Dark matter halos and the anisotropy of ultra-high energy cosmic rays

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Several explanations for the existence of Ultra High Energy Cosmic Rays 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 cosmic rays. We have calculated the anisotropy expected for various models of the dark matter distribution and find that at present data are too sparse above $4 \times 10^{19}$ eV to discriminate between different models. However we show that with data from three years of operation of the southern section of the Pierre Auger Observatory significant progress in testing the proposals will be made.

*Subject headings:* Cosmic Rays: origin - anisotropy — galactic halo — dark matter
1. Introduction

The problem of the origin of ultra high-energy cosmic rays (UHECR) is receiving considerable attention. The situation is very well known and need only be summarized briefly. Shortly after the discovery of the cosmic background radiation Greisen (1966) and Zatsepin and Kuzmin (1966) pointed out that interactions of cosmic ray protons and nuclei with the 2.7 K radiation field would severely deplete the number of events at energies beyond about $4 \times 10^{19}$ eV. General acceptance that events exist beyond what has come to be known as the GZK cut-off has been long in coming but recently a consensus has emerged that there is indeed an excess of events beyond $10^{20}$ eV which cannot be explained by observational errors or uncertainties in energy estimates.

Very recently (Takeda et al. 1998) the Japanese AGASA project has reported 6 events above this energy with a spectrum which appears to be in contradiction with what would be expected if the sources of these particles were universal, although, as demonstrated by Medina Tanco (1998), the number of events is not large enough to rule out an association with nearby extragalactic luminous matter.

The agreement of the AGASA spectrum with those from the other giant shower detectors serves to underline the reality of the events of greater than $10^{20}$ eV reported from them. We note that 13 events have been reported overall for which the energies are claimed to be above $10^{20}$ eV: AGASA (7) (Takeda et al. 1999), Volcano Ranch (1) (Linsley 1963), Haverah Park (4) (Lawrence, Reid and Watson 1991), Fly’s Eye (1)(Bird et al 1993) and Yakutsk (1) (Efimov et al. 1991)). The distribution of events recorded by each experiment is in reasonable agreement with their individual exposures (Watson 1998). Not only are the particles above $10^{20}$ eV unexpected in the face of the GZK cut-off but also many theorists find it impossible to envisage electromagnetic methods of acceleration to these energies.

The experimental situation with regard to the arrival direction distribution of UHECR
is less clear cut than it is for the energy spectrum. Using a data set dominated by Haverah Park events, Staněv et al. (1995) claimed that cosmic rays above $4 \times 10^{19}$ eV showed a correlation with the direction of the Super Galactic Plane: the level of significance was 2.5 - 2.8 sigma. Later studies with AGASA data (Hayashida et al. 1996) and with Fly’s Eye data (Bird et al. 1998) did not support this claim. Very 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 $4 \times 10^{19}$ 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 but they find some evidence of clustering on an angular scale of 2.5°: there are three doublets and one triplet, the chance occurrence of which is calculated as less than 1%. The triplet and a doublet, which becomes a triplet if a $10^{20}$ eV event from Haverah Park, lie close to the Super Galactic Plane. This work extends a similar earlier analysis by Uchihori et al. (1997) using a set of data containing events from several experiments. If clustering of cosmic rays is established in very much larger data sets it will have profound implications for our ideas about cosmic ray origin. For example Farrar and Biermann (1998) have claimed an association with radio-loud QSOs for 5 of the most energetic events. While their statistical analysis has recently been challenged by Hoffman (1999), the idea is now capable of an independent test with the precise directions of the new AGASA events (Takeda et al. 1999). So far evidence for departures from isotropy have proved elusive.

At $4 \times 10^{19}$ 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 (Berezinsky, Kacheltiess and Vilenkin (1997), Benkali, Ellis and Nanopoulos (1998) and Birkel and Sarkar (1998)).
That such a bold hypothesis is advocated is a measure of the difficult situation in which observation has placed theoretical expectation. The situation is so acute that ideas such as the acceleration of Dirac monopoles by the galactic magnetic field (Kephart and Weiler 1996) and the breakdown of Lorentz invariance (Gonzalez-Mestres 1997, Coleman and Glashow 1998) are amongst those proposed to solve the enigma.

