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Telescope Array Introduction

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Abstract: The Telescope Array (TA) is the largest experiment in the northern hemisphere studying ultrahigh energy cosmic rays. It is located in Utah and consists of a surface detector of 507 scintillation counters deployed on a grid of 1.2 km spacing, and 38 fluorescence telescopes located at three sites looking inward over the surface array. For cosmic rays from 1 to 200 EeV, TA makes measurements of their flux and composition, carries out searches for anisotropy in cosmic ray pointing directions, and for photon and neutrino primaries.

TA has deployed a 40 MeV electron accelerator, called the ELS, in the field of view of one of its fluorescence detectors. The ELS beam, fired vertically, is approximately equivalent to a 1 EeV air shower near shower maximum. This beam is used for calibration purposes, and as a test beam for new detection technologies.

The TA Low Energy Extension (TALE) is an addition to TA, consisting of fluorescence detectors and an infill array of scintillation counters, which will increase our range of sensitivity from 0.03 EeV to 200 EeV. In this energy range lie the second knee of the spectrum, the galactic-extragalactic transition, and the energy to be reached by the LHC.

The TA Radar (TARA) RD project is searching for radar reflections from cosmic ray air showers. The TARA radar transmitter is located near the eastern edge of the TA surface array, and the receiver is just beyond the western edge. This geometry allows radar signals to be compared with the characteristics of cosmic ray showers detected by TA.

There are three other extension to TA that are described here: the NICHE project, the Muon Detector Project, and TAx4.

Keywords: Telescope Array, cosmic ray, ultrahigh energy, high energy, spectrum, composition, anisotropy

1 Introduction

The Telescope Array (TA) is the largest experiment studying ultrahigh energy cosmic rays (UHECR, above 1 EeV) in the northern hemisphere. A hybrid experiment, it consists of a surface detector and a fluorescence detector. The main aim of TA is studying the astrophysics of cosmic rays: the UHECR spectrum, their composition, and searches for anisotropy to learn about the UHECR sources. TA has an electron accelerator, the ELS, which shoots an electron beam vertically into the air 100 m in front of one of our fluorescence detectors, for calibration purposes and as a test beam. The TA Low Energy Extension (TALE) consists of 10 fluorescence telescopes and 105 scintillation infill counters, and will extend the energy reach of TA by a factor of 30 in the lower end, allowing important studies to be made in this energy region. The TA RAdar (TARA) R&D project is searching for radar echoes of UHECR showers. The TA Low Energy Extension (TALE) and the TA RAdar Experiment (TARA) are co-located with TA. There are three more TA projects at various stages of preparation, called the NICHE project, the Muon Detector Project, and TAx4.

2 The Telescope Array Experiment

TA consists of a surface detector (SD) of 507 scintillation counters deployed in the desert of Millard County, Utah, plus a fluorescence detector (FD) of 38 fluorescence telescopes deployed at three sites around the SD, and overlooking it. TA has been collecting data since 2008.

The SD counters are 3 m^2 in area, and are located on a rectangular grid of side 1.2 km covering about 750 km^2. Each counter consists of two layers of plastic scintillator, and is read out by a radio system.

The fluorescence telescopes at two sites were built new for TA, and the third site contains telescopes from the High Resolution Flys Eye (HiRes) experiment, reconditioned and redeployed at the TA site. All telescopes cover from 3 to 31 degrees in elevation angle, hence measure the depth of shower maximum for cosmic rays of energy greater than 1×10^{18} eV. The FD system operates at night when the moon is down (a duty cycle of about 10%).

Figure 1 shows the spectrum of ultrahigh energy cosmic rays measured by the surface detector of TA. The spectrum can be described by power laws in three energy ranges: for log(E) between 18.0 and 18.6 the power is -3.3; between 18.6 and 19.6 the power is -2.7, and for log(E) $>$ 19.6 the power is -4.5. The two breaks are called the ankle (log(E) = 18.6) and the GZK cutoff (19.6), and they appear at the correct theoretical locations for extragalactic protons interacting with photons of the CMBR.

