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ULTRA HIGH ENERGY COSMIC RAY HORIZONS

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Abstract. We calculate the horizons of ultra high energy cosmic rays assuming different nuclei primaries ranging from proton to iron at ultra high energies ($6 \cdot 10^{19}$). We show that sources of ultra high energy protons and heavy nuclei can originate from distances up to $\sim$ 180 Mpc, while low and intermediate mass nuclei can only originate in the local universe ($<$ 50 Mpc.)

1 Introduction

Recent results from the Pierre Auger Observatory (Abraham et al. 2007) show a significant correlation between arrival directions of cosmic rays and nearby extragalactic objects, implying that the cosmic ray flux at ultra high energies is anisotropic. These results constitute evidence for the hypothesis that the propagation of ultra high energy cosmic rays is mainly constrained by photo-pion interactions with the cosmic radiation background, or, equivalently, that their flux is suppressed due to the GZK effect.

The observed anisotropy should be a reflection of the distribution of their sources in the nearby universe. In this work we use the Monte Carlo propagation code developed in (Allard et al. 2005) to calculate the distances that contain a given fraction of the sources of cosmic rays that arrive at Earth with an energy above a given energy threshold (E_{th}). We refer to these distances as the "horizon", and we calculate them as a function of E_{th}, for different source primaries.

2 Method

Consider the *integrated* cosmic ray flux at Earth, $d\mathcal{F}(E_{th}, z)$, produced by sources with a redshift between z and $z + dz$, and a given fraction f. We define the horizon $H(E_{th}, f)$ as the distance for which the following relation is satisfied:

$$f = \frac{\int_0^{z_{hor}} dz \frac{d\mathcal{F}(E_{th},z)}{dz}}{\int_0^{\infty} dz \frac{d\mathcal{F}(E_t h,z)}{dz}} \tag{2.1}$$

The horizon is then readily obtained by $H(E_{th}, f) \simeq 4.22 \cdot 10^3 z_{hor}(E_{th}, f)$. We consider energies above 60 EeV, energy at which Auger observes the onset of anisotropy.

The evaluation of equation 2.1 is done by means of the Monte Carlo nuclei propagation code developed in (Allard et al. 2005). The code propagates nuclei from their sources, following all nuclear secondaries resulting from interactions with the radiation backgrounds. In the case of protons, the dominant interaction in the considered energy range is phtopion production off CMB photons. In the case of heavier nuclei, the dominant interaction is via the delta resonance which results in the "erosion" of the primary by loss of one or several nucleons.

We considered a power law energy distribution at injection with spectral indices ranging from -3 to -2. The assumed source distribution is homogeneous and redshift independent (at the energies considered only contribution from sources up to redshift 0.1 are relevant). We assumed nuclear primaries ranging from proton to iron.

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3 Results and Discussion

The interactions of protons and compound nuclei with the CMB are different and we discuss them separately. At the energies considered, the main energy loss mechanism is dominated by pion production for protons and by giant delta resonance interactions for nuclei. The interaction length, however, is dominated in both cases by pair production. Since this interactions are of very low inelasticity they will be ignored in the subsequent discussion.

The effects of photopion interactions on the propagation of protons are well known since (Greisen 1966 and Zatsepin and Kusmin 1966) and have been extensively studied in, e.g., (Berezinsky 2004). Above the threshold for pion production against CMB photons (at $\sim 6 \cdot 10^{19} eV$) the interaction length reduces to around 10 Mpc. These interactions are of large inelasticity ($\sim 20\%$).

The total interaction lengths for compound nuclei is dominated by delta resonance interactions with low density infra-red photons up to a threshold energy where interactions with the high density CMB photons become dominant. The cross section for the delta resonance process is approximately proportional to A. This fact, together with the fact that the energy of a photon in the rest frame of the nuclei is proportional to the gamma factor of the nuclei in the lab frame (Γ), implies that the interaction lengths for two nuclei with the same Γ factor differ by a factor given by the ratio of their mass numbers (the smaller interaction length corresponding to the heavier nucleus).

The first energy range dominated by interactions with infra-red photons corresponds to Γ smaller than $5 \cdot 10^9$. In this range the interaction length decreases from over 4Gpc/A at $\Gamma \sim 5 \cdot 10^8$ to about 500/A Mpc at $\Gamma \sim 5 \cdot 10^9$.