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 (Berezinsky, Blasi and Vilenkin 1998, Dubovsky and Tinyakov 1998, Hillas 1998a, 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. Calculations and Discussion

2.1. Anisotropy associated with the halo

In what follows, 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.

If UHECR are gamma-rays or neutrons, then their propagation is rectilinear and no further assumptions are required. If, on the other hand, UHECR are mainly charged
particles, as it seems more likely from the muon content of the largest AGASA event (Hayashida et al. 1996) and the profile of the largest Fly’s Eye event (Bird et al. 1993), then they will be deflected by the magnetic field inside the halo. In the latter case, a good description of the topology and intensity of the halo magnetic field, $B_H$, is necessary for a rigorous estimate of the anisotropy observed at Earth. Unfortunately, there are large uncertainties regarding $B_H$ (Kronberg 1994, Beck et al. 1996, Vallée 1997). However, the higher the particle energy, the smaller the deflection. Using an axisymmetric, spiral field without reversals and with even (quadrupole type) parity in the perpendicular direction to the galactic plane (Stanev 1997), which is consistent with the observations of our own and other spiral galaxies (Beck et al. 1996, Kronberg 1994), it has been shown (Medina Tanco 1997, 1998, Medina Tanco et al. 1998) that, upon traversing a 20 kpc halo: (a) protons with $E \sim 4 \times 10^{19}$ eV are deflected through angles $\alpha < 10^\circ$ ($\alpha < 5^\circ$ at galactic latitude $|b| > 60^\circ$) unless their trajectories cross the central regions of the galaxy; (b) the deflections suffered by protons are reduced to $\alpha < 5^\circ$ at $E \sim 10^{20}$ eV for most directions; (c) heavier nuclei, in particular Fe, are deflected by up to $40^\circ$ for most arrival directions even at energies as high as $E \sim 2 \times 10^{20}$ eV. In what follows 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, $n_H(\mathbf{r})$ where $\mathbf{r}$ is the position vector in a galactocentric reference system. Therefore, the incoming flux of UHECR from a solid angle $\delta \Omega(\mathbf{r}')$, around the direction $\mathbf{r}'$, defined in a geocentric coordinate system is:

$$\delta \Phi \propto \int_{V_{\delta \Omega}} \frac{n_H[\mathbf{r}(\mathbf{r}')]}{r'^2} dV = \int_{0}^{r_H(\mathbf{r}')} n_H[\mathbf{r}(\mathbf{r}')] \delta \Omega dr'$$

(1)
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 $r(r')$ 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 $r'$ is:

$$\frac{\delta \Phi}{\delta \Omega} \propto \int_{0}^{r_H(r')} n_H (R_\odot + r') dr'$$

(2)

where $R_\odot$ 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 projection (Fisher, Lewis and Embleton 1993) 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, $\Xi(\delta)$, 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° N, mid-way between those of AGASA (36° N) and Yakutsk (62° 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. Nevertheless, the flatness of the rotation curves of spiral galaxies implies that the density inside the halo must decrease roughly as $1/r^2$. Caldwell and Ostriker (1981) parametrised the density of dark matter in the plane of the galaxy by a core-halo type model ($n_H \propto (1 + r^2/r_c^2)^{-1}$), and assumed that the halo is spherical (see also, Binney and Tremaine 1987, Sciama 1993). However, N-body simulations of the dissipationless formation of halos (Frenk et al. 1988, Katz 1991, Katz and Gunn 1991, Dubinski and Carlberg 1991, Dubinski 1992, Warren et al. 1992) indicate that the final shape is flattened. For the flattest halos obtained in the
absence of dissipation the axial ratio, $q$, equals 0.4. In an observational study of our own galaxy, van der Marel (1991) found $q > 0.34$.

