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On Using Skymaps to Find the Origins of Ultra High Energy Cosmic Rays

Abstract

Skymaps are used to visually show correlations between BL Lac objects and Ultra High Energy Cosmic Ray (UHECR) events detected by the AGASA, HiRes, and Pierre-Auger experiments. We also qualitatively discuss the Aitoff-Hammer projection used to create the skymap.

Introduction to Cosmic Rays and Ultra High Energy Cosmic Rays

Cosmic Rays are particles moving through space that intercept the earth. A cosmic ray can hypothetically be any particle or nuclei, though this paper will assume it to be a proton.

Cosmic Rays are abundant. For example at the surface of the earth, muons have a flux of about one per square centimeter per second, with energies between 10^8 eV and 10^{15} eV. But as we climb to higher energies, the flux of cosmic rays attenuates dramatically to less than one per square kilometer per century. Despite this small flux, these Ultra High Energy Cosmic Rays (or UHECRs), are of considerable interest.

Particles with ultra high energies on the order of 10^{20} eV are interesting for several reasons. First, unlike the paths of regular cosmic rays, UHECR trajectories are nearly straight. In our current models, we assume that cosmic rays are usually charged and often protons [12]. If most cosmic rays are indeed charged, then the path of that charged particle can be altered by intergalactic magnetic fields. Since the magnitude of these magnetic fields is for the most part unknown, the degree to which the cosmic ray is deflected from its original path cannot be determined reasonably for regular cosmic rays. So while the right ascension and declination coordinates of ordinary cosmic rays are easy to trace with detectors, the coordinates of their origins remain unknown. Therefore, we cannot uncover the source object in the sky that accelerated them towards earth. Moreover, their flux is isotropic across the sky, so ordinary cosmic rays do not appear to all originate from one source.

However, UHECRs have profoundly greater energies than ordinary cosmic rays, by several orders of magnitude. So when they pass through intergalactic magnetic fields, the consequent deviation from their original paths is minimal [12]. Hence, the point in the sky where the cosmic ray is detected may theoretically point to its origin, possibly some radio source. So correlating that point with celestial objects nearby can reveal the source object of the UHECR. This is the crux of UHECR experiments today.

Finding autocorrelations between UHECRs can be useful. If many UHECRs have similar positions in the sky, they may all point back to a common origin nearby. Unfortunately, the flux of UHECRs is largely isotropic, and any "clusters" found so far have only two to three events. Looking for anisotropies in UHECR flux is still an area of ongoing research, but if any such substantial "clusters" are found, they will be small compared to the overall flux of UHECRs across the earth,

So far, no large UHECR anisotropies have been found to align with the galactic center [12]. Because the trajectory of a UHECR is hardly deflected in intergalactic space, one may conjecture that UHECRs originate from outside of our galaxy. If the extragalactic origins are radio-loud sources such as quasars and BL Lac objects, studying UHECRs can potentially bear information on the behavior of these objects.

UHECRs can also give insight into high energy physics. Because their energies are on the order of 10^{19} to 10^{20} eV, millions of times greater than the energies attained by manmade accelerators, to examine UHECRs is currently the only way to study very high energy physics at these energies. Specifically, UHECRs can give insight into the validity of the GZK cutoff theory, a prediction that essentially no cosmic rays over 6 times 10^{19} eV can be detected on earth.

The theory behind the GZK cutoff involves the cosmic microwave background, or CMB. When a cosmic ray particle travels very fast with an energy of 6 times 10^{19} eV and above, the CMB blueshifts into a gamma ray with respect to the particle. So should it collide with a photon of the CMB, the incident cosmic ray would loose up to 20% of its energy, and it no longer has "ultra high energy." The mean-free-path of a UHECR in the CMB background is about 50 Mpc relative to earth, or 1% of the horizon of the universe. And on average, a particle with an energy above the GZK cutoff will collide with a blueshifted CMB photon once every 20 million years. Since they appear to have extragalactic origins, UHECRs must travel hundreds of millions of light years in order to reach earth. Hence, because of their relatively short mean-free-path they must suffer a collision before reaching our detectors, loosing their "ultra high energy." Therefore, we should not detect any UHECRs of extragalactic origins on earth, according to the GZK cutoff theory.