At $\Gamma \sim 5 \cdot 10^9$ interactions with the denser CMB photons become dominant. Above this threshold, the interaction length decreases much more drastically, becoming smaller than 1Mpc/A for $\Gamma \sim 10^{10}$. Note that while this Γ corresponds to an energy of $\sim 4 \cdot 10^{19}$ eV for He, it corresponds to an energy of $\sim 2 \cdot 10^{20}$ eV for Fe. Above this threshold energy, the universe becomes opaque for compound nuclei and photodisintegration down to pure nucleons is completed in a few megaparsecs.

These qualitative conclusions reflect in the horizons plotted in figures 1(left) and 1(right). Both figures show the horizon as a function of energy for two cases: figure 1(left) corresponds to requiring a given composition *at the sources* while figure 1(right), to requiring a given composition *at the Earth.* The displayed horizons correspond to a spectral index that fits the ultra high energy spectrum for each assumed composition. This implies spectral indices in the range between -2.3 and -2.0.

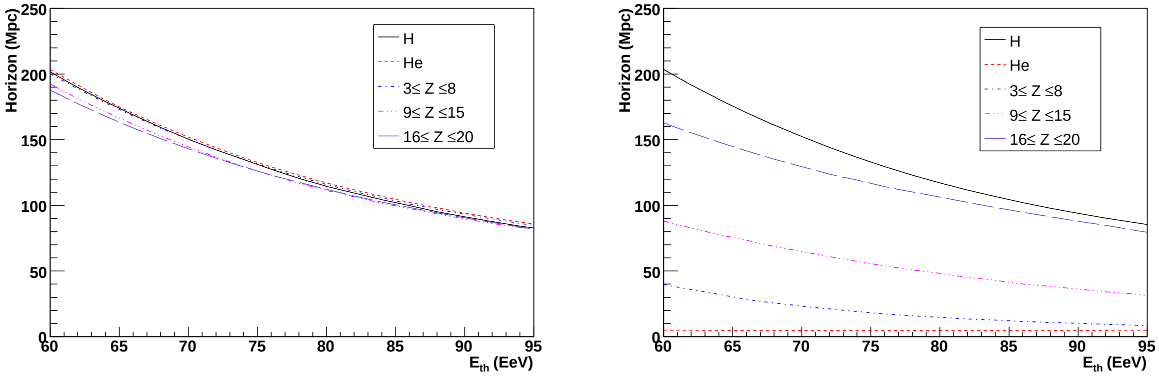

Fig. 1. Ultra high energy horizons. **Left**: assuming the indicated composition at the source (equal fraction of primaries in the indicated Z range). **Right**: requiring the indicated composition at Earth.

Figure 1(left) illustrates the fact that horizons are depend very little on source composition in the case of no particle identification at Earth. This observation is due to two facts: firts, light and intermediate nuclei photodisintegrate very quickly so the analysis reduces to the proton case and second, heavy nuclei have horizons that are very similar to those of protons. These two facts are evident in figure 1(right). Light and intermediate nuclei have horizons ranging between 4 Mpc for He and less than 90 Mpc for Si. The fact that heavy nuclei have a similar horizon to that of proton is a rather remarkable coincidence. The interaction processes in this energy range are different (photopion for proton and delta resonance for nuclei) as well as the responsible photon backgrounds (CMB for protons and infra-red for nuclei). The resulting interaction length is, however, of the same order of magnitude, resulting in similar propagation features.

4 Conclusions

In this work we calculate the horizons for ultra high energy cosmic rays in the energy range between 60 EeV and 100 EeV . They are defined as the distance to the Earth that contains a given fraction of their sources. We considered the case of different composition at the source and at the Earth.

We find that the horizons are very similar independent of the source composition. This is a consequence of the fact that light and intermediate nuclei photodisintegrate very quickly, resulting in an equivalent input flux which is almost composed of pure protons, and that heavy nuclei have a horizon which is very similar to that of proton. Their size evolve with energy, and is around 200 Mpc at 60 EeV and reduces to around 100 Mpc at 100 EeV.

However, if particle if particles can be identified at Earth, the results have a different interpretation. For example, for He particles arriving at Earth with an energy above 60 EeV, 90% of their sources are within 4 Mpc. For CNO or other heavier particles, up to Si, arriving at Earth with an energy above 60 EeV, 90% of the source are within 90 Mpc.

If particle identification ar Earth is ever possible, and the ultra high energy cosmic ray flux turned out to be dominated by light and intermediate nuclei, the perspectives for charged particle astronomy become extremely interesting: the flux is dominated by very nearby sources (at distances up to tens of Mpc), which should be few (unless source density is very high) and easy to identify even if deflections are not small.

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