UHECR correlations taking account of Galactic magnetic deflections

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Abstract: We predict the arrival direction distribution of cosmic rays as a function of rapidity under different source hypotheses including 1) their sources are hard X-ray AGNs and 2) their sources uniformly sample the matter distribution of galaxies, using the regular component of the Jansson-Farrar 2012 model for the Galactic magnetic field. We report the correlations of published UHECRs, rescaling event energies so as to reconcile the spectra of the different experiments, and allowing for an overall energy uncertainty. Different composition hypotheses are discussed.

Keywords: uhecr, auger, magnetic field

1 Introduction

The predicted arrival directions of Ultrahigh Energy Cosmic Rays (UHECRs) are sensitive to assumptions on the distribution of sources, composition at the source, propagation to our galaxy, and deflection in the magnetic field of the Galaxy. We present a correlation analysis framework that considers each of these in turn, and show the results two models, one in which the sources are smoothly distributed according to the galaxy density, and another in which the sources are a subset of the Swift BAT hard X-Ray AGNs.

2 Source Distribution

We consider two models for the distributions of ultra high energy cosmic rays (UHECRs). One hypothesis is that the cosmic rays are produced by hard X-ray AGNs. To test this we use the Swift-BAT catalog of hard X-ray sources [1], with distances corrected for peculiar motion. We use a volume limited sub-catalog of the Swift-BAT sources. This set of candidate sources is plotted in Fig. 1. The sources are sparse, which makes the catalog very predictive and easy to test. However, if the catalog is incomplete, or if we have guessed wrong about the subset of galaxies that produce cosmic rays, then any correlation study will not find a match.

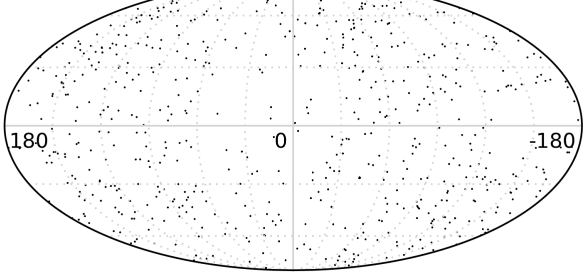

Figure 1: Distribution of extragalactic hard X-ray AGN candidate sources from the Swift-BAT catalog

To test the hypothesis that UHECR are produced by sources that track the overall galaxy density, we consider a second model in which we allow UHECR to be produced proportionally to the density of galaxies. The density field of galaxies is taken from two density maps created from the 2MRS [2, 3]. Each of the two master density maps provide a three dimensional binned density of galaxies in our neighborhood. We closer map, credited to Willick, has a higher resolution, and extends out to 120Mpc/h. Beyond 120Mpc/h we use the Masters catalog, which extends to 200Mpc/h. Beyond 200Mpc/h the density of galaxies is taken to be homogeneous and isotropic. Fig 2 shows the integrated density along the line of site out to 120Mpc/h in galactic coordinates. As with the BAT catalog, there is a trade-off in using this approach. By using a density field rather than point sources the method is insensitive to uncertainties in the location of a specific source, or incompleteness in the catalog. However the difference between the distribution of the density field galaxies and a homogenous distribution is not as great as for the BAT hypothesis.

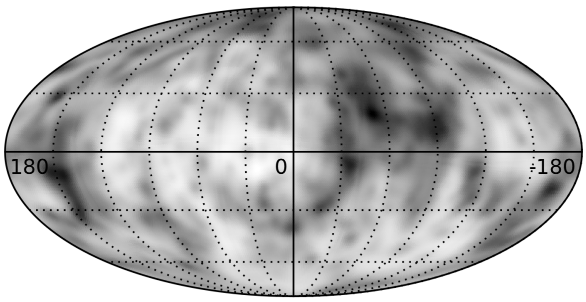

Figure 2: Galaxy density constructed from the Willick density map, integrated along the lines of sight out to 120 Mpc/h

By studying the propagation, deflection and correlation of cosmic rays with respect to these two hypotheses we investigate the merits and drawbacks of each approach.

3 Composition and Propagation

We use CRPropa [4] to model the propagation of cosmic rays from source to earth. We take the injection spectrum of cosmic rays to be proportional to $E^{-2.3}$. We take two models for the composition of the cosmic rays at the source

- either pure proton, or a ratio of charges derived from the galactic ratios of cosmic rays measured by the CREAM experiment [5]. Table 1 gives the relative abundance of each charge at the source.

Element	Relative Abundance
H	5
He	5
C	0.429
N	0.038
O	1
Ne	0.208
Mg	0.448
Si	0.793
Fe	3.844

Table 1: The relative abundance (normalized to oxygen) of galactic cosmic rays measured by the CREAM experiment, hereafter referred to as the CREAM model.

