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Horizons and Anisotropies of Ultra-High Energy Cosmic Rays

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Abstract: We study the propagation of ultra-high energy (UHE) cosmic rays assuming that sources trace the large scale structure (LSS) distribution of dark matter in the nearby universe. We propagate nuclei from protons to iron and determine their horizons as a function of energy and mass: low and intermediate mass nuclei can only originate from very nearby sources above a few 10^{19} eV and the composition above $10^{19.5}$ is mainly protons with a possible small fraction of iron ($\leq$ 10%). We show sky maps of the expected anisotropies for UHE protons with $10^{19.5}$ eV, 10^{20} eV, and $10^{20.5}$ eV arriving from the local dark matter distribution based on constrained dark matter simulations. We also show maps for possible point sources that trace the LSS distribution with number densities of 10^{-3} and 10^{-5} Mpc^{-3} and for exposures from 10^5 to 7×10^5 km^2 sr yr.

Introduction

The window for particle astronomy is likely to open somewhere above $10^{19.5}$ eV. Current cosmic ray data at the highest energies show sky maps consistent with isotropic distributions, but as high aperture observatories, such as the Pierre Auger Observatory, reach higher exposures, departure from isotropy is expected both from the limited horizon in particle propagation and the weakening of the effects of cosmic magnetic fields. Here we estimate the exposures necessary to observe anisotropic distributions of the ultra-high energy cosmic ray (UHECR) sky. We calculate the horizons for different nuclei with energies above 10^{19} eV and produce maps of the sky assuming the sources of UHECRs trace the dark matter distribution in the nearby universe. From the dark matter distribution we also generate point source maps for different source densities and a given number of events or exposure. We use the new unit of exposure named the Linsley, L = $1\ \mathrm{km}^2\ \mathrm{sr\ yr}$, after the UHECR pioneer, John Linsley (1925 - 2002). In these units, AGASA reached a 1.6 10^3 L, Auger South will explore the 10^4 L range most of its life, and Auger North will add to Auger South in reaching the 10^5 L scale much sooner (in 6 years) and reaching 10^6 L at the ends of its lifetime.

We calculate the horizons of UHE nuclei with the propagation code developed in [1]. By horizon we mean the distance from where a large fraction of events for a given energy can reach Earth. The fraction of events coming from a source closer than a distance D that contribute to the spectrum above a given energy are shown in Fig. 1 for UHECR protons, He, CNO, and Fe-like (Z $\geq$ 20) nuclei. In this calculation, the predicted spectrum and composition are fit to current data as in [2, 3] with an injection spectral index of 2.3 and a continuous source distribution down to 5 Mpc. Fig. 1 shows that protons and Fe-like nuclei with energies below $10^{19.5}$ eV can reach the Earth from about 1 Gpc away, while CNO nuclei can travel 300 Mpc and He nuclei about 100 Mpc at these energies. This unimpeded propagation in Gpc scales combined with the effects of cosmic magnetic fields can explain the observed isotropic distribution seen in current data at ultra high energies. At energies around $10^{19.9}$ eV, the He horizon is down to 10 Mpc, the CNO horizon is at 30 Mpc, while protons can still come from 250 Mpc and Fe-like nuclei from 200 Mpc. Even if a mixed composition is injected at UHECR sources, the observed composition on Earth will be dominated by protons with a small trace of Fe. At these energies and above, charge particle astronomy is within reach of high exposure observatories.

Given the proton dominance and limited horizon at ultra high energies, the sky distribution of UHECRs from high exposure observatories should become anisotropic at some critical energy depending on the source spectrum, density, and evolution. To estimate the anisotropy of sky maps of different energies, we use the dark matter distribution derived from constrained N-body cosmological simulations with gas dynamics of the Local Supercluster (LSC) region (a 30 h^{-1} Mpc region around the Virgo cluster) from [4] based on [5]. The simulated structures closely mimic the real nearby universe including the Local Group, the Coma and Virgo clusters, the Great Attractor, the Perseus-Pices, and the Local Supercluster, in approximately correct locations. The MARK III survey of peculiar velocities of the observed structures inside 80 h^{-1} Mpc sphere is used to constrain the initial conditions. We use a constant density of dark matter for regions beyond the simulated cosmological box equal to the mean density at a given redshift.

Fig. 2 shows sky maps in galactic coordinates of the integrated density of dark matter along the line-of-sight within the horizon of protons of energies $10^{19.5}$ eV, 10^{20} eV, and $10^{20.5}$ eV. The signal contrast is in a logarithmic scale ranging from 0 to 0.59 for $10^{19.5}$ eV, 0 to 1.7 for 10^{20} eV, and 0 to 2.2 $10^{20.5}$ eV. The dotted line is the exclusion zone of Auger South (zenith $> 60°$) and dashed line is the exclusion zone of Auger North. For a continuous source density $\rho(\mathbf{r})$, the relative flux of cosmic rays in the direction **n** is computed with the relation:

$$\Phi(\mathbf{n}, E) = \int_{\rm los} \rho(n, r) H(r, E) dr$$

where $H(E, r)$ is the energy losses horizon. The integral is estimated along the line of sight, from the position of the Milky Way to a distance where the probability to reach the Earth becomes negligeable.

