ULTRA HIGH ENERGY COSMIC RAYS: present status and future prospects

A A Watson

Department of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK

Abstract Reasons for the current interest in cosmic rays above $10^{19}$ eV are described. The latest results on the energy spectrum, arrival direction distribution and mass composition of cosmic rays are reviewed, including data that were reported after the meeting in Blois in June 2001. The enigma set by the existence of ultra high-energy cosmic rays remains. Ideas proposed to explain it are discussed and progress with the construction of the Pierre Auger Observatory is outlined.

0.1 Introduction

For the purposes of this review I define ultra high-energy cosmic rays (UHECRs) as those cosmic rays having energies above $10^{19}$ eV. There is currently great interest in them, partly because we have little idea as to how Nature creates particles or photons of these energies. Also we know enough about their energy spectrum and arrival direction distribution to believe that we have an additional problem: their sources must be reasonably nearby (within 100 Mpc) but there is no evidence of the anisotropies anticipated if the galactic and inter-galactic magnetic fields are as weak as astronomers tell us.

The distance limit comes from a combination of well-understood particle physics and the universality of the 2.7 K radiation. Interactions of protons and heavier nuclei with this, and other, radiation fields degrade the energy of particles rather rapidly. In the case of protons, the reaction is photopion production, while heavier nuclei are photodisintegrated by the 2.7 K radiation and the diffuse infrared background. These effects were first recognised by Greisen, and by Zatsepin and Kuzmin, and lead to the expectation that the energy spectrum of cosmic rays should terminate rather sharply above $4 \times 10^{19}$ eV (the GZK cut-off). Above $4 \times 10^{19}$ eV about 50% of particles must come from within 130 Mpc, while at $10^{20}$ eV the corresponding distance is 20 Mpc.

The most recent data suggest that particles do exist with energies beyond the GZK
cut-off and that the arrival direction distribution is isotropic. The mass of the cosmic rays above $10^{19}$ eV is not known, although there are experimental limits on the fraction of photons that constrain one of the models proposed to resolve the enigma.

0.2 Measurement of UHECR

The properties of UHECRs are obtained by studying the cascades, or extensive air showers (EAS), they create in the atmosphere. Many methods of observing these cascades have been explored. Currently two approaches seem to be most effective. In one, the density pattern of particles striking an array of detectors laid out on the ground is used to infer the primary energy. At $10^{19}$ eV the footprint of the EAS on the ground is several square kilometres so detectors can be spaced many hundreds of metres apart. Alternatively, on clear moonless nights, the fluorescence light emitted when shower particles excite nitrogen molecules in the atmosphere can be observed by massive photomultiplier cameras. This technique, uniquely, allows the rise and fall of the cascade in the atmosphere to be inferred.

The primary energy of the initiating particle or photon is deduced in different ways. For the detector arrays, Monte Carlo calculations have shown that the particle density at distances from 400 – 1200 m is closely proportional to the primary energy. Such a density can be measured accurately (usually to around 20%) and the primary energy inferred from parameters found by calculation. The estimate of the energy depends on the realism of the representation of features of particle interactions within the Monte Carlo model, at energies well above accelerator energies. The currently favoured model (QGSJET) is based on QCD and is matched to accelerator measurements. Although this model appears to describe a variety of data from TeV energies up to $10^{20}$ eV [14], one cannot be certain of the systematic error in the energy estimates.

For the fluorescence detectors, the primary energy is found by integrating the number of electrons in the cascade curve and assuming that their rate of energy loss is close to that at the minimum of the $dE/dx$ curve for electrons, $\sim 2.2$ MeV per g cm$^{-2}$ in the case of air. A small model-dependent correction must be made to account for the energy carried by muons and neutrinos into the ground. Ideally, one wants to compare estimates of the primary energy made in the same shower by the two techniques operating simultaneously, but this has yet to be done at these energies. So far all that has been possible is to compare estimates of the fluxes at nominally the same energy.

0.3 The Energy Spectrum, Arrival Direction Distribution and Mass of UHECRs

0.3.1 Energy Spectrum

At the time of the Blois meeting (June 2001) data on the energy spectrum from a number of experiments had seemed in good accord [13]. In particular, the rates of events at $10^{19}$ eV reported by different experiments were in agreement at the 10 – 15% level. In addition, preliminary data from the Utah-based HiRes group, reported at the International Cosmic Ray Conference in 1999, showed 7 events above $10^{20}$ eV, in good agreement with the number anticipated from the flux reported by the Japanese AGASA array.
The situation has now changed dramatically. At the international meeting in Hamburg (August 2001), the AGASA group reported additional data, quite consistent with their earlier work, and described 17 events above $10^{20}$ eV. The HiRes group reported on monocular data obtained with one of their cameras from an exposure slightly greater than that of the AGASA group. Assuming a spectrum similar to that reported earlier by the AGASA group, the HiRes team had expected to see about 20 events above $10^{20}$ eV, but observed only 2. This unexpected discrepancy is not yet understood.