The energy loss of UHECR are highly charge dependent. In Fig. 3 we plot the density of protons (left) and heavy UHECR (Z=20-26, right) that reach our galaxy in the energy range $47.3 < E(EeV) < 53.1$. The color scale of each plot is locally normalized. The summed flux for the heavy CRs in this energy band is approximately a quarter of the flux of the protons. There are smaller scale structures in the proton sky map than the heavy cosmic ray sky map. Proton cosmic rays have a longer path length than heavier cosmic rays in this energy range, and so can originate from more distant structures.

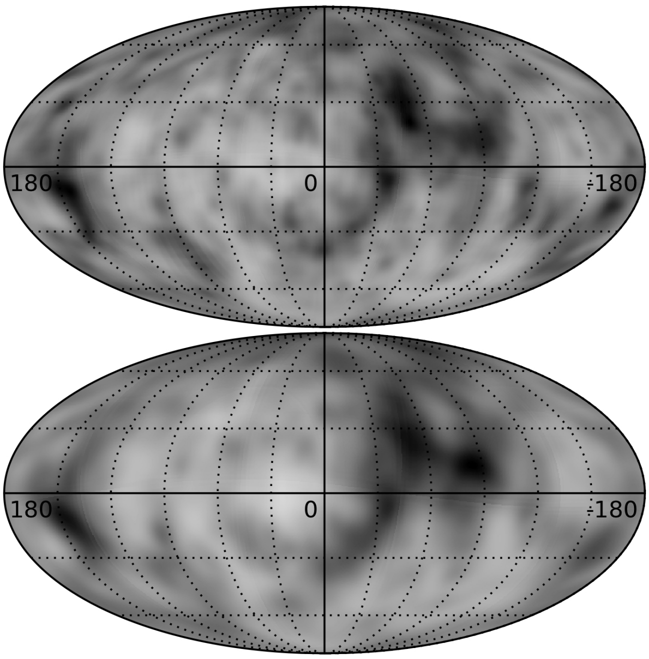

Figure 3: The distribution of undeflected cosmic rays with $Z = 1$ (top) and $Z = 20-26$ (bottom) that reach the galaxy with energy in the range $47.3 < E(EeV) < 53.1$ from a CREAM model of the particle injection at the source.

We create the local spectrum of cosmic rays by propagating 100,000 cosmic rays at 2.5Mpc steps. For each pixel in resolution 9 Healpix sky map we sum the spectrum along all distance steps weighted by the galactic density map. For the BAT model, we propagate cosmic rays from each source.

4 Galactic Deflections

We model the deflections of the cosmic rays using the Jansson-Farrar model for the regular component of the galactic magnetic field [6]. The forward tracking is calculated by backtracking a resolution 11 Healpix grid of cosmic rays at evenly spaced steps in $\log_{10} E$. The backtracking map is converted to a forward tracking map using Liouville's theorem, guaranteeing that an isotropic distributions of cosmic rays incident on the galaxy will result in a locally isotropic distribution of cosmic rays at earth.

Each energy step and charge of cosmic rays is forward tracked separately. Fig 4 shows the forward tracked all-sky maps for proton cosmic rays (left) and heavy cosmic rays (Z=20-26, right) in the energy band $47.3 < E(EeV) < 53.1$. As before the maps are locally normalized and the relative normalization between the proton and heavy UHECR map is around 4:1. At these energies, the proton deflections are of order ten degrees, and the overall structure is retained. The heavy cosmic rays have much lower rigidity, and the deflections are large. The structure of the magnetic field distorts the sky map, resulting in distinct structures. This is in disagreement with the received wisdom that iron UHECR would be effectively isotropic.

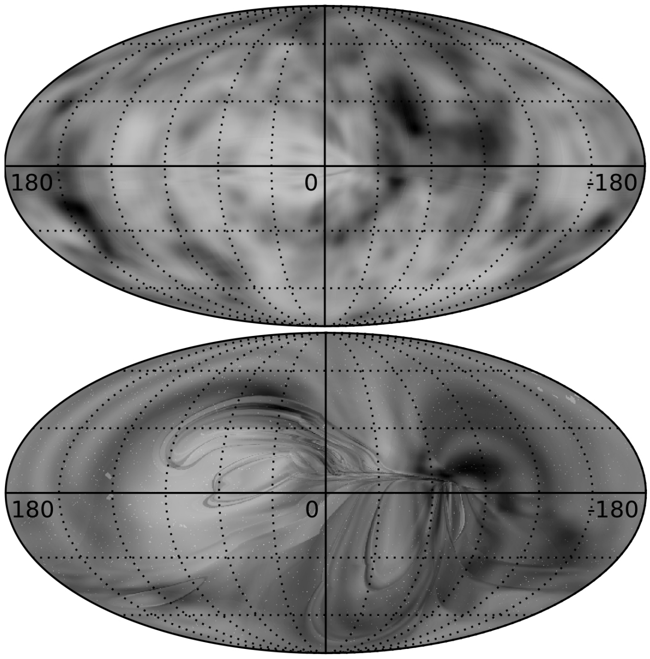

Figure 4: The distribution of cosmic rays as in Fig. 3, after deflections in the galactic magnetic field.

