Prospects for Charge Particle Astronomy above 57×10^{18} eV

Patrick Younk*

Colorado State University, Fort Collins, Colorado 80523, United States

***Abstract*. Results from the Pierre Auger Observatory suggest that a direct measurement of a ultra-high energy cosmic ray source may soon be possible. The near-term prospects for such a measurement largely depend on the expected flux of the brightest source relative to the total flux. This quantity is termed $\bar{Q}$. In this paper, we summarize a recently published result pertaining to the value of $\bar{Q}$. We discuss the implications of the result.**

***Keywords*: Charge particle astronomy**

I. Introduction

Charge particle astronomy is the measurement of source objects with cosmic ray (CR) messenger particles. This observational science has not yet been realized, however the discovery of anisotropic cosmic rays above 57×10^{18} eV [1], [2] by the Pierre Auger Observatory [3] indicates that a source detection may occur in the near future.

A prerequisite for charge particle astronomy is that the particles are not confined (or shielded) by the Galactic magnetic field. At the highest energies, it is expected that this condition is met. If this is true, the near-term prospects for charge particle astronomy largely depend on the flux of the brightest source relative the total flux. For example, the Pierre Auger Observatory detects approximately 23 CR above 57×10^{18} eV per year [1]. If the brightest source contributes 10% of the flux, the Pierre Auger Observatory will detect 23 events from this source in a decade. If, on the other hand, the flux of the brightest source is far below 1%, the Pierre Auger Observatory may not detect more than one CR from this source during its 20-year operational lifetime.

In this paper, we summarize the result pertaining to the flux of the brightest source that was first described in Ref. [4]. We discuss the implications of the result.

II. Calculating the Relative Flux of the Brightest CR Source

We denote the flux of the brightest CR source relative the total flux as $\bar{Q}$. To calculate $\bar{Q}$, two general conditions were postulated. The first condition was that the source objects are associated with galaxies, but the sources are relatively rare or rarely active such that many galaxies, such as our own and our closest neighbors, do not contain a luminous source. This implies a source number density $dN/dV < 10^{-2}$ Mpc^{-3}. The second condition was that the CR particles are protons or heavy nuclei such as iron and the Greisen-Zatsepin-Kuzmin (GZK) energy loss processes [5], [9] are occurring. Above 10^{20} eV, the energy loss length for protons and iron is tens of Mpc. This effectively limits the propagation distance of the highest energy CR to 100 Mpc, which implies a source number density $dN/dV > 10^{-6}$ Mpc^{-3}. These two conditions are consistent with a large number of leading source scenarios.

$\bar{Q}$ was calculated by averaging the results of many Monte Carlo realizations. A single Monte Carlo realization was formed as follows. N sources were each assigned a random sky position, a distance r, and a luminosity L. The sky positions were chosen to follow a flat distribution (each sky position has equal probability of containing a source). To take into account the local over-abundance of galaxies (potential sources), the source distances were chosen to follow a radial density function

$$dN/dr = \begin{cases} 30Nr/D^3 & : r \leq 10 \text{ Mpc} \\ 3Nr^2/D^3 & : r > 10 \text{ Mpc}. \end{cases} \quad (1)$$

out to a maximum distance of 350 Mpc. (Beyond 250 Mpc, the flux from a source is greatly diminished by the GZK effect. Therefore, the results are insensitive to the upper limit on r as long as the limit is greater than 250 Mpc.) For the distribution of luminosities, two scenarios were considered. The first scenario was that the luminosities are distributed as a power-law $dN/dL \propto L^{-2}$ with L ranging over 3 orders of magnitude. The second scenario was that the luminosities are all equal.

The flux in the energy range $E > 57 \times 10^{18}$ eV from each source was computed as

$$q = \omega A L r^{-2}$$

with ω being the relative sky exposure of the observatory and A being the GZK attenuation factor [6]. The ω function developed in Ref. [7] was used with a detector at latitude $-35°$ (the location of the Southern site of the Auger Observatory) and a maximum zenith angle acceptance of 60° (a standard quality cut implemented by the Pierre Auger Collaboration). The relative flux of the brightest source was computed as $Q = \max\{q_1, \ldots, q_N\}/\text{sum}\{q_1, \ldots, q_N\}$. $\bar{Q}$ was calculated by averaging over 1000 realizations. This was repeated for several different source densities.

The results of this analysis are shown in Fig. 1. The error bars represent the 10-90% quantiles of each set of realizations. At a source density of 10^{-6} Mpc^{-3}, the expected value of $\bar{Q}$ for the first scenario is 40% and the 10-90% quantile range is 19% to 70%. At a source density of 10^{-2} Mpc^{-3}, the expected value of $\bar{Q}$ for

