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Constraints on the UHE photon fluxes from inclined showers in Haverah Park

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Abstract. Using data from inclined events ($60^\circ < \theta < 80^\circ$) recorded by the Haverah Park shower detector, we show that above 10^{19} eV less than 41% of the primary cosmic rays can be photons at the 95% confidence level. Above 4×10^{19} eV less than 65% of the cosmic rays can be photonic at the same confidence level. These limits place important constraints on some models of the origin of ultra high energy cosmic rays. Details of two new events above 10^{20} eV are reported.

1 Introduction

The highest energy cosmic rays above the Greisen Zatsepin Kuzmin cut-off (GZK, 1966) are a mystery both in terms of their origin and their mass composition. Conventional acceleration mechanisms, so called ‘bottom up’ scenarios, predict an extragalactic origin with mainly proton composition as, although nuclei of higher charge are more easily accelerated, they are fragile to photonuclear processes in the strong photon fields to be expected in likely source regions (Hillas, 1984). “Top down” models explain the highest energy cosmic rays as arising from the decay of some sufficiently massive “X-particles”. These models predict particles such as nucleons, photons and even possibly neutrinos as the high energy cosmic rays, but not heavy nuclei. In some models (Berezinsky et al., 1997; Birkel et al., 1998) these X-particles are postulated as long-living metastable superheavy relic particles (MSRP) clustering in our galactic halo. For these MSRP models a photon dominated primary composition at 10^{19} eV is expected. Other top down models (Bhattacharjee et al., 1992) associate X-particles with processes involving systems of cosmic topological defects which are uniformly distributed in the universe, and predict a photon dominated composition only above $\sim 10^{20}$ eV. These models are affected by the constraint that the low energy photons ($\sim$100 MeV) arising from interactions of UHE photons with the cosmic microwave background cannot be larger than the observed diffuse low energy flux (Chi et al., 1992). Observations above 10^{19} eV are currently consistent with both interpretations (Bird et al., 1995; Hayashida et al., 1994). There is however some partial evidence against the photon hypothesis. Shower development of the highest energy event (Bird et al., 1995), is inconsistent with a photon initiated shower (Halzen et al., 1995) while AGASA measurements of the muon lateral distribution of the highest energy events are compatible with a proton origin (Nagano et al., 1999). No measurement of, or limit to, the photon flux above 10^{19} eV has been reported.

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Here we present the first analyisis of EeV showers of large zenith angles. This analysis was possible partly because of recent advances in understanding geomagnetic deviations of muons in inclined showers that allow smooth parameterizations of the muon density profiles at ground level (Ave et al., 2000b). The analysis has revealed new cosmic ray data including two events with energy exceeding 10^{20} eV. More importantly we demonstrate that such measurements together with measurements of the vertical cosmic ray flux, provide a new method for constraining photon composition of ultra high energy cosmic rays, opening new possibilities for detectors in construction. We describe the proposed method which we have applied to the Haverah Park data and the limit obtained for photon composition at energies above 10^{19} eV (Ave et al., 2000c).

2 Inclined showers

For primaries arriving at zenith angles, $\theta > 60^\circ$ the shower particles reaching sea-level are dominated by muons, with a relatively small contribution of electrons and gammas arising mainly from muon decay (Ave et al., 2000a) that mimics the muon lateral distribution. Detailed simulations reveal that the shape of the lateral distribution of muons in inclined showers is constant with energy and is insensitive to shower to shower fluctuations in longitudinal development (Ave et al., 2000a). To a good approximation the same lateral distribution function also applies to different primaries. In general differences between the lateral distributions and energy spectra of muons in photon and hadronic showers are of particular importance. For inclined showers, however, the differences decrease as the zenith angle increases because the mean height of muon production also increases for both types of primary. At $60°$, the lowest zenith angle considered, the differences in the constant density contours are below 20 $\%$ for distances between 300 and 1000 m.

As a result different particles and different hadronic models can be described by a function that gives the normalization in terms of the primary particle energy. The normalization has been shown to scale with energy with good precision (Ave et al., 2000a). We find $N_\mu \propto E^\alpha$ with α equal to 0.924, 0.906 and 1.20 for proton, iron and gamma primaries respectively (Ave et al., 2000b). From our simulations we find that photons are expected to produce fewer muons than protons (a factor $\sim$9 at 10^{19} eV). The relative total muon numbers at 10^{19} eV are 1.0, 1.36, 0.11 for proton, iron and gamma primaries respectively.