However, cosmic rays with energies above the GZK cutoff have observed [13]. This incongruence between theory and experiment can be resolved in many ways, but perhaps the most interesting solution is the possibility that Lorentz invariance is violated at these ultra high energies.

So if the incoming positions of UHECRs in the sky correlate with BL Lac, a contradiction between experiment and the GZK cutoff theory will be confirmed, and physics at ultra high energies will perhaps need to be reexamined.

Detecting UHECRs

When a UHECR enters the earth's atmosphere, it can be detected in one of two ways. First, one can detect its fluorescence. When a UHECR passes nearby an atom, usually nitrogen, in the atmosphere, it transfers energy to the atom via a weak and brief electromagnetic interaction with the electrons in the atom. While the atom does not necessarily ionize, its electrons become excited, and then as they return to their ground states, the atom releases photons. This is called fluorescence, and the number of photons emitted via fluorescence indicates the energy of the incoming UHECRs. Detecting fluorescence in the atmosphere is one method of identifying UHECRs, but it can only be done on nights with no moon. The HiRes experiment tracks UHECR events via fluorescence detection.

Tracing particle showers from UHECRs with ground detectors is the second method of detection, and it works as follows. When an incoming UHECR traverses the earth's atmosphere it collides with other particles, producing an abundance of charged and uncharged pions along with other particles. The charged pions then decay into muons and neutrinos on the outside of the particle "shower," and fall to earth hundreds of meters from the axis of the shower. The actual energy of the source cosmic ray depends on the density of the particle shower. On the inside of the shower, an electromagnetic "cascade" begins. The pions without charge decay into gamma rays which in turn produce electron positron pairs. The electrons in turn then emit gamma rays via Breemsstrahlung radiation which produce additional electron positron pairs. These particles release Breemsstrahlung radiation also, producing another generation of electron and positron pairs, and the process continues. As the number of electrons and positrons increases in the middle of the shower, the average energy of all of the particles reduces until about 80 MeV. At this point, the critical energy of this sequence is attained, and no additional photons, electrons, or positrons are produced. The AGASA experiment detects UHECRs via ground detection.

The Pierre-Auger experiment uses both ground and fluorescence detection. In the experiment, the particle shower generated by an incoming cosmic ray is tracked with water tank detectors. These detectors work in the following way: when the particle from the shower enters the tank at nearly the speed of light, it emits Cherenkov radiation in the water. Photomultiplier tubes inside the tank detect this radiation and then determine the energy of the particle intercepting the tank. The tanks are spaced about 1.5 kilometers apart. Since the particle shower hits many tanks, the cumulative detection signal from all of the tanks allows physicists to reconstruct and analyze the particle shower and its source UHECR. Auger also uses fluorescence detection, but currently, this and at least two thirds of the full scale tank array are still under construction.

Presenting UHECR events: Skymaps

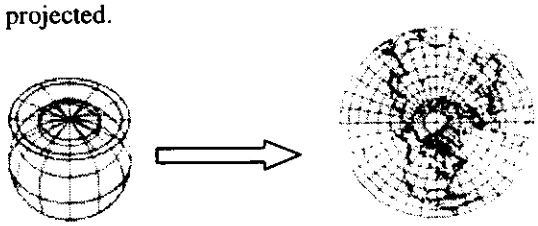
In order to uncover their origins, the positions of UHECRs in the sky need to be correlated with potential source objects, and then the smallest of these correlations can be visually demonstrated on a skymap. The presentation of these correlations on a skymap is ideal for these reasons: it compacts the entire celestial sky on a 2:1 ellipse, correlations are made easy to see, and the plots can be generated in either elliptical or galactic coordinates, allowing one to see different attributes of the sky, such as the celestial equator (in equatorial coordinates), or the galactic plane (in galactic coordinates).