For our calculation we have assumed a bi-axial ellipsoid as an approximation to a flattened halo density profile; in cylindrical galactocentric coordinates $(\rho, \phi, z)$:

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

where $r_c$ is a characteristic, essentially unknown, scale. The spherical limit, $q = 1$, corresponds to the isothermal halo model of Caldwell and Ostriker (1981).

Navarro, Frenk and White (1996) (NFW), on the other hand, investigated the structure of dark halos in the standard Cold Dark Matter model, and found that the spherically averaged density profile can be fit over an interval of two decades in radius by scaling a "universal" profile. Their halo profiles are approximately isothermal over a large range in radii, but shallower than $r^{-2}$ in the central region and steeper than $r^{-2}$ near the virial radius:

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

where $r_s$ is a characteristic radius (not the halo core). In our analysis we consider halo profiles given by both eq. (3) and (4).

Figure 1 shows a step-by-step graphical description of our procedures. In figure 1a the density profile, given by (3) with $q = 0.4$ and $r_c = 8$ kpc is shown. The horizontal axis, $\rho$, runs along the galactic plane, while the vertical axis, $z$, is perpendicular to the galactic plane. Figure 1b shows the flux of UHECR per unit solid angle, originated by the density profile in 1a, in galactic coordinates with the galactic centre at the center of
the figure. Figure 1c shows $\delta \Phi / \delta \Omega$ from figure 1b rotated into equatorial coordinates.

Figures 1d and 1f are the Schmidt projections of $\delta \Phi / \delta \Omega$ from 1c onto planes tangent to the North and South pole respectively. Figures 1e and 1g show the Schmidt projections 1d and 1f convoluted with the response in declination of Haverah Park (54° N) and Auger South (Malargüe, Argentina) respectively. For the Malargüe site (35° S) we have used the Haverah Park declination distribution (appropriately mirrored and shifted) as the actual declination distribution has yet to be measured and the Pierre Auger Observatory will use water-Cerenkov tanks of the same depth as those used at Haverah Park. It is from these later figures, and similar ones for other halo models, that the anisotropies discussed below has been calculated.

We have used the amplitude and phase of the first harmonic to characterize the anisotropies. Thus (e.g., Linsley 1975), the amplitude is:

$$r_{1h} = \sqrt{a_{1h}^2 + b_{1h}^2}$$

(5)

where:

$$a_{1h} = \frac{2}{N} \sum_{i=1}^{N} \cos \alpha_i$$

$$b_{1h} = \frac{2}{N} \sum_{i=1}^{N} \sin \alpha_i$$

(6)

the phase is

$$\Psi_{1h} = \tan^{-1} \left( \frac{b_{1h}}{a_{1h}} \right)$$

(7)

and $\alpha_i$ is the right ascension of an individual event.

The rms spread in amplitude and phase of the first harmonic are given by:
\[ \Delta r = \sqrt{\frac{2}{N}} \]  

(8)

and

\[ \Delta \Psi = \frac{1}{\sqrt{2k_0}} \]  

(9)

where \( k_0 = \frac{r_{1h}^2 N}{4} \). Another quantity of interest is the number of events required for a signal-to-noise ratio of \( n_\sigma \) standard deviations either in amplitude or phase:

\[ N_r(n_\sigma) = \frac{2n_\sigma^2}{r_{1h}^2}, \quad N_\Psi(n_\sigma) = \frac{2n_\sigma^2}{r_{1h}^2 \Psi_{1h}^2} \]  

(10)

In figure 2 \( N_r(n_\sigma = 3) \) is shown for the set of models described by equation (3) as a function of the characteristic length \( r_c \) and different values of \( q \), covering very flat solutions \( (q = 0.2) \) to the isothermal solution \( (q = 1.0) \). The magnitude of \( r_{1h} \) depends on the halo model: for the models described by equation (3) \( r_{1h} \) decreases as \( q \) increases at constant \( r_c \), while at constant \( q \), \( r_{1h} \) decreases as \( r_c \) increases. The curves have been calculated for Haverah Park, but they are also representative of what would be expected for AGASA and Yakutsk. We note that the grand total number of events with \( E > 4 \times 10^{19} \) eV for the Northern Hemisphere sites is \( N \sim 100 \). Therefore, it is not possible, with the present data to measure the amplitude of the first harmonic at the 3\( \sigma \) level required to have statistically significant discriminators between any dark halo model density profiles.