The ratio of the number of muons in proton and photon showers decreases with shower energy because of the rise of the photoproduction cross section and also because of the decrease of the pair production and bremsstrahlung cross sections (due to LPM suppression (Landau and Pomeranchuk, 1953)). Our conclusions on the photon flux are not sensitive to the choice of model: the implementation of photohadronic interactions in the AIRES code (Sciutto, 1999) and CORSIKA code (Heck et al., 1998) (using the parameterization of (Stanev et al., 1985)) give predictions of the total muon number that are equal to within 10% at 10^{20} eV.

Inclined showers have been analysed using a combination of Monte Carlo techniques and muon density parameterizations, see (Ave et al., 2000b,a) for details. For zenith angles in the range $60°$ - $89°$ (in $1°$ steps) muon density maps were generated using the model (Ave et al., 2000b) with inputs from AIRES for the QGSJET hadronic model (Kalmykov and Ostapchenko, 1993) with 10^{19} eV protons. Different azimuth angles are modeled as described in (Ave et al., 2000b).

The simulation of different primary energies and compositions is achieved by scaling the muon density maps described above. We adopt parameters appropriate to proton primaries to give a conservative estimate of the shower energies by comparison with what would be derived from the assumption of gamma ray primaries. By fitting density maps for proton primaries on an event by event basis we thus obtain equivalent proton energies E_p. For other primaries the energy is related to E_p by an energy dependent multiplicative factor which is $\sim$6 (0.7) for gamma (iron) primaries at $E_p = 10^{19}$ eV. i.e. a photon would require an energy 6 times that of a proton to produce a given density map.

3 Haverah Park Data Analysis

We have analysed the data from the Haverah Park array, a 12 km^2 array of water-Čerenkov detectors (Lawrence et al., 1991). The data were recorded between 1974 and 1987 and comprise around 8000 events with $\theta > 60°$ from an on-time of 3.6×10^8 s. A combined analysis of arrival directions and energy was performed.

The Haverah Park arrival directions were determined originally using only the 4 central triggering detectors. We have reanalysed the arrival directions of showers having original values of $\theta > 56°$, taking into account all detectors which have timing information. This reanalysis produces smaller arrival direction uncertainties. The rate, as a function of zenith angle, obtained with the new zenith angles, is consistent with earlier predictions showing that the zenith angle reconstruction and the response of the array to inclined showers are well understood (Ave et al., 2000a).

The curvature of the shower front has been investigated using the AIRES code for inclined showers and found to be consistent with the simple approximation of a spherical front centered on the mean production height of the muons (e.g. at $60°$ the radius of curvature is 16 km (Ave et al., 2000b)). Beyond $\sim 80°$ curvature effects are rather small and it is usually sufficient to assume a plane front (Bertou et al., 1997). When the detected muon number is small there is a systematic effect on the curvature correction and large fluctuations due to limited sampling of the shower front. Therefore, we disregard the timing information from detectors with < 15 detected equivalent muons. Because of the dependence of the curvature fit on the position of the shower core a three step iteration was needed to give convergence of the core location and direction fits.

The observed densities were fitted against predictions using the maximum likehood method. Poissonian errors, measurement errors and errors due to the uncertainty in detector geometry were included. Some events contain saturated detectors which were accounted for using a gaussian integral for the likelihood function. A three dimensional grid search was made to find the impact point and energy of the shower. The energy was varied in the range $10^{17} < E_p < 10^{21}$ eV in steps of 0.1 in $\log_{10}(E_p/\mathrm{eV})$. The impact point was varied over a grid of 12 km $\times$ 6 km in 40 m steps in the perpendicular plane, the grid asymmetry being necessary to accommodate the ellipticity of inclined showers.

The muon signal was taken from the muon density maps described in the previous section. In addition to the electromagnetic contribution due to muon decay which is present at all core distances at the 20% level for these detectors, the tail of the electromagnetic part of the showering process is important at zenith angles below $70°$ and core distances less than 500 m. This contribution is modeled using AIRES with QGSJET and is radially symmetric in the shower plane. The tail of the electromagnetic part of the shower contributes 10% of the total water-Čerenkov signal at 500 m from the core for a $60°$ shower.

