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UHECR Anisotropy and the Galactic Halo

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Abstract

Several explanations for the existence of Ultra High Energy Cosmic Rays (UHECR) invoke the idea that they originate from the decay of massive particles created in the reheating following inflation. It has been suggested that the decay products can explain the observed isotropic flux of UHECR. We have calculated the anisotropy expected for various models of the dark matter distribution and find that present data are too sparse above 4×10^{19} eV to discriminate between different models. However, after three years of operation of the southern part of the Pierre Auger Observatory great progress in testing the proposals is expected.

1 Introduction:

Recently the AGASA group (Takeda et al. 1999) have released details of 581 events above 10^{19} eV recorded by them. Of these 47 are above 4×10^{19} eV and 7 are above 10^{20} eV. There is no evidence within this consistent data set to support an anisotropy associated with the Super Galactic Plane, or any other large scale structure. Indeed, so far, evidence for departures from isotropy have proved elusive.

At 4×10^{19} eV about 50% of the events are expected to come from within 130 Mpc while at 10^{20} eV the 50% distance is only 19 Mpc (Hillas, 1998b). The isotropy of these events which must originate so close to our galaxy has prompted a number of authors to propose that the particles may come from the decay of super-heavy relic particles gravitationally bound within the galactic halo. Such super-heavy relics are postulated as having been created in the re-heating which may follow early Universe inflation (e.g., Berezinsky, Kachelriess and Vilenkin,1997; Birkel and Sarkar, 1998).

The question of super-heavy relics residing in the galactic halo and providing a small fraction of the cold dark matter has attracted recent attention -- Hillas 1998a, Dubovsky and Tinyakov 1998, Berezinsky and Mikhailov 1998 and Benson, Smialkowski and Wolfendale 1998. In the latter two papers estimates of the anisotropy expected have been made and Benson et al. have compared their predictions with observation. The present paper extends these analyses and presents the results of the calculation in a way which demonstrates acutely the need to have improved measurements of the UHECR from both the Northern and the Southern Hemispheres to help resolve the issue of a halo contribution to the UHECR.

2 Numerical method and physical model:

We will limit the analysis to the anisotropy observed at Earth due to the possible origin of UHECR from the decay of primaries resident in the galactic halo. While we have been motivated by the idea of the decay of super-heavy relic particles our results are of relevance to any type of source of UHECR distributed throughout the galactic halo. Furthermore, only rectilinear propagation will be considered and so, unless the UHECR are neutral, the results should only be applied to the highest energy particles.

The emissivity of UHECR per unit volume is proportional to the number density of potential sources in the halo, $n_{SHR}(\mathbf{r})$ which, in turn, we will assume to be proportional to the dark matter density inside the galactic halo, $n_H(\boldsymbol{r})$ where $\boldsymbol{r}$ is the position vector in a galactocentric reference system. Therefore, the incoming flux of UHECR from a solid angle $\delta\Omega(\boldsymbol{r}')$, around the direction $\boldsymbol{r}'$, defined in a geocentric coordinate system is $\delta\Phi \propto \int_{V_{\delta\Omega}} \frac{n_H[\underline{r}(\underline{r}')]}{\underline{r}'^2} dV = \int_0^{n_H(\underline{r}')} n_H[\underline{r}(\underline{r}')]\delta\Omega d\underline{r}'$, where $V_{\delta\Omega}$ is the volume of the cone of solid angle $\delta\Omega$, r_H is the external radius of the halo and $\boldsymbol{r}(\boldsymbol{r}')$\$ is the coordinate of the volume element dV in the reference system with origin on the galactic center. Thus, the incoming UHECR flux per unit solid angle from the direction $\boldsymbol{r}'$ is $\frac{\delta\Phi}{\delta\Omega} \propto \int_0^{n_H(\underline{r}')} n_H(\underline{R}_{sun} + \underline{r}')\delta\Omega d\underline{r}'$, where $\boldsymbol{R}_{\rm sun}$ is the position of the Sun in the galactocentric reference system. To ensure that each direction on the celestial sphere has an equal weight and that the symmetry of the problem is preserved in the calculation of the anisotropy, an equal area Schmidt of the sky onto a plane tangent to the appropriate celestial pole is used. The projected area is populated with pixels of equal area. The fluxes, $\delta\Phi/\delta\Omega$, are then calculated for each pixel, and modulated by the exposure of a typical experiment, which is a function that depends only on declination. For experiments in the Northern hemisphere, the Haverah Park exposure at $E > 10^{19}$ eV, was used as typical, since it is located at latitude 54^o N, mid-way between those of AGASA (36^o N) and Yakutsk (62^o N). However Haverah Park used water-Cerenkov detectors so that the declination response was broader than for the scintillator array of AGASA and Yakutsk.