It is clear from Fig. 2 that to observe anisotropies in the UHECR sky large exposures are necessary at energies above $10^{19.5}$ eV. The expected signals for large scale anisotropies and small scale clustering depend on the number of events that can be collected above $10^{19.5}$ eV, which depends on the achieved exposures and the spectrum at the highest energies. For an exposure of $5 \times 10^4 L$, the number of events above 10^{20} eV range from 20 for a spectrum with maximum energy $E_{max} = 10^{20}$ eV to 70 for $E_{max} = 10^{21}$ eV, while for $7 \times 10^5 L$, the number of events grows to 300 for $E_{max} = 10^{20}$ eV up to 1000 for $E_{max} = 10^{21}$ eV. At $10^{19.9}$ eV, the number of events range from 1000 to 2200 for $7 \times 10^5 L$, while for $5 \times 10^4 L$ the range is from 70 to 800, for $E_{max} = 10^{20}$ eV and 10^{21} eV respectively. Somewhere in this energy and exposure range hides the beginning of charged particle astronomy.

Astrophysical sources are likely to be distributed according to the density field in Fig. 2. Although a few models for the origin of UHECRs are based on the decay of dark matter, most models of UHECR sources are based on discrete extragalactic sources that cluster on large scales following the dark matter density. (Dark matter decay models are photon dominated and have a sky distribution dominated by the Galactic dark matter halo, unlike the sky maps in Fig. 2, and have been excluded by recent Auger data [6].) To show how sky maps of UHECR events should look like for different exposures, a source distribution and evolution need to be specified for a given energy. In Fig. 3, we show examples of full sky maps of events expected above 10^{20} eV for a source density assigned proportionally to the dark matter density field. On the left panel, we show a realization of the sky with of 10^{-5} Mpc^{-3} and exposure of 10^5 L, while on the right panel, a source density of 10^{-3} Mpc^{-3} and exposure of 7×10^5 L is shown. Clearly the observation of sources will be possible for exposures above 10^5 L, if sources follow a large range of densities, from the denser galaxy distribution numbers of 10^{-3} Mpc^{-3} to rarer galaxies or groups of galaxies with 10^{-5} Mpc^{-3}, as long as sources are present within about 100 Mpc.

The origin of UHECRs continues to be a mystery almost after a century of cosmic ray studies. Key to unveiling these extremely energetic sources is large exposure observatories such as the proposed Auger North [7].