Figure 3 shows phase vs. amplitude of the first harmonic for dark halo models (3) and (4) (NFW) for \( 2 < r_c < 50 \) kpc and \( 10 < r_s < 100 \) kpc respectively. For model (3) flattenings \( 0.2 \leq q \leq 1 \) 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, Uchihori et al. 1997, 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 detected so far by each experiment is so small that statistical fluctuations may even dominate the results.

Figures 4 and 5 show how much the situation can improve using the Southern site of the Auger experiment (Malargüe, Argentina, $\sim 35^\circ$ South) which is to be developed. Comparing figures 3 and 5 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 $r_c \sim 10$ kpc. Location is not enough, however, and figures 2 and 4 imply 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 $\sim 570$ events are expected above $4 \times 10^{19}$ eV, and that should allow $3\sigma$ 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 $\pm 15^\circ$. Simulated error boxes are shown in figure 5 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 which is measured. Therefore, after three years of
operation, it should be possible to exclude some dark halo models.

2.2. Anisotropy associated with Andromeda (M31)

It is a well known fact in gamma ray burst research, that a halo origin of the bursts
is ruled out by the non-observation of clustering of events in the direction of Andromeda
galaxy (M31, the largest galaxy in the local group at a distance of only \(D \sim 670\) kpc).
That much the same reasoning should apply to the present UHECR problem has been most
recently discussed by several authors (Benson, Smialkowski and Wolfendale 1998, Dubovsky
and Tinyakov 1998). However, very different values have been quoted in these works for the
contribution of Andromeda in UHECR. We have therefore made an independent calculation
of the magnitude of the effect. The ratio between the incoming UHECR flux originating in
Andromeda and that originating in the halo of our own galaxy inside a given solid angle \(\delta\Omega\)
can be expressed as:

\[
\frac{\Phi_{M31}}{\Phi_{MW}} \sim \frac{\zeta}{D^2} \times \frac{\int_{V_H} n_H dV}{\int_{V_{\delta\Omega}} n_H dV} \quad (11)
\]

where the second factor on the right hand side of the equation is a function that depends
only on the particular halo model assumed and \(\zeta \sim 2\) is the ratio between the masses of the
halos of Andromeda and the Milky Way. The integration volume \(V_H\) is the volume of the
Galaxy halo and \(V_{\delta\Omega}\) is the volume defined by the cone of solid angle \(\delta\Omega\) pointing in the
direction of Andromeda.

Figure 6 shows \(\Phi_{M31}/\Phi_{MW}\) for a \(10^9 \times 10^9\) solid angle (the expected spread due to
deflection of a \(4 \times 10^{19}\) eV proton arriving from Andromeda - e.g., Medina Tanco et al.
1997) for several isothermal (i.e., \(q = 1\) in eq. (3)) halo models. The three models have
been normalized in such a way as to give the same contribution to the galactic rotation curve at a galactocentric distance of $r_o = 18$ kpc and differ in the ratio $\eta$ between the total halo mass and the dark matter mass inside $r_o$. Galactic dark halos with $\eta = 2, 5$ and 10 are considered. The results show that the contribution from Andromeda increases faster than the contribution from our own galaxy as the mass of the halo is increased. Due to the limited size of the present UHECR sample ($\sim 0.5$ events per $10^\circ \times 10^\circ$ solid angle), nothing can yet be said about the existence of an UHECR contribution originated in the dark halo of Andromeda.