The distribution of dark matter inside the halo is by no means certain. For our calculation we have assumed two types of models. One set of models corresponds to a bi-axial ellipsoid, intended as an approximation to a flattened halo density profile; in cylindrical galactocentric coordinates (ρ,φ,z):

$$n_H \propto \left[1 + \frac{1}{r_c^2}\left(\rho^2 + \frac{z^2}{q^2}\right)\right]^{-1} \tag{1}$$

where r_c is a characteristic, essentially unknown, scale. The spherical limit, q=1, corresponds to the isothermal halo model (Caldwell and Ostriker, 1981). The other set of models is due to Navarro, Frenk and White (1996) (NFW):

$$n_H \propto \left[\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2\right]^{-1} \tag{2}$$

where r_s is a characteristic radius (not the halo core).

We have used the amplitude and phase of the first harmonic to characterize the anisotropies. Thus, the amplitude is $r_{1h} = \sqrt{a_{1h}^2 + b_{1h}^2}$, where $a_{1h} = \frac{2}{N}\sum_{i=1}^{N}\cos\alpha_i$ and $b_{1h} = \frac{2}{N}\sum_{i=1}^{N}\sin\alpha_i$, the phase is $\Psi_{1h} = \tan^{-1}\left(\frac{b_{1h}}{a_{1h}}\right)$ and α_i is the right ascension of an individual event. The rms spread in amplitude and phase of the first harmonic are given by $\Delta r = \sqrt{2/N}$ and $\Delta\Psi = 1/\sqrt{2k_0}$, where $k_0 = r_{1h}^2 N/4$.

3 Results:

Figure 1 shows phase vs. amplitude of the first harmonic for dark halo models (1) and (2) (NFW) for $2 < r_c < 50$ kpc and $10 < r_s < 100$ kpc respectively. For model (1) flattenings $0.2 \le q \le 1$ are shown. For every model, the larger the amplitude of the first harmonic the more centrally concentrated is the halo (i.e., smaller r_c or r_s). The error bars represent 68% confidence levels for Volcano Ranch (6 events, Linsley 1980) Haverah Park (27 events, Reid and Watson 1980), Yakutsk (24 events, Afanasiev et al. 1995) and AGASA (47 events, Hayashida et al. 1996, Takeda et al. 1999) at $E > 4 \times 10^{19}$ eV, and 95% confidence for the 104 events of the four experiments combined. For the latter the error box is also shown in shades of gray in the background. Note the strong increase of the uncertainty range in phase as the amplitude decreases. It is evident that the data available at present are insufficient to restrict any particular dark matter halo model. At most it can be said that the data are not incompatible with UHECR originating in a spherical, or only slightly flattened halo (q > 0.6). An isothermal halo is as acceptable as, and is indistinguishable from, a NFW type of halo model, regardless of the value of their characteristic scales. Furthermore, the number of events is so small that statistical fluctuations may even dominate the results.