The BAT source hypothesis shows a similar story. In Fig. 5 we plot the distribution of proton and heavy UHECR in the energy range $47.3 < E(EeV) < 53.1$. Here the cosmic ray arrival directions have been smeared by a 2D Gaussian in which 68% of the distribution is within 1 degree of the center. This makes the individual sources easier to plot, and models a 1 degree uncertainty in the measurement of the arrival direction. The distribution of proton UHECR follows the BAT sources relatively closely - it's easy to make out the super-galactic plane for example. The distribution of deflected heavy UHECR are more widely spread, but are far from isotropic.

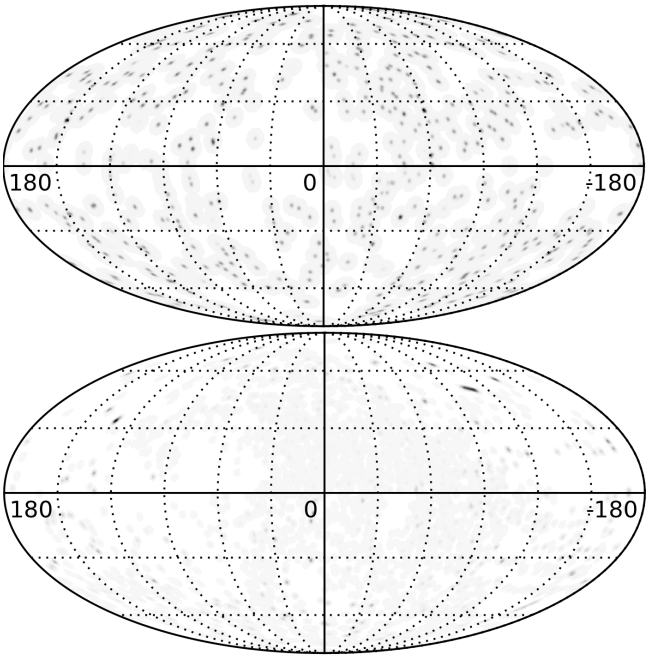

Figure 5: Distribution of protons (top) and heavy ($Z = 20-26$) cosmic rays (bottom) from the BAT distribution of sources after deflection in the galactic magnetic field, in the energy range $47.3 < E(EeV) < 53.1$.

We construct maps in the same manner for each energy step, for each charge of cosmic ray, and for each source hypothesis.

5 Correlations

We take the published events from the Auger [7], Telescope Array [8], HiRes [9] and AGASA [10] collaborations, with energies corrected according to the recommendation of the Spectrum Working Group [11]. We take the energy uncertainty to be 12% and model it as a Gaussian uncertainty in $\ln E$. We take the angular uncertainty to be 1 degree, modeled as a 2D Gaussian.

$$q(E_0, E_k) = \frac{1}{\lambda\sqrt{2\pi}} \exp\left(-\frac{(\varepsilon_k - \varepsilon_0)^2}{2\lambda^2}\right), \quad (1)$$

where $\varepsilon = \ln(E)$ and λ is the energy uncertainty.

For each cosmic ray we define the quantity:

$$\overline{p}(E_0, \mathbf{r}_0) = \int \sum_k P(E, \mathbf{r}) q(E_0, E_k) Q(\mathbf{r}_0, \mathbf{r}) d^2\mathbf{r}, \quad (2)$$

where k indicates the energy bins in $\log E$, $\mathbf{r}_0$ is the direction of the cosmic ray, $Q(\mathbf{r}_0, \mathbf{r})$ is a 2D Gaussian that models the measurement uncertainty in the direction of the cosmic ray, E_0 is the energy of the cosmic ray, $q(E0, E_k)$ is a Gaussian in $\ln E$, quantifying the energy uncertainty, $P(E, \mathbf{r})$ is a set of values from the deflected sky maps in energy steps in $\ln E$ that correspond to the likelihood of seeing a cosmic ray of a given energy in a portion of the sky after forward tracking through the GMF. This also include the Auger exposure.

