Large-Angular-Scale Clustering as a Clue to the Source of UHECRs

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Abstract: We show that future Ultra-High Energy Cosmic Ray samples should be able to distinguish whether the sources of UHECRs are hosted by galaxy clusters or ordinary galaxies, or whether the sources are uncorrelated with the large-scale structure of the universe, independently of magnetic deflection.

Introduction

Identifying the sources of ultrahigh energy cosmic rays (UHECRs, here $E \gtrsim 10^{19}$eV $\equiv 10$ EeV) is complicated by the deflection they presumably experience in Galactic and extragalactic magnetic fields, as well as their relatively poor arrival direction determinations, typically $\sim 1°$. Theoretical estimates of the magnetic fields and their correlation lengths vary over a wide range, but there are two pieces of empirical evidence indicating either that some UHECRs are neutral or that net magnetic deflections are small in at least some directions. First, there are ~ 8 excess correlations between UHECRs and BL Lacs, at the $\lesssim 1°$ level, in a sample of 271 UHECRs with a chance probability of $\sim 10^{-4}$[6, 2, 8]. Secondly, a group of 5 UHECRs has been identified, whose arrival directions are consistent with coming from a point source with negligible magnetic deflection [1, 5]. Nevertheless, arrival directions of most UHECRs are not known well enough to match their positions with specific astrophysical objects.

In this paper, we show how techniques developed for the study of cosmological Large Scale Structure can be a valuable diagnostic as to the source of UHECRs. In particular, we propose that the large-scale *bias* of a UHECR sample is a robust measure of the clustering properties of the source, that is quite insensitive to magnetic deflection over the range of probable deflections. We begin by reviewing the definition of the bias of a sample and giving examples of the bias values for a number of known classes of possible sources. Then we demonstrate what we can learn, in principle, from the large-scale clustering of UHECR samples of different sizes. Next we discuss how to deal with the unknown depth of a UHECR sample, using the GZK effect. We close with a summary of our results and future work.

Galaxy Bias

The clustering of galaxies in the universe is typically quantified by the two-point correlation function or its analog in Fourier space, the power spectrum. The two-point correlation function $\xi(r)$ of any class of objects (e.g., galaxies of a certain luminosity or color) is defined as the excess number of pairs of such objects at physical separation r over that expected for a random (Poisson) distribution. The shape of the galaxy correlation function depends on the clustering of the underlying dark matter density field, which is determined by gravitational physics, as well as any non-gravitational processes that can affect where galaxies form and survive relative to the dark matter. The relative clustering of galaxies and dark matter is referred to as galaxy bias, and it is usually defined as $b(r) = \sqrt{\xi_{gg}(r)/\xi_{mm}(r)}$, where $\xi_{gg}(r)$ is the correlation function of galaxies and ξ_{mm} is that for dark matter. In principle, the bias can have a non-trivial scale dependence; however, in a Cold Dark Matter (CDM) universe where galaxy formation is a local process (i.e., the efficiency of galaxy formation does not depend on the matter density field at large distances), $b(r)$ becomes scale-independent on large scales [12, 11]. In other words, the galaxy correlation function has the same shape as the dark matter correlation function on large scales ($\gtrsim 3-4$ Mpc), and their relative amplitude, or bias, can be expressed as a single constant b. This property has made it possible to use the observed clustering of galaxies on large scales to constrain the underlying dark matter distribution [14].

In CDM models, the large-scale bias of a population of objects depends only on their mass, with more massive objects, such as clusters of galaxies, clustering more strongly than less massive objects, such as ordinary galaxies [10, 13, 3]. The most massive galaxy and x-ray clusters have bias values of $\sim 3-4$ relative to the dark matter; really bright galaxies, such as ULRGs, have bias values of ~ 2; galaxies with luminosities near $L_\star$ are unbiased with bias values of ~ 1, and faint dwarf galaxies are anti-biased with bias values as low as ~ 0.7. Active galaxies, such as AGN and BLLacs are clustered like ordinary galaxies of the same luminosity.

The correlation function of dark matter cannot be observed directly and can only be predicted theoretically given a cosmological model. It is therefore useful, when studying bias observationally, to measure the relative bias of different astrophysical objects. For example, the relative bias of a population A and galaxies is $b_A/b_g = \sqrt{\xi_{AA}/\xi_{gg}}$, where ξ_{AA} and ξ_{gg} are the large-scale autocorrelation function amplitudes of population A and galaxies, respectively. An alternative way to determine the relative bias of two populations is to measure their cross-correlation function. For, example, the relative bias of objects A and galaxies can also be written as $b_A/b_g = \xi_{Ag}/\xi_{gg}$, where ξ_{Ag} is the cross-correlation function between population A and galaxies. When the size of sample A is small, as is the case for samples of UHECRs, its autocorrelation function is very noisy and it is more robust to measure bias using cross-correlations.

Though the bias of a given population is most straightforward to measure using 3D data, it is also possible to constrain using 2D (angular only) data. In this case, the relevant measurements are ratios of the angular correlation function $\omega(\theta)$.

Large-Angle Clustering of UHECRs

Measuring the clustering of UHECRs on large scales can yield a clue as to the nature of their astrophysical sources. This is due to the simple fact (outlined above) that astrophysical objects of different masses have different clustering strengths. We demonstrate this by creating mock samples of UHECRs assuming different astrophysical sources and examine their resulting clustering.