Fluorescence light is emitted by nitrogen molecules excited by the passage of charged particles in the cosmic ray air shower, and its intensity is proportional to the number of charged particles in the shower. Hence a fluorescence detector measures the development profile of a cosmic ray shower. With the FD one can see the shower grow, until the average electron reaches the critical energy of about 90 MeV, after which more electrons are absorbed than created, and the shower decays. The variable most closely correlated with the composition of the primary cosmic rays is the depth of shower maximum, called Xmax. At constant energy,

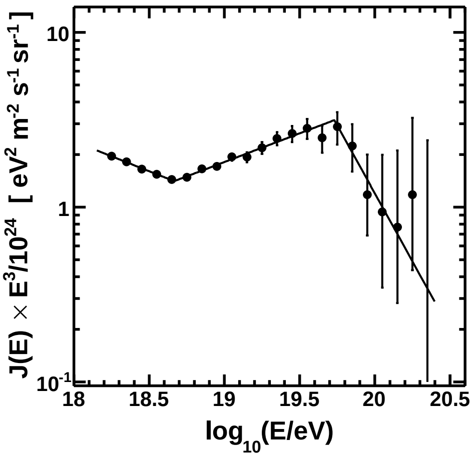

Figure 1: Spectrum of ultrahigh energy cosmic rays, measured by the TA surface detector. The flux times E^3 is shown vs log(E). The lines are a broken power law fit to the data.

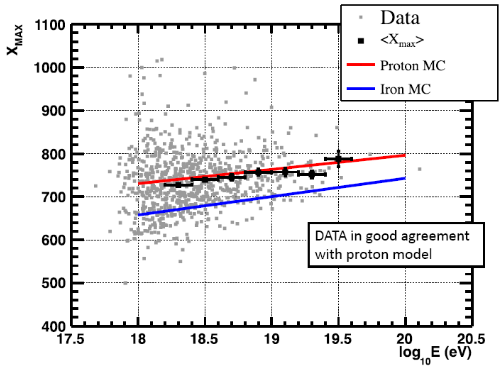

Figure 2: Mean Xmax vs log(E). The dots are individual events, and the data points are the means of events' Xmax values in energy bins. The lines are predictions from the QGSJet-II model for protons (red) and iron (blue) primaries.

proton primaries have a deeper Xmax than those of heavy nuclei, e.g., iron.

The mean Xmax data from one of the TA fluorescence detectors, working in hybrid mode with the TA SD, is shown in Figure 2. Our data indicate that the composition of ultrahigh energy cosmic rays is certainly light, and resembles the prediction of QGSJet-II for protons. This measurement is consistent with the interpretation that the breaks in the spectrum at $10^{18.6}$ eV and at $10^{19.6}$ eV are caused by interactions of cosmic ray protons and photons of the cosmic microwave background radiation (CMBR).

The search for anisotropy in the pointing directions of UHECR has not resulted in any signal of outstanding statistical significance. We still do not know what UHECR sources are. However the sources must be associated with the distribution of matter in the local large scale structure of the universe for high energy cosmic rays, since above about 4×10^{19} eV the bending of cosmic rays' trajectories is smaller than the angular size of the structures.

In the search for correlations between cosmic rays pointing directions and the local large scale structure of the universe (on the 250 Mpc scale) we made a model based on the 2MASS XSCz catalog of galaxies and tested the data distribution against the model, and also against an isotropic model. The Kolmogorov-Smirnov test was used, and the p-value shows that both the structure model and an isotropic model are both consistent with the data; i.e., the statistical power of the data is still too weak to make a clear determination.

3 The Electron Light Source

The Electron Light Source (ELS) is an electron accelerator that sends a beam of 40 MeV electrons vertically into the air. Built at the KEK laboratory, the maximum beam intensity is 10^9 electrons per pulse, and pulses widths are adjustable between 20 ns and 1 μsec. The ELS is located 100m in front of one of the fluorescence detectors of TA, and is used to calibrate the detector. Since an air shower from a cosmic ray of energy 10^{18} eV has about 10^9 electrons and positrons, the ELS beam is similar to a 10^{18} eV shower.