Drawing Skymaps

Data from the HiRes, AGASA, Pierre-Auger experiment and the BL Lac catalogues were plotted on skymaps. Also, in order to discover if BL Lac are a source of UHECRs, angular correlations between BL Lac and UHECR events as well as autocorrelations on UHECR events were also plotted on skymaps.

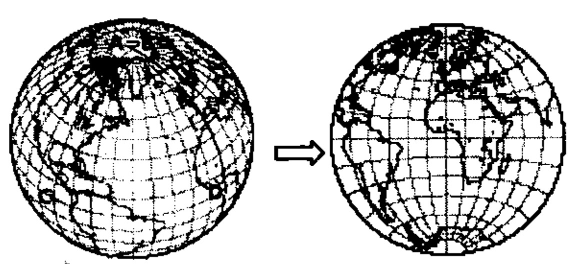
To generate these skymap plots, the right ascension and declination coordinates of events and BL Lac objects were projected onto a map of the sky in either equatorial or galactic coordinates using an Aitoff-Hammer projection. The Aitoff-Hammer projection has attributes which make it appropriate for mapping the celestial sphere onto a plane. Foremost, it is a modification on Lambert's azimuthal equal-area projection.

Lambert's projection is an azimuthal projection, meaning that it is generated on a plane tangent to one of the poles of the sphere to be projected.

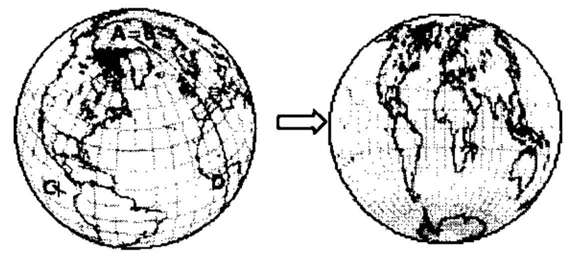


If the point of tangency between the sphere and the plane is taken to be the center of the projection, then Lambert's and all other azimuthal projections have these two properties always: areas are preserved and directions are preserved from the center point. Additionally, Lambert's projection exhibits minimal shearing and scaling compromises far from the center, but it also has a major limitation.

In its stock formulation, Lambert's projection only shows one hemisphere of a globe, making it impractical for mapping the whole celestial sphere. So we employ a modification of that projection, the Aitoff-Hammer projection instead. In the Aitoff-Hammer projection, the longitudinal values resulting from Lambert's projection are doubled, which allows both hemispheres of a globe to be mapped into a single hemisphere. So instead of mapping

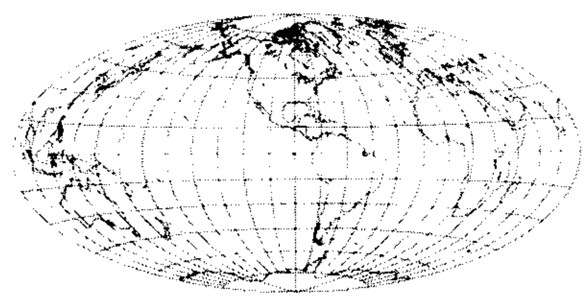


we fit the whole globe into one hemisphere thus:



The single hemisphere is then scaled horizontally outward to an ellipse whose axes make a ratio of 2:1.

All in all, the image of a globe under an Aitoff-Hammer projection looks like this:



The Aitoff-Hammer projection also has both equatorial and oblique aspects, meaning that the center point lies on the equator and the axis of the map projection is not perpendicular to the axis of the globe. As for its graticule, the center meridian contains the minor axis of the ellipse and the equator contains the major axis. The meridian lines are unequally spaced curves concave towards the center meridian, and the parallels are also unequally spaced curves, but concave towards the poles. This bends points at the edge of the map up, giving it a "wrap around" effect.