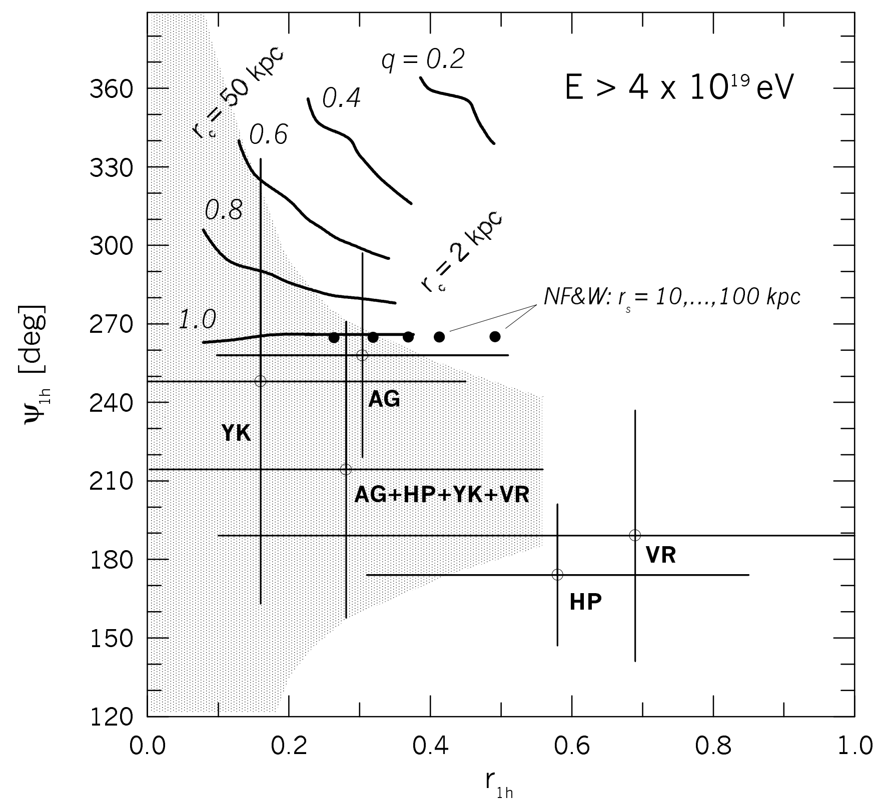

Figure 1: First harmonic for models 1 and 2. The heavy dots are for NFW. The lines identify models described by equation (1).

Figures 2 shows how much the situation can improve using the Southern site of the Auger experiment (Malargüe, Argentina, ≈ 35° South) which is to be developed. Comparing figures 1 and 2 it is evident that an experiment located in the Southern Hemisphere has a larger potential to discriminate between halo models than one located in the Northern hemisphere for small N, provided $r_c \gtrsim 10$ kpc. Location is not enough, however, and it can also be shown (Medina Tanco and Watson, 1999) that a significantly larger exposure is needed to make a difference from the current status. After three years of operation of the 3000 km^2 Southern hemisphere Auger detector, roughly ≈ 570 events are expected above 4×10^{19} eV, and that should allow 3σ amplitude determinations for the flatter halo models (the constraints on phase are always smaller). As an example, suppose that a measured harmonic amplitude is regarded as being established when the probability that it could have arisen from a random distribution through a chance fluctuation is less than 10^{-3}. It follows that with 500 events an amplitude of 24% would be detectable and the phase would have an uncertainly of ± 15°.Simulated error boxes are shown in figure 2 for this supposed amplitude and for one of 70%. It is clear from the figure that such a result would eliminate a number of halo possibilities depending on the value of the phase

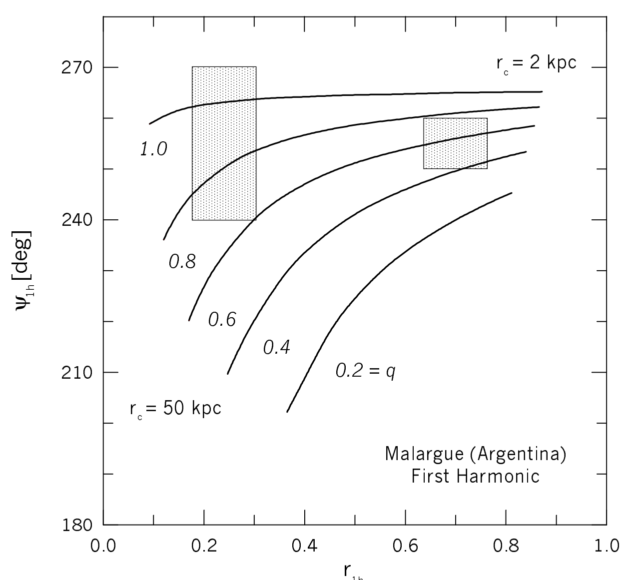

Figure 2: The impact of Auger South (Malargüe)

which is measured. Therefore, after three years of operation, it should be possible to exclude some dark halo models.