3. Comments on related work

Other authors have recently discussed the anisotropy expected if the UHECR are produced by the decay of super-heavy relic particles in the galactic halo (or indeed by any other sources distributed in a similar way). Berezinsky and Mikhailov (1998) have used the Isothermal distribution of dark matter (Kravtsov et al 1997) and the distribution predicted by the numerical simulations of Navarro, Frenk and White (1996) to predict the amplitudes of the first and second harmonics and the phase of the first harmonic for the geographical location of the Yakutsk array (latitude $= 62^\circ$ N). This is an extension of the calculation outlined in Berezinsky, Blasi and Vilenkin (1998) in which a wide-ranging overview of the signatures from topological defects is given. The amplitudes and phases which they predict are very similar to those found in our calculation (figure 3). For the Isothermal model they calculate the phase to be $250^\circ$ and find that the amplitude of the first harmonic varies from 0.40 to 0.14 as $r_c$ changes from 5 to 50 kpc. For the NFW model the same phase is found and the harmonic amplitude varies from 0.38 to 0.31 as $r_s$ changes from 30 to 100 kpc. These results are in reasonable agreement with our work (figure 3).

Berezinsky and Mikhailov state that dominance of a halo component at about $10^{19}$
eV can probably be excluded by the AGASA data which contains nearly 600 events above this energy. However in our view this is not a very strong conclusion as there is no acute problem at $10^{19}$ eV comparable to that which exists at higher energy. Particles of $10^{19}$ eV can probably be produced in several locations by electromagnetic processes. Additionally there is no difficulty in explaining the isotropy as a reasonable fraction of the particles may be iron nuclei. This is allowed by the necessarily model-interpretation of the Fly’s Eye data and the limited statistics (Bird et al. 1995, Ding et al., 1997). Iron nuclei cannot, of course, be created by the decay of dark matter particles.

Benson, Smialkowski and Wolfendale (1998) have used data from a variety of experiments to discuss the dark matter contribution from two halo possibilities, one in which an extensive (100 kpc) magnetic halo is postulated and one in which the dark matter density distribution follows the Navarro, Frenk and White (1996) model. They make comparisons with their predictions using data at $(1 - 5) \times 10^{18}$ eV from Akeno and Yakutsk and above $3 \times 10^{19}$ eV using data from AGASA, Volcano Ranch, Haverah Park, Yakutsk and Sydney as discussed in Chi et al. (1992).

It does not seem possible, to us, to extract meaningful information on the super-heavy relic content of the halo from the arrival direction distribution of events as low in energy as $(1 - 5) \times 10^{18}$ eV. Here there are likely to be many iron nuclei present and, as at $10^{19}$ eV, there is no enigma to be resolved which necessitates the postulate of dark matter particles.

In our discussion of the data above $4 \times 10^{19}$ eV we have used the 104 events (figure 3) from Volcano Ranch, Yakutsk, Haverah Park and AGASA. We have shown that this number of events is insufficient to discriminate against models other than those with rather flat distributions ($q < 0.4$). We believe that it is inappropriate to try to draw conclusions using observations made with the Sydney array as Benson, Smialkowski and Wolfendale (1998) have attempted. Of the 80 events with energies above $4 \times 10^{19}$ eV in the Sydney catalogue,
60 have zenith angles smaller than 60 degrees. However the mean multiplicity of struck stations in only 5.0 and 60% of these events have 3 or 4 fold multiplicity. This means that the core location, and hence the reconstructed muon size, is very uncertain. There are also well-documented difficulties with the instrumentation of the Sydney experiment (e.g. Watson 1991) and with the models used to estimate the energies (Hillas 1990). The conclusions reached by Chi et al. (1992) about the Sydney data result in an energy spectrum (figure 7a of Chi et al.) which is not consistent with the modern spectra from AGASA, Haverah Park and Fly’s Eye. For several reasons, therefore, we deem it prudent to ignore those data.