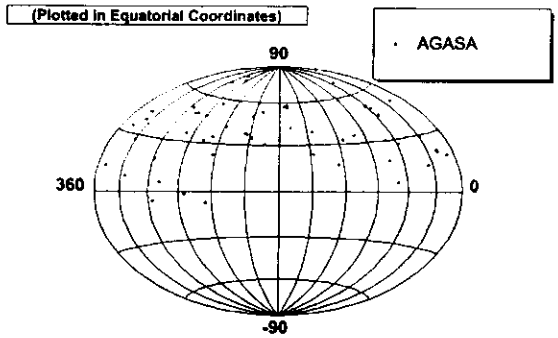
The projection is governed by these transformation equations:

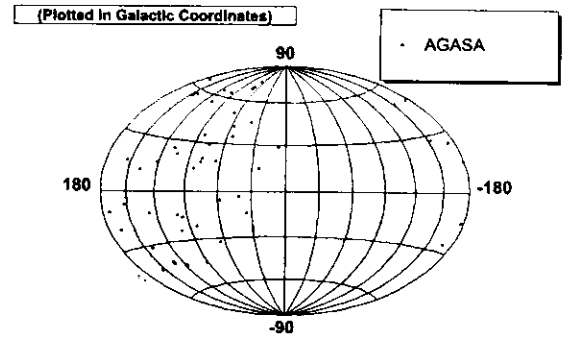
$$x = \frac{2R\sqrt{2}\cos\varphi\sin\frac{\lambda}{2}}{\sqrt{1+\cos\varphi\cos\frac{\lambda}{2}}};\; y = \frac{R\sqrt{2}\sin\varphi}{\sqrt{1+\cos\varphi\cos\frac{\lambda}{2}}}$$

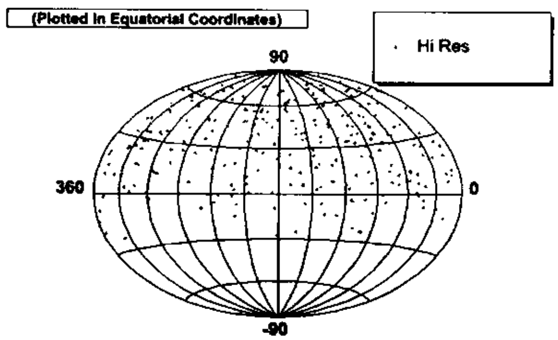
Here, phi is right ascension and lambda is declination. R is the minor radius of the ellipse. In the skymaps presented in this paper, R=90. For more information on maps, visit http://www.progonos.com/furuti/MapProj/CartIndex/cartIndex.html or http://www.3dsoftware.com/Cartography/USGS/MapProjections/

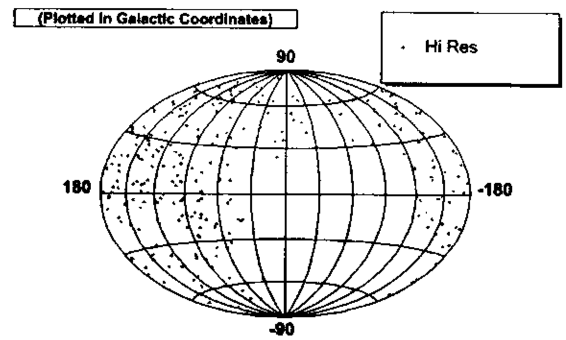
Skymaps

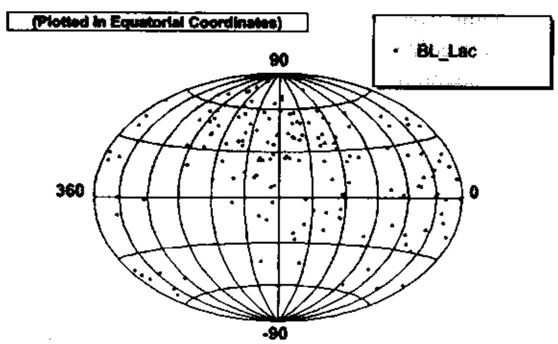
The following catalogues were plotted on skymaps: the BL Lac (2001) catalogue [9], and UHECR events from the AGASA, HiRes, and Pierre-Auger experiments, all in both equatorial and galactic coordinates.