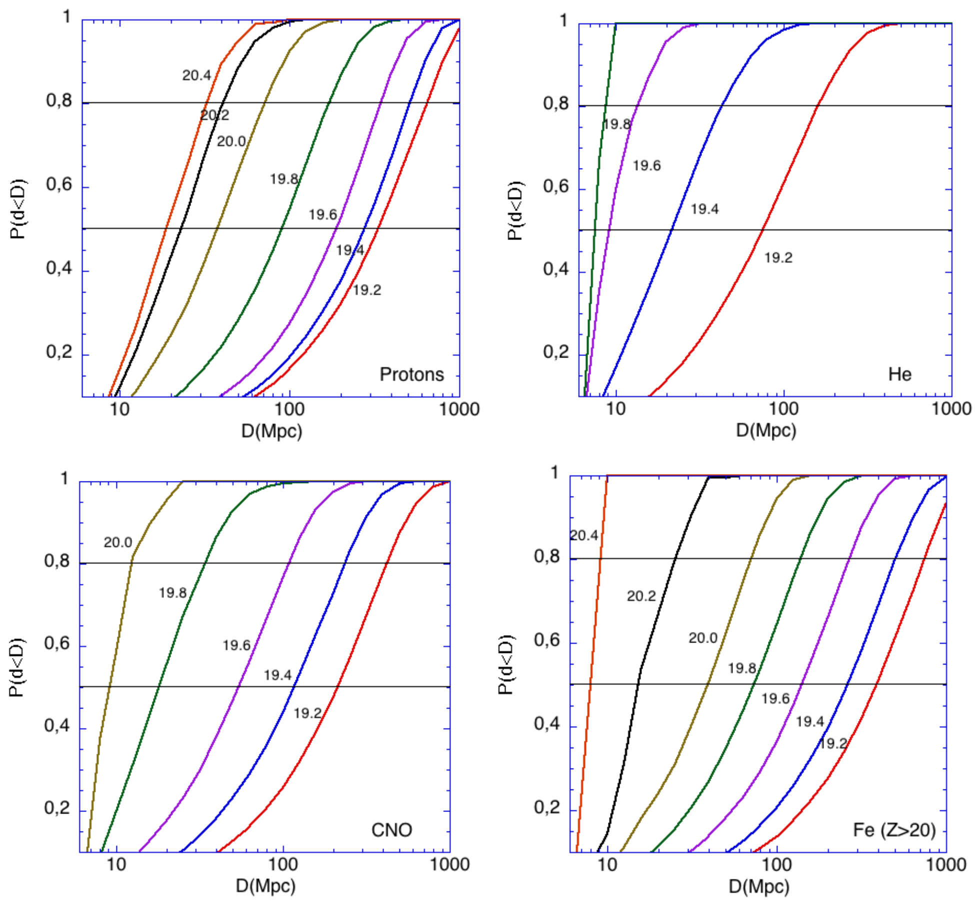

Figure 1: Fraction of the events from a source closer than a distance D, contributing to the spectrum above a given energy (the log of the energy is given by labels) as a function of D for proton(upper left), He (upper right), CNO (lower left) and heavy ($Z \geq 20$) (lower right) nuclei. For the figures shown we assume an injection spectral index 2.3 and a continuous source distribution down to 5 Mpc.

Acknowledgements

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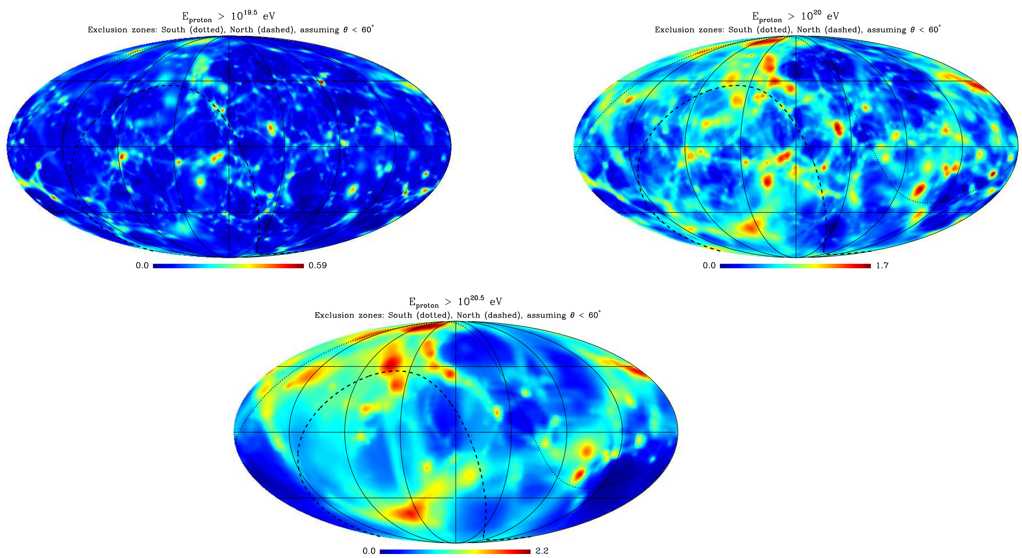

Figure 2: Sky maps in galactic coordinates of integrated density of dark matter along the line-of-sight within the horizon of protons of energies $10^{19.5}$, 10^{20} and $10^{20.5}$ eV (logarithmic scale). The dotted line is the exclusion zone of Auger South (zenith $> 60°$) and dashed line is the exclusion zone of Auger North.

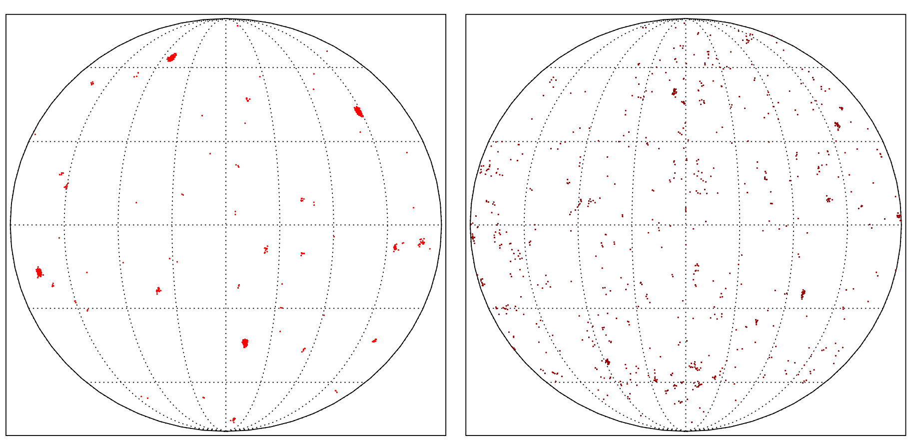

Figure 3: Examples of full sky maps of events expected above 10^{20} eV using Auger North and South sky exposures. Left: source density of 10^{-5} Mpc^{-3} and exposure of 10^5 L. Right: source density of 10^{-3} Mpc^{-3} and exposure of 7×10^5 L. Sources assigned proportionally to the dark matter density field.