5]. The energy loss length for a given composition of the UHECR, and propagation effects.

The secondary nuclei produced via photodisintegration carry approximately the same Lorentz factor as the initial nucleus. It is hence convenient to express the energy of a nucleus with mass number $A$ as $A \epsilon t$ where $t$ denotes the energy per nucleon. The differential interaction rate corresponding to the production of a nucleus with mass number $B$ and energy $E$' from a nucleus with mass number $A > B$ and energy $E > E'$ can be approximated as $\frac{\Delta A}{A} \epsilon (E') \simeq \Gamma_{A \rightarrow B}(E) \delta (E' - B/A \epsilon t)$ where $\Gamma_{A \rightarrow B}$ is the partial width of the transition.

Since, in this analysis, we are not concerned with the direction of the source we can imagine sitting at the center of a sphere with radius $r_c$, with emission rate spectrum $\delta A(E)/(4\pi r_c^2)$. The point-source flux is described by Boltzmann’s equation [6].
case of iron primaries, the ensemble fluctuation could even allow for a distinctive upward wiggle in the spectrum before the GZK cutoff causes it to plummet. (Candidate nearby sources of heavy nuclei include starburst galaxies [19] and ultra-fast spinning newly-born pulsars [20, 21].)

4 JEM-EUSO discovery reach

From Fig. 2, it is evident that current volume of data at the highest energies is not sufficient to disentangle the ensemble fluctuation phenomenon from statistical fluctuations. Now we consider whether the JEM-EUSO mission will attain sufficient exposure during its projected lifetime to identify ensemble fluctuations for certain assumptions about the source distribution and primary composition.

The Pierre Auger Observatory is currently the world’s largest CR detector. Between 1 January 2004 and 31 December 2010 the observatory collected an integrated exposure of $\mathcal{E} = 20,905$ km$^2$sr yr [3]. For the JEM-EUSO baseline design, a factor of 9 increase in annual exposure above $9 \times 10^{10}$ GeV is expected. To project the resulting JEM-EUSO event rate, we scale the latest published Auger energy spectrum [3] according to the relative exposure between the Auger Observatory and JEM-EUSO [11, 12].

From this estimate of JEM-EUSO statistics, we find the expected ratio of the ensemble to statistical fluctuations, $\sqrt{\sigma^2_{\text{loc}} / \sigma^2_{\text{stat}}}$. Figure 3 contains a contour of this ratio in the plane of the maximum energy attained at the source, $E_{\text{max}}$, vs. the observed energy $E$. The precipitous rise in this ratio in the region of extremely high energy is clearly evident.

Finally, in Fig. 4 we display $\sqrt{\sigma^2_{\text{loc}}}$ for the case of $E_{\text{max}} = 10^{12}$ GeV compared to statistical uncertainties for various JEM-EUSO exposure times and two different assumptions for $r_{\text{min}}$. The solid blue line indicates the relative fluctuation for iron, while the red line corresponds to the proton and iron, respectively, under the assumption that $r_{\text{min}} = 10$ Mpc [13]. The right two figures illustrate the situation for the case of $r_{\text{min}} = 3$ Mpc. Note the striking dependence of the size of the ensemble fluctuation on the proximity of the nearest source. In fact, the rightmost figure indicates that for the...
Ensemble fluctuations persist in the limit of large statistics, and may therefore become evident given a sufficiently large data sample. While current data sets are not large enough to discern these fluctuations, future observatories with huge exposure will afford an opportunity to turn up this phenomenon. Here we have shown that JEM-EUSO will provide a lower bound on the extragalactic magnetic field, and may therefore become evident given a sufficiently large data sample. While current data sets are not large enough to discern these fluctuations, future observatories with huge exposure will afford an opportunity to turn up this phenomenon. Here we have shown that JEM-EUSO will provide a lower bound on the extragalactic magnetic field.

5 Conclusions

Ensemble fluctuations are variations in mean energy spectrum predictions reflecting the finite number and distribution of local sources. This phenomenon is one manifestation of the cosmic variance, and provides information complementary to direct searches for the CR sources. (It would perhaps be even more interesting to see no variation in the energy spectra of two sky samples.)

Acknowledgment: We thank Etienne Parizot for some valuable discussion. This work was supported by NASA (11-APRA11-0058 and 11-APRA11-0066) and NSF (CAREER PHY-1053663, PHY-1068696, PHY-1125897, and PHY-1205845).

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