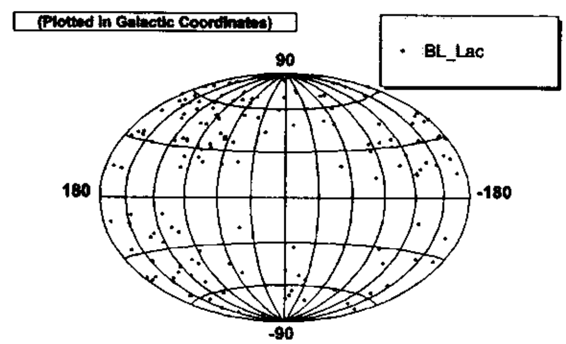


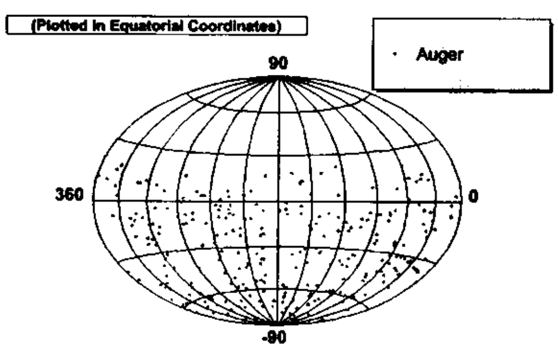


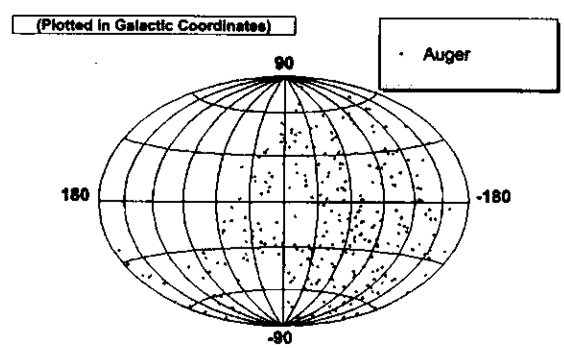










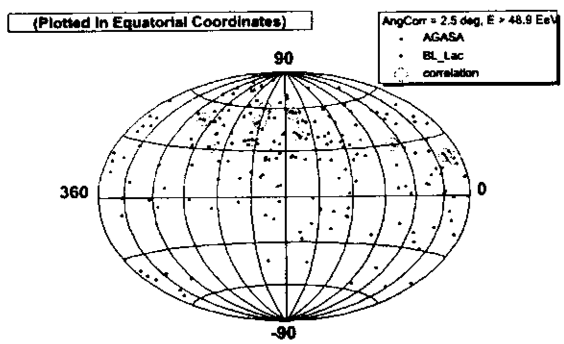


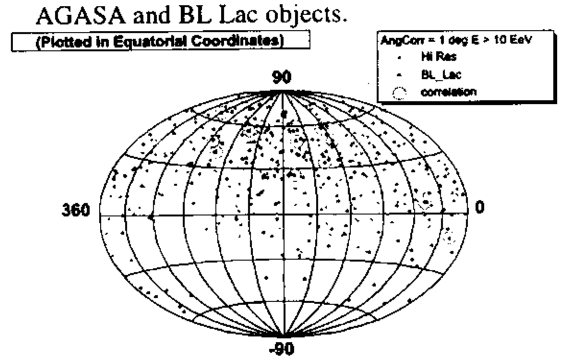
The published HiRes catalog [8] only includes events over 10^{19} eV, and the AGASA catalog [11] only includes events over 4 times 10^{19} eV. Also, the Auger catalog only shows events over 10^{19} eV with a zenith angle below 60 degrees.