In addition to use for calibration purposes, the ELS is being used by groups from around the world searching for radio signals from cosmic ray showers. Several groups are searching for molecular bremsstrahlung signals and radar echoes. Radiation, consistent with Maxwell's equations, has been seen from the ELS.

4 TA Low Energy Extension

There are many interesting questions about the astrophysics of cosmic rays in the 10^{16} eV and 10^{17} eV decades. In this region there should appear the iron knee of galactic sources, the transition between galactic and extragalactic sources, and the second knee of the spectrum. In the study of these physics topics there is a close connection between spectrum and composition. Studying this is the aim of the TA Low Energy Extension (TALE).

The detectors of TALE are being deployed at this time. The 10 fluorescence telescopes are in place and in operation, and the first 16 surface detectors of an infill array are also running. The fluorescence telescopes, which observe from 31 to 60 degrees, in order to see lower energy cosmic ray showers, are reconditioned telescopes from the HiRes experiment. The spacing of the infill array is 400 m for the closest counters, 600 meters for those of intermediate distance, and 1200 m for those which are filling in the area to the main TA SD array. These detectors will be able to measure the spectrum and composition (through Xmax measurements) of cosmic rays of energies 10^{17} eV and higher. In addition three new fluorescence telescopes are being constructed which have mirrors three times larger than those of HiRes. They will extend the energy range of TALE down to 3×10^{16} eV.

5 TA Radar Experiment

Significantly larger detectors, to collect better statistics at the highest energies, are needed to identify sources via anisotropy studies. Estimates of magnetic bending for protons above about 4×10^{19} eV are 3 - 6 degrees, in the galactic and extragalactic fields. Unfortunately there are no strong sources easily visible, so good statistics are needed to identify a source. Because of the prohibitive cost, it may be impossible to build a significantly larger detector using existing technologies. Hence it is important to explore new detection techniques.

Detection of air showers at a distance (rather than by carpeting the ground with counters) would be an advantage. Fluorescence detectors do this, but have only a 10% duty cycle. Radio waves emitted by showers have not been proven to be a successful technology in this sense. But there is a hint that showers reflect radio waves: the Mariachi experiment used TV transmitters in Manhattan, a school array of scintillation counters on western Long Island, and a radio receiver on eastern Long Island to search for bistatic radar (transmitter and receiver in different locations) reflections, and found several coincidences between radio signals and counter events.

The TARA project aims to provide a more controlled test of the bistatic radar technique. It started with a 1.5 kW transmitter operating at 54.1 MHz located east of the TA SD, and a receiver just west of the SD, to look for coincidences between radar signals and either the SD or FD of TA. As a cosmic ray air shower propagates down through the atmosphere, the constantly changing distance between the radar transmitter and the shower, and receiver and shower, a time-dependent phase change occurs in the received signal which is then seen as a chirp: the signal falls in frequency at a df/dt rate of about 1-3 MHz/μsec. This characteristic can be used to trigger on radar reflections. The details of the frequency vs. time graph (spectrogram) can be used to determine the geometry of the cosmic ray shower.

TARA is now operating a 40 MW transmitter, and has sharpened the width of the radio beam. The smart receiver, located 40 km away, uses a system of filters matched to expected df/dt values to identify chirps and trigger below the noise level.

6 Other TA Extensions

6.1 Non-imaging Cherenkov Experiment (NICHE)

TALE will reach down to an energy of 3×10^{16} eV, so to see lower in energy, with a detector sensitive to the depth of shower maximum, Xmax, one must use the atmospheric Cherenkov technique. No previous, or currently existing, Cherenkov light experiment has a fluorescence detector against which the experimenters can calibrate energy and Xmax measurements on an event-to-event basis. So with TA and TALE setting the energy scale from the GZK cutoff over three orders of magnitude, the possibility exists of reaching lower in energy using non-imaging Cherenkov counters. With an array of simple Cherenkov counters (essentially phototubes looking upwards), deployed within the TALE infill array, one can use counter timing to reconstruct shower geometry, counter pulse heights to reconstruct counter energy, and counter signal widths to reconstruct Xmax. The NICHE Cherenkov array will cover an energy range reaching from $10^{15.5}$ to above 10^{17} eV. The NICHE experiment has been proposed but not yet funded.