4. Conclusions

We have calculated the anisotropy of UHECR to be expected at specimen locations in the Northern and Southern hemispheres on the assumption that the particles are created in the decay of super-heavy relic particles within the galactic halo. Several models describing the distribution of cold dark matter have been considered. 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 Pierre Auger Observatory, construction of the Southern part of which is scheduled to begin in 1999.

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Figure Captions

**Figure 1:** A graphical example of the procedure followed is shown. (a) Halo density (cylindrical galacto-centric coordinates) given by eq.(3) with $q = 0.4$ and $r_c = 8$ kpc; distances are in kpc and density contours are linear; the density distribution is shown for one-quarter of the Galaxy. (b) UHECR flux produced by dark matter distribution (a) as seen in galactic coordinates. (c) As (b) but in equatorial coordinates. (d) Schmidt projection of (c) onto the North Pole. (f) As (d) but for the South Pole. (e) and (g) are the projections (d) and (f) convoluted with the response in declination of Haverah Park and Auger South respectively. First harmonics have been calculated over figures of type (e) and (g) for a variety of halo models.

**Figure 2:** Number of events necessary for an amplitude determination significant at the $3\sigma$ level for several halo models. Note that the existing Northern hemisphere database (AGASA, Haverah Park Volcano Ranch and Yakutsk) at $E > 4 \times 10^{19}$ eV comprises only 104 events.

**Figure 3:** Phase versus amplitude of the first harmonic for the several models described in the text. The heavy dots are NFW models for $r_s = 10, 20, 30, 50$ and 100 kpc. The lines identify models described by equation (3) for $2 \leq r_c \leq 50$ kpc and $0.2 \leq q \leq 1.0$. $r_s$ and $r_c$ are explained in the text. Error bars correspond to 68% C.L. for the available data from Volcano Ranch (VR, 6 events), Yakutsk (YK, 24), AGASA (AG, 47) and Haverah Park (HP, 27) with $E > 4 \times 10^{19}$ eV. The 95% C.L. error bars for the combination of the experiments (AG+HP+YK+VR, 104) is also shown. The shaded region denotes the 95% C.L. combined error box, and stresses the increase of the error in phase as the amplitude decreases.
**Figure 4:** Same as figure 2 but calculated for Malargüe, Argentina, the Southern site of the Auger experiment.

**Figure 5:** Same as figure 3 but calculated for Malargüe. The error boxes are two simulated 68% C.L. data points, corresponding to hypothetical first harmonic amplitudes equal to 0.24 and 0.7 respectively as would be found after 3 years of observation (i.e., ∼500 events with $E > 4 \times 10^{19}$ eV).

**Figure 6:** The contribution of Andromeda (M31). Ratio between the flux of UHECR originating in the halo of Andromeda and in our own halo, within a cone of $10^\circ \times 10^\circ$ centered in the direction to M31. The calculations shown are for the isothermal halo (eq. (3) with $q = 1$). The models are normalized to reproduce the galactic rotation curve inside $r_o \sim 18$ kpc, but differ in the total mass of the Galaxy halo, $M_{MW} = \eta \times M(r \leq r_o)$, where $\eta$ 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 $\sim 0.5$ events on a sky area of $10^\circ \times 10^\circ$ so not conclusion may be drawn.
Figure 1.a-c
Figures 1.d-g
Figure 2

Northern hemisphere: Haverah Park

$N_r$

$r_c [\text{kpc}]$

$q = 0.2$

$0.4$

$0.6$

$1.0$

$0.8$
Figure 3
Figure 4

Southern hemisphere: Malargue

$N_r$

$r_c$[kpc]
Figure 5
Figure 6

\[ \frac{M_{M31}}{M_{MW}} = 2 \]

\[ \frac{\Phi_{M31}}{\Phi_{MW}} \]

[Graph showing the relationship between \( \frac{\Phi_{M31}}{\Phi_{MW}} \) and \( r_c \) in kiloparsecs (kpc).]

\[ \eta = 2 \]