We use the Sloan Digital Sky Survey (SDSS) [15] to create a volume-limited sample of galaxies that is complete out to a distance of $200h^{-1}$Mpc. We select a sample of massive galaxy clusters taken from the [4] group and cluster catalog. Based on their luminosities, we estimate these clusters to have masses greater than $10^{14}h^{-1}M_\odot$. Finally, we create a large sample of randomly distributed points in the same volume. We measure angular cross-correlation functions of each of these samples with the galaxy sample (so, for the galaxy case, we are measuring the autocorrelation) using the Landy-Szalay [9] estimator:

$$\omega_{12}(\theta) = \frac{N_{D_1D_2} - N_{D_1R} - N_{D_2R} + N_{RR}}{N_{RR}},$$

where $N_{D_1D_2}$ is the number of pairs as a function of θ between the two data samples (in this case, galaxies and something else), N_{D_1R} and N_{D_2R} are the number of pairs as a function of θ between each data sample and the random sample, and N_{RR} is the number of random-random pairs. Figure 1 shows the resulting angular correlation functions: cluster-galaxy, galaxy-galaxy, random-galaxy. As expected, the cluster-galaxy correlation function has a higher amplitude than the galaxy-galaxy correlation function on all angular scales, and the random-galaxy correlation function is equal to zero by construction.

These three curves represent predictions for the UHECR-galaxy cross-correlation function in the three distinct cases that UHECRs originate from astrophysical sources that: (1) live in massive clusters, (2) live in ordinary galaxies, and (3) are uncorrelated with the large-scale structure of the universe, such as sources within the Milky Way galaxy. The three cases predict different measured UHECR-galaxy correlation functions even at large angles, where UHECR direction uncertainties due

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Figure 1: Predicted UHECR-galaxy angular cross-correlation functions for the cases that the astrophysical sources of UHECRs are (1) uncorrelated with the large-scale structure in the universe (*black line*), (2) ordinary galaxies (*green curve*), and (3) clusters of galaxies (*magenta curve*). The blue shaded region shows the 95% (2σ) measurements using 200 mock samples of 1000 UHECRs each, where the UHECRs are assumed to originate in galaxies. The red shaded region shows the same, but for mock UHECR arrival directions containing 3° random Gaussian errors.

to measurement error and magnetic deflections are unimportant.

We next examine how well we can distinguish between these different predictions assuming a sample of 1000 UHECRs. For the purpose of this test, we assume that the sources of UHECRs are, in fact, ordinary galaxies. We create a mock UHECR sample by randomly selecting 1000 galaxies from our SDSS galaxy sample. We create 200 independent mock samples in this way and measure their cross-correlation with all galaxies. The shaded blue region in Figure 1 contains 95% (2σ) of the mock realizations. We then simulate arrival direction uncertainties by applying a random 3° Gaussian smearing to all our mock UHECRs and repeating the correlation function measurements. The red shaded region in Figure 1 shows the 95% dispersion for these new measurements. As expected, the 3° smearing drastically reduces the correlation function at small angular scales, but has a negligible effect on scales larger than $\sim 2°$. Figure 1 shows that with a sample of 1000 UHECRs, the measured clustering at large angles ($\geq 4°$) alone can easily distinguish between the "cluster", "galaxy", and "random" hypotheses.

We note that although the sample of 1000 UHECRs is large compared to current available samples, the sample depth in the above illustration is also large ($200h^{-1}$Mpc). The angular clustering will have a higher signal in shallower samples because each angular bin will mix in fewer uncorrelated pairs, so we can get away with smaller UHECR samples in shallower volumes. We will explore the UHECR sample size required as a function of sample depth in our poster.

The Depth of UHECR Samples

In the previous section, our mock UHECR samples were created in the same volume as the potential astrophysical sources we considered (galaxies and clusters). In reality, however, we do not know the distance of a given UHECR source, so comparing the clustering of UHECRs and a given candidate population of sources is not straightforward.

The 2D angular correlation function on a given angular scale includes a mixture of pairs at different physical scales. The deeper a given sample of objects is, the lower its measured angular correlation function because each angular bin includes more physically uncorrelated pairs that dilute the signal. We therefore must know the depth of our UHECR sample in order to interpret the measured angular correlations. For example, if we cross-correlate a sample of UHECRs of unknown depth with a sample of galaxies of depth 100Mpc and measure a low amplitude of $\omega(\theta)$ (i.e., a low bias value), that could mean that the sources of the UHECRs are low mass objects in the galaxy sample volume, or are high mass objects in a deeper volume.

Fortunately, the GZK energy loss phenomenon provides a way to put a limit on the depth of a UHECR sample. The rapid variation with energy of the energy loss (see, e.g., Fig. 1 of [7]) means that an ensemble of UHECRs of a given energy has a rather well-defined horizon within which they are produced. If we assume that the energies of UHECRs are well determined, we can use the GZK effect to solve for the distance distribution of our UHECR sample, given an initial energy spectrum of cosmic rays.

Once we know the distance distribution of a given UHECR sample, we can select a corresponding galaxy sample that spans the same depth, since this will maximize the signal in the cross-correlation function. However, this is not essential. As long as we know the distance distribution of both samples, we can predict what their angular cross-correlation would be given various hypotheses of the astrophysical sources of the UHECRs.

Summary and Discussion

In this paper, we have proposed a method for using the large-scale clustering, or "bias", of UHECRs to constrain the nature of their astrophysical sources. Using the clustering signal at large angular separations enables us to avoid UHECR arrival direction uncertainties due to measurement errors and magnetic deflections. The basic outline of the method is as follows:

1. Select a sample of UHECRs and, using the GZK effect and an assumed initial cosmic ray energy spectrum, estimate the distribution of distances for the sample.

2. Select a sample of galaxies whose redshift distribution matches that of the UHECRs.

3. Compute the UHECR-galaxy angular cross-correlation function.

4. Use the large-angle amplitude of this function to test specific hypotheses about the nature of astrophysical sources of the UHECRs. In particular, constrain their mass scale.

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