The detector signals were measured in units of vertical equivalent muons. Using the GEANT based package, WTANK (de Mello Neto, 1998), we find that this unit corresponds to an average number of 14 photoelectrons, consistent with an early experimental estimate of 15 photoelec-

MR	Zenith (°)	RA (°)	Dec. (°)	$\log_{10}(E_p/\mathrm{eV})$	
14050050	65	86.7	31.7	20.09	0.30
18731630	60	318.3	3.0	20.06	0.04
14182627	70	121.2	8.0	19.85	0.49
19167320	72	152.5	25.9	19.82	0.07
15301069	74	50.0	49.4	19.78	0.08
12753623	74	304.9	17.1	19.75	0.12
12519070	70	47.7	8.8	19.62	0.10

Table 1. Zenith angle, arrival direction coordinates and shower energy (assuming proton primary) of selected showers with energy $> 4 \times 10^{19}$ eV. MR is the event record number.

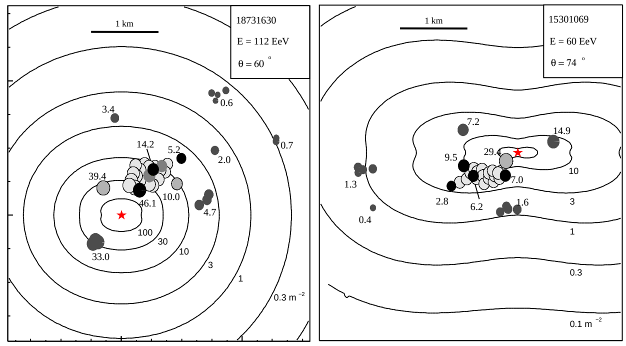

Fig. 1. Density maps of two events in the plane perpendicular to the shower axis. Recorded muon densities are shown as circles with radius proportional to the logarithm of the density. The detector areas are indicated by shading; the area increases from white to black as 1, 2.3, 9, 13, 34 m^2. The position of the best-fit core is indicated by a star. Selected densities are also marked. The y-axis is aligned with the component of the magnetic field perpendicular to the shower axis

trons (Baxter, 1967). For inclined showers additional effects, such as direct light on the photomultiplier tubes, delta rays, and pair production and bremsstrahlung by muons inside the tank, increase this number. For a given zenith angle, the recorded signals are converted into the number of photoelectrons and hence the muon density. The simulations take full account of stopping muons and the resulting decay electrons.

The photoelectron distributions from a water detector show long tails due to the processes mentioned above (Ave et al., 2000a). We therefore expect an excess of upward over downward fluctuations from the average detector signal. For each event the number of deviations >2.5 σ expected is calculated from the expected photoelectron distributions. We reject signals having (upward or downward) deviations greater than 2.5 σ, recalculating the best fit core after any rejection. Of 211 densities in the events of table 1 we rejected 13 upward deviations (the expected number was 17) and rejected 4 densities with downward deviations $> 2.5\sigma$.

The described analysis yielded 46 events with $E > 10^{19}$ eV. Seven events have energies $> 4 \times 10^{19}$ eV which are summarized in Table 1, and two events have energies $> 10^{20}$ eV.

Errors in the energy and core determination were determined from the likelihood function as in (Lampton et al., 1976). In addition to this error, an error in energy arises due to the uncertainty in the zenith angle. The error from the zenith angle determination and the error from the fit for core and energy are added in quadrature to give the total error shown in table 1. To guarantee the quality of events the following cuts were made: (i) the distance from the central triggering detector to the core position in the shower plane < 2 km, (ii) χ^2 probability for the energy and direction fits > 1 %, (iii) the downward error in the energy determination be less than a factor of 2. For $> 80°$ no showers pass cut (iii). Further work with improved cuts is in currently in progress.

In figure 1 are density maps for two events. These are plotted in the plane perpendicular to the shower direction together with the contours of densities that best fit the data. In each figure the array is rotated in the shower plane such that the y-axis is aligned with the component of the magnetic field perpendicular to the shower axis. In figure 1b the asymmetry in the density pattern due to the geomagnetic field is apparent. For both events the core is surrounded by recorded densities and is well determined.