For each cosmic ray we compare measures of $\overline{P}(E_0, \mathbf{r}_0)$ for different hypotheses, such as the probability that the cosmic ray originated from a set of sources with pure proton injection spectra, p_{proton}, versus an isotropic distribution of cosmic rays, p_{iso}. The ratio of the likelihoods provides a measure of the likelihood of each hypothesis for each cosmic ray.

We define the likelihood measure for the ensemble of cosmic rays to be:

$$LM = \sum_i w p_{proton} + (1 - w) p_{iso}. \quad (3)$$

The source fraction w is calculated by maximizing the likelihood measure LM.

5.1 Proton vs Isotropic

Fig. 6 shows the ratio p_{proton}/p_{iso} for each cosmic ray in the combined data set. The majority of values are close to zero, due to the sparseness of the set of BAT hard X-ray sources used. Maximising the likelihood function gives a value for the source fraction of 2.5%.

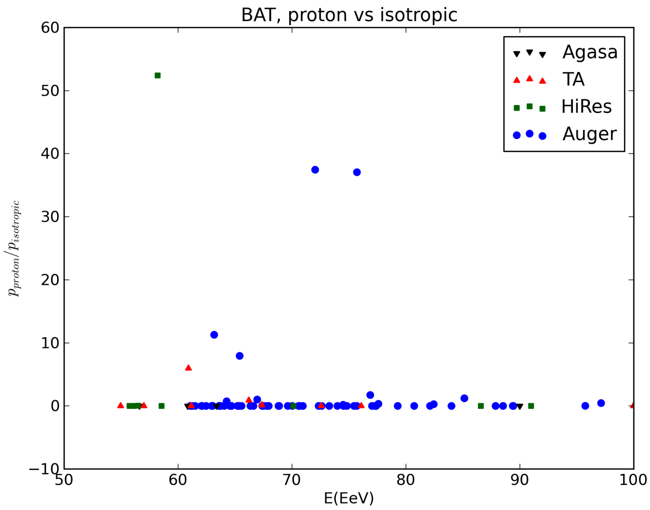

Figure 6: The relative value of p_{iso} and p_{proton} for each cosmic ray in the sample, assuming sources are BAT hard X-Rays. Maximising the likelihood gives a proton source fraction of 2.5%

Fig. 7 shows the relative values for p_{proton}/p_{iso} for the 2MRS density distribution of galaxies. There is a smooth continuum of values between events that are more likely to be proton ($p_{proton}/p_{iso} > 1$ and those that are better described by an isotropic distribution ($p_{proton}/p_{iso} < 1$). Maximising the likelihood for the set gives a proton fraction of 30%.

6 Conclusions and future work

We present a calculation of correlations of UHECRs, taking into account different source, spectrum and composition hypotheses, and accounting for deflections in the galactic magnetic field. The simplest case has been completed, considering only the regular component of the galactic magnetic field, ignoring extra-galactic deflections and taking either a pure proton spectrum or a mixed composition with relative abundances according to the CREAM measurement of the abundance of relativistic Galactic cosmic rays, with

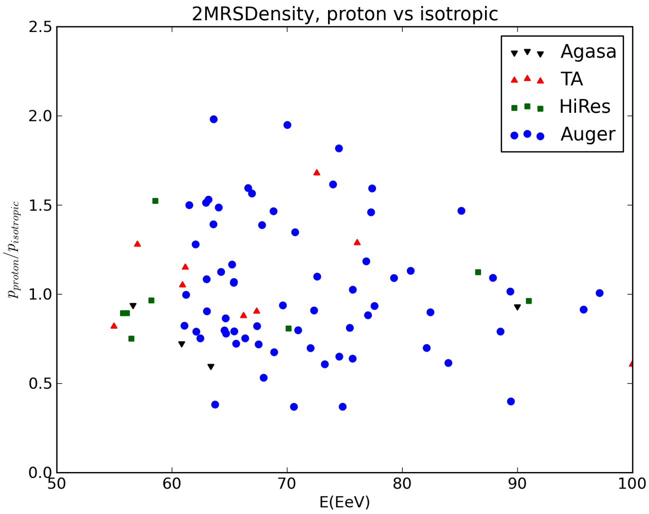

Figure 7: The relative value of p_{iso} and p_{proton} for each cosmic ray in the sample, assuming a 2MRS density distribution of sources. Maximising the likelihood gives a proton fraction of 30%.

an spectrum at the source proportional to $E^{-2.3}$, and no maximum rigidity cut-off. A future work will extend each of these areas, considering different spectra, composition, extra-galactic deflections, and the effect of a random component of the Galactic magnetic field on the predicted UHECR sky.

Acknowledgment: The work of GF, RJ and JR was supported by the grants NASA NNX10AC96G, NSF PHY-1212538, NSF PHY-0900631 and NSF PHY-0970075

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