Notice that in the in the HiRes and the AGASA equatorial plots, UHECR events are distributed across only the northern celestial hemisphere. Since the AGASA experiment and the HiRes experiment are both located in the northern hemisphere on earth, both experiments can only see UHECR events from that region of space. The rotation of the earth allows each experiment to see the entire hemisphere. Similarly, the Auger experiment, located in Argentina, can only see UHECR events in the southern celestial hemisphere.

In the galactic plots, the distribution of UHECR events is isotropic rather than dense around the galactic center, suggesting that UHECRs are not coming from our galaxy. If true, then the origins of UHECRs are potentially extragalactic.

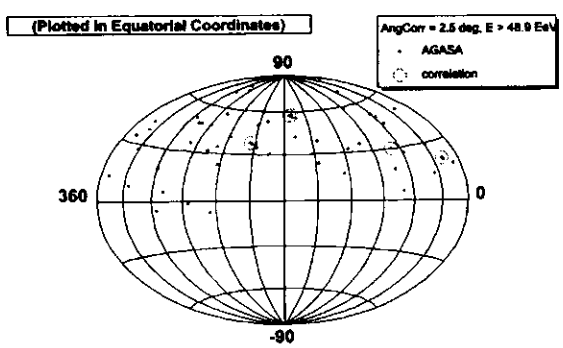
The following are correlation plots between events of HiRes and BL Lac objects and AGASA and BL Lac objects.

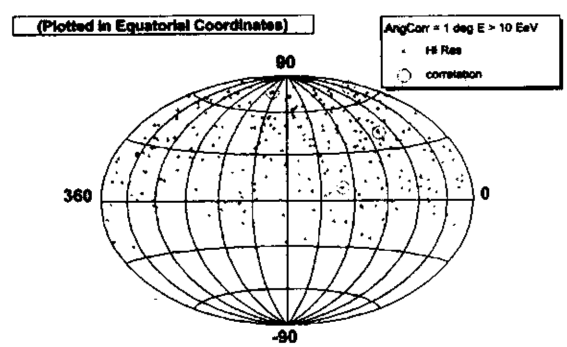




In these correlation plots, we see ten correlations between AGASA data and the BL Lac catalogue and twelve correlations between HiRes data and the BL Lac catalogue. For AGASA, an angular separation of 2.5 degrees or less determined a correlation, and for HiRes, an angular separation of 1 degree or less determined a correlation [10]. From these plots, one could conjecture that some BL Lac may be the source of UHECR events.

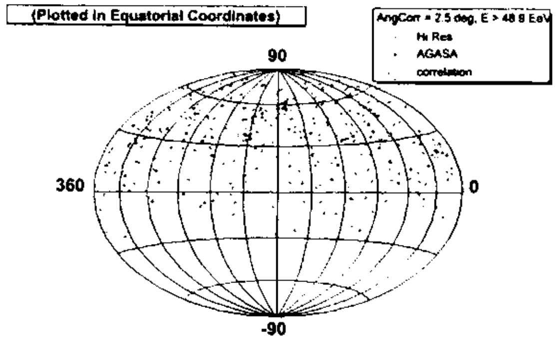
The following are autocorrelations on events detected by the HiRes and AGASA experiments using the same angular separation cuts.





In the autocorrelations plots, AGASA had three doubles and one triple. Moreover, HiRes had four doubles. These small clusters may suggest anisotropies in the distribution of UHECR events across the celestial globe.

Lastly, a correlation between the data from the AGASA and the HiRes was plotted to find any correlations between UHECR events from either experiment. Such correlations could point to potential anisotropies



The most striking correlation between the two experiments is near the center meridian (180 degrees right ascension) where five points are collectively all separated by less than 2.5 degrees. This strong correlation again could suggest a small anisotropy in the distribution of UHECR events.

Conclusions

UHECR events, though rare, can give new insight into high energy physics. To find their origins, we look for correlations between UHECR events and objects such as BL Lac in the sky.

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