6.2 Muon Detector Project

TA is planning to install muon counters inside the SD array. The purpose is to compare measured muon rates with those predicted from hadronic models. The TA experiment has made an excellent Monte Carlo simulation of its surface detector. All quantities of interest, counter pulse heights, zenith angle distributions, energy histograms, etc., agree between the data and Monte Carlo. However, models such as QGSJet predict that in a shower there should be 27% more energy deposit in our SD counters than is actually observed. Other experiments have observed a deficit of muons in cosmic ray showers, but this doesnt seem to be the case for us. The Pierre Auger Observatory infers about a 50% muon deficit in their surface detector water tanks, but our scintillation counters are about 6 times less sensitive to muons, which would result in a discrepancy in energy deposited of about 7%. Clearly a measurement of the actual number of muons in a cosmic ray air shower is called for.

Our plan is to construct a 25 m^2 detector, under shielding to absorb electrons, photons, and hadrons, in the middle of the TA surface detector. We will be able to compare the measured density of muons with predictions as a function of energy and distance from the shower core. This project has been funded.

6.3 TAx4

TAx4 is a project to expand the TA surface detector by a factor of 4, so it covers 3000 km^2 in area. The plan is to build 500 more scintillation counters and deploy them in an array of 2.08 km spacing. This array, plus the existing TA SD would reach the design size. There is plenty of room at the TA site to expand on the northern, western, and southern sides of the TA SD. The new array would need a fluorescence detector overlooking it to set the energy scale, so the TAx4 plan includes a fluorescence detector of 10 telescopes. These will be HiRes telescopes. Proposals for the new SD counters and the FD site development are being prepared for fall, 2013 submission.

The aim of the design is to collect data for anisotropy studies at the highest energies. An anisotropy signal due to the local large scale structure of the universe (the local 250 Mpc) really should be present at energies larger than 4×10^{19} eV, where the extragalactic and galactic magnetic fields have an effect on cosmic rays trajectories smaller than the size of the local large scale structures. Our calculation is that 20 TA years of data will be sufficient to determine unambiguously whether this anisotropy exists. Instead of waiting for 15 more years (the TA SDs five-year point was reached in early May, 2013) it would be much better to enlarge the TA SD and reach the required statistical power in 1/3 the time.

7 Summary

The Telescope Array Experiment is the largest studying ultrahigh energy cosmic rays in the northern hemisphere. The TA collaboration consists of groups from the U.S., Japan, Korea, Russia, and Belgium. Five years of data have been collected, and results are available on the spectrum, composition, and anisotropy of cosmic rays.

The spectrum has been measured for energies above 1×10^{18} eV, and shows two features: the ankle and the GZK cutoff. A fit to the spectrum shows that these features are exactly at the energies expected when cosmic ray protons of extragalactic origin interact with photons of the CMBR. The quality of these fits are excellent.

The composition has been measured using the Xmax technique, and when one compares the measurements to models one sees that the composition is certainly light, probably mostly protons, at all energies above $10^{18.2}$ eV.

Thus a consistent interpretation arises that in the 10^{18} eV decade and above that extragalactic sources accelerate protons to the highest energies. The majority of nuclei accelerated in the sources must be broken up by spallation either in the vicinity of the sources or upon propagating from the sources over extragalactic distances to the earth. The hope of identifying these sources has eluded us up to now. TAx4 will make important advances here. TARA is investigating a new technology to expand these studies.

At lower energies much physics remains to be done: studying the second knee, the galactic/extragalactic transition, and the details of proton air interactions at the LHC energy and above. TALE and NICHE are poised to make these studies.

TA, TALE, and NICHE will be able to make important measurements of spectrum and composition from the knee region up, over five decades in energy, with a single energy scale calibrated with the known energy of the GZK cutoff.

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