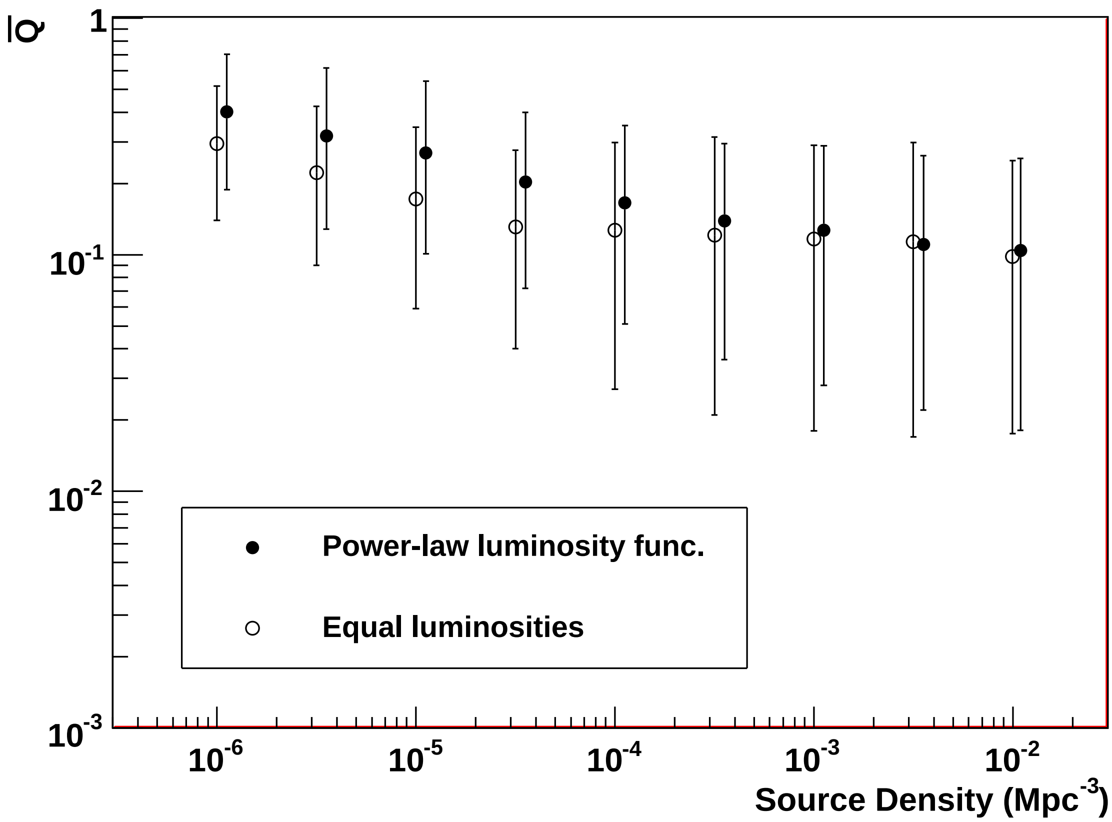

Fig. 1: The expected flux, relative to the total flux, of the brightest cosmic ray source above 57×10^{18} eV as a function of source number density. The points are slightly offset on the x-axis for clarity.

the first scenario is 10% and the 10-90% quantile range is 1.8% to 26%.

At source densities greater than 10^{-4} Mpc^{-3}, the results flatten (i.e., $\bar{Q}$ is nearly independent of source density). This is the source density above which the closest sources are expected to be within 10 Mpc and the linear region of Eq. 1 to be important.

The relatively weak dependence of $\bar{Q}$ on source density is caused by two effects which somewhat balance each other. The first is that a greater number of sources will tend to diminish the relative flux of the brightest source by increasing the background. The second is that a greater number of sources will tend to increase the flux of the brightest source since there is a greater probability of a source being relatively close or luminous or both. For the special case $dN/dr \propto r$, the tendencies exactly balance such that $\bar{Q}$ is independent of source density.

III. Discussion

We expect that the flux at earth from any particular extragalactic CR source is nearly constant over a time span of several years. Even if the particles are accelerated in a rather short burst, the CR pulse is broadened in time because of magnetic deflections, with the highest energy particles arriving first. It has been shown in Ref. [8] that a time broadening of 100 years or more for a 100 Mpc distant source is a reasonable expectation based on our present knowledge of extragalactic magnetic fields.

If we assume the flux from the brightest source is steady and $\bar{Q}$ is 10%, then we expect the Pierre Auger Observatory to acquire 2.3 events from this source per year. The angular size of the source is dependent on the magnetic rigidity of the particle and the intervening magnetic fields, both of which are not well constrained. However, even if the source covers a $20^\circ \times 20^\circ$ area (approximately 1% of the sky observed by the Pierre Auger Observatory), the number of events from this region will be ten times the expected amount from an isotropic background. In this respect, a source detection is expected to occur in a matter of years.

A source detection will cause the field of ultra-high energy cosmic rays to development rapidly on several fronts. If the CR source is unambiguously correlated with a known astronomical object, we will learn about the acceleration mechanism through direct measurement. Measurements of the angular size and morphology of the source will give us information on the intervening magnetic fields and the particle charge. Indeed, it may be possible to set firm limits on the particle charge based on the angular size of the source and from current limits on the galactic magnetic field. If this is the case, observations of air shower development may produce important measurements pertaining to particle physics and the fundamental nature of matter.

The author thanks his fellow Pierre Auger collaborators, and acknowledges the support of the National Science Foundation (award number PHY-0838088) and the Michigan Space Grant Consortium. Figure 1 and portions of the text are copyrighted by the American Astronomical Society.

REFERENCES

[1] Pierre Auger Collaboration [J. Abraham, et al.] 2007, Science, 318, 939
[2] Pierre Auger Collaboration [J. Abraham, et al.] 2008, Astropart. Phys., 29, 188
[3] Pierre Auger Collaboration [J. Abraham, et al.] 2004, Nucl. Instrum. Methods, A523, 50
[4] P. W. Younk, Astrophys. J. Lett., 696, L40
[5] K. Greisen, Phys. Rev. Lett., 16, 748
[6] D. Harari, S. Mollerach, & E. Roulet, J. Cosmol. and Astropart. Phys., 11(2006), 012
[7] P. Sommers, Astropart.Phys., 14, 271
[8] E. Waxman, Phys. Rev. Lett., 75, 386
[9] Z. T. Zatsepin & V. A. Kuzmin, Zh. Eksp. Teor. Fiz. Pis'ma Red., 4, 144