4 Photon Bound

The data described in the previous section are compared to the result expected from different primaries using the primary cosmic ray spectrum and a Monte Carlo calculation. As input for the cosmic ray spectrum we take the parameterization recently given in (Nagano and Watson, 2000), noting that the agreement between the fluorescence estimates of the spectrum and those made by other methods implies that we have mass independent knowledge of the spectrum measured in the near-vertical direction. The flux above 10^{19} eV is known to within 20% uncertainty.

The Monte Carlo simulation generates showers with a distribution according to the input spectrum, and these showers are converted into detector signals. The generated signals are analysed in exactly the same way as the data yielding a prediction of the inclined shower spectrum. These predictions can be scaled for different compositions using the scaling laws described above and compared to the actual data. The rate observed for inclined showers is consistent with a proton dominated primary composition and significantly above that expected if the primary composition is dominated by photons.

Figure 2 shows the resulting integral spectra, for three primary compositions, compared to the data. These simulated spectra are somewhat dependent on the high energy interaction model used. The result is shown for the AIRES air-shower code with the QGSJET interaction model. The SIBYLL hadronic interaction model (Fletcher et al., 1994) produces fewer muons than QGSJET (36% less at 10^{19} eV) resulting in reconstructed energies that are higher by $\approx 40\%$.

From figure 2 we deduce that above 10^{19} eV less than 41% of the primary cosmic rays can be photons, with a 95% con-

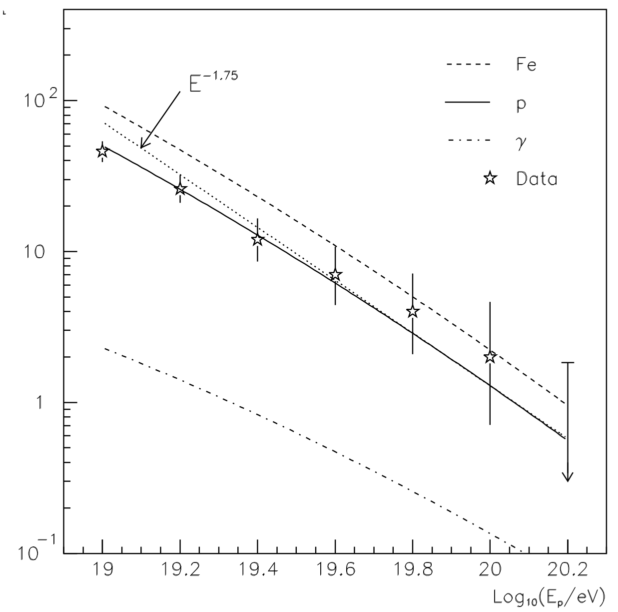

Fig. 2. Integral number of inclined events as a function of energy for the Haverah Park data set compared to the predictions for iron, protons and photon primaries. Here the energy is calculated assuming a proton primary. The slope of the assumed primary spectrum ($E^{-1.75}$) is shown to illustrate the increase of trigger efficiency with energy.

fidence level. Above 4×10^{19} eV less than 65% can be photons at the same confidence level. Here we have assumed that downward or upward fluctuations from the observed integral numbers by 2 standard deviations could be accounted for by appropriate contributions of protons plus gamma rays.

5 Summary and Conclusions

We have demonstrated that inclined cosmic ray shower can be analysed using parameterizations. We have analysed the inclined shower data above 10^{19} eV from the Haverah Park array. and developed a new method for studying composition at such energies combining inclined and vertical air shower data. We have obtained the first limit on photon composition at energies above 10^{19} eV, applying it to the Haverah Park data. Our bound is conservative because we have not taken into account the interactions of the high energy photons in the magnetic field of the earth (McBreen and Lambert, 1981; Bertou et al., 2000). This has the effect of converting a single energetic photon into a few lower energy photons. As the total number of muons in a shower initiated by a single photon scales with $E^{1.2}$, the number of muons in a shower initiated by a single photon exceeds the total number of muons in the multiple photon showers of lower energy.

These limit set important constraints to TD mechanisms as the origin of the highest energy cosmic rays. With the Southern Auger Observatory (3000 km^2) a ratio as small as 10% could be explored at 10^{19} eV with 3 years of data using this new technique.

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