If UHECR sources are located in the Galactic halo, then Andromeda galaxy (M31, the largest galaxy in the local group at a distance of only D ≈ 670 kpc) could have a sizable contribution to the observed anisotropy. The ratio between the flux of UHECR originating in the halo of Andromeda and in our own halo, within a cone of $10^o \times 10^o$ centered in the direction to M31 is shown in Figure 3 for the isothermal halo (eq. (1) with q=1). The models are normalized to reproduce the galactic rotation curve inside $r_o \approx 18$ kpc, but differ in the total mass of the Galaxy halo, $M_{MW} = \eta \times M(r \leq r_o)$, where η is the mass of our halo in units of the mass inside r_o = 18 kpc. At present, the average number of UHECR detected above $E > 4 \times 10^{19}$ eV is only ≈ 0.5 events on a sky area of $10^o \times 10^o$ so not conclusion may be drawn.

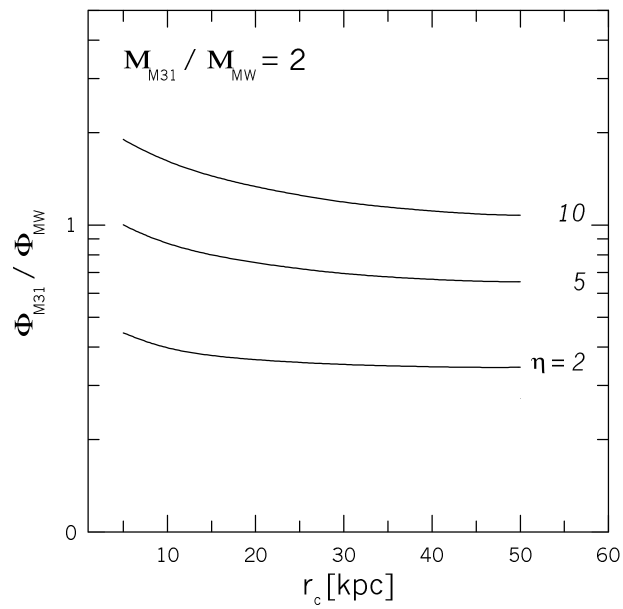

Figure 3: The contribution from Andromeda

4 Conclusions:

We conclude that our calculations are in good agreement with other work but that it is premature to draw inferences about the existence, or otherwise, of sources of UHECR lying within the halo of our galaxy. The issue could be resolved relatively quickly by the Southern part of the Auger Observatory, the engineering array for which is scheduled to begin in 1999.

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References

Afanasiev, B.N. et al., 1995, Proceedings of 24th International Cosmic Ray Conference (Roma), **2**, 796.

Benson A. Smialkowski A. and Wolfendale A. W., 1998, Astroparticle Phys., submitted.

Berezinsky V., Kachelriess M. and Vilenkin A. 1997, Phys Rev Letters **79** 4302

Berezinsky V.S. and Mikhailov A. A., 1998, astro-ph/9810277, Phys. Rev. Letters submitted.

Caldwell J. A. R. and Ostriker J. P., 1981, ApJ, **251**, 61.

Hayashida N. et al., 1996, Phys. Rev. Lett., **77**, 1000.

Hillas A. M., 1998a, Nature, **395**, 15.

Hillas, A.M., 1998b, Proc. Conference on High Energy Interactions, Gran Sasso, July 1998, to be published.

Linsley, J, 1980, Cat. HECR (Ed. M. Wada) World Data Center C2 for CR, IPCR, Itabashi, Tokyo, **1**, 1-59.

Medina Tanco G. A and Watson A. A., 1999, Astroparticle Phys., in press.

Navarro, J.F, Frenk, C.S., \& White, S.D.M. 1996, ApJ **462**, 563.

Reid, R.J.O. and Watson, A.A, 1980, Cat. HECR (Ed. M Wada) World Data Center C2 for CR, IPCR, Itabashi, Tokyo, **1**, 61 - 97 and additional events.

Takeda M. et al., 1998, Phys.Rev.Lett., **81**,1163

Takeda M. et al., 1999, astro-ph/9902239.