The data from Fly’s Eye (the earliest fluorescence experiment), Haverah Park (a ground array that used water-Cherenkov detectors), HiRes and AGASA are shown in figure 1. There are several points to note. The Haverah Park energy estimates have been re-assessed using the QGSJET model. In the range $3 \times 10^{17}$ to $3 \times 10^{18}$ eV there is very good agreement between the Fly’s Eye, Haverah Park and HiRes results. A recent Haverah Park analysis suggests that protons and iron are in the ratio 35:65 in this energy range. With this mixture the spectrum agreement is even better. This implies that the QGSJET model provides an adequate description of important features of showers up to $10^{18}$ eV. However, the AGASA energies have also been estimated with the QGSJET model under the assumption that the primaries are protons at energies above $3 \times 10^{18}$ eV, the lowest AGASA energy plotted. There is no evidence as to what mass species is dominant at the highest energies but the methods used would lead to an estimate lower by only about 20% if iron nuclei were assumed. This change would be insufficient to reconcile the AGASA-HiRes differences, particularly with regard to the point at which the spectrum slope flattens above $10^{18}$ eV. However a combination of a change in the QGSJET model and iron primaries (for which there is no evidence) might
go some way to aligning the different results at the highest energies.

There are also unanswered questions about the HiRes data. The ‘disappearance’ of the events reported as being above $10^{20} \text{ eV}$ in 1999 is attributed to a better understanding of the atmosphere which is now claimed to be clearer than had previously been supposed. The Hamburg results were prepared using an ‘average atmosphere’ so presumably subsequently some events will be assigned larger energies and some smaller ones. Two further issues need resolving. Firstly, an accelerator-based calibration of the fluorescence yield led to the claim ‘that the fluorescence yield of air between 300 and 400 nm is proportional to the electron dE/dx.’ This claim is not consistent with information tabulated in the paper, where it is shown that the yield from 50 keV electrons is similar to that from 1.4 MeV electrons. Also the dE/dx curve plotted there, normalised to the 1.4 MeV measurements, does not fit the accelerator data for 300, 650 and 1000 MeV electrons. The latter discrepancy is about 15 – 20% and in such a direction as would increase the HiRes energies. Secondly, Nagano et al. has described a new measurement of the yield in air from 1.4 MeV electrons. In what seems to be a very careful study, they find that the earlier results gave a higher yield at 356.3 nm and 391.9 nm than is found now. Nagano attributes the absence of background corrections as being responsible for at least some of the discrepancies. The longer wavelengths become increasingly important when showers are observed at the large distances common at the highest energies because of Rayleigh scattering. The magnitude of the adjustments that need to be made to the HiRes data are presently unclear and further fluorescence yield measurements are certainly required.

At the Hamburg meeting, the HiRes group also reported data from their stereo system. With 20% of the monocular exposure, they found 1 event with an energy estimated as being close to $3 \times 10^{20} \text{ eV}$, the energy of the largest event found with the Fly’s Eye detector. My opinion is that the spectra from AGASA and HiRes will come together as further understanding is gained of the models and of the atmosphere. Knowledge of the mass composition will also help considerably. For now it seems that trans-GZK events do exist but that the flux of them is less certain than appeared a few years ago.

### 0.3.2 Arrival Direction Distribution

The angular resolution of shower arrays and of fluorescence detectors is typically 2 – 3°. The arrival direction of the 59 events with energy above $4 \times 10^{19} \text{ eV}$ registered by the AGASA group is shown in figure 2. The distribution is isotropic and there is no preference for events to come from close to the galactic or the super-galactic planes. The AGASA group draw attention to a number of clusters, where a cluster is defined as a grouping of 2 or more events within 2.5°. It is claimed that the number of doublets (5) and triplets (1) could have arisen by chance, with probabilities of 0.1% and 1%. The implications of such clusters would be profound but the case for them is not proven. The angular bin was not defined a priori and the data set used to make the initial claim for clusters is also being used in the ‘hypothesis testing’ phase. Furthermore, I note that the directions of the 7 most energetic events observed by Fly’s Eye, Haverah Park, Yakutsk and Volcano Ranch do not line up with any of the 6 cluster directions.

It is hard to understand the isotropy if the local extragalactic magnetic field is really just $10^{-9}$ gauss. A proton of $10^{20} \text{ eV}$ would be deflected by only about 2° over a distance of 20 Mpc if the field has a 1 Mpc correlation length. If the fields were much higher, as
Figure 2: AGASA arrival direction distribution for 59 events above $4 \times 10^{19}$ eV. The most energetic events ($> 10^{20}$ eV) are shown by squares [20].

has been suggested [9], then the lack of anisotropy might be understood, but more energy is then stored in the magnetic field and this might create other difficulties. Similarly, if the charge of the particles initiating the showers was much higher than $Z=1$, the isotropy could be explained.

0.3.3 Mass Composition

Interpretation of the data on UHECRs is hampered by our lack of knowledge of the mass of the incoming particles. Data from several experiments can be interpreted as indicating a change from a dominantly iron beam near $3 \times 10^{17}$ eV to a dominantly proton beam at $10^{19}$ eV. But the situation is unclear and quite open at higher energies. The data are just too limited and the interpretations are ambiguous as both the fluorescence detectors and ground arrays rely on shower models to deduce composition information.

It is unlikely that the majority of the events claimed to be near $10^{20}$ eV have photons as parents as some of the showers have the normal numbers of muons (the tracers of primaries that are nuclei) and the profile of the most energetic fluorescence event is inconsistent with that of a photon primary [10]. Furthermore, there is now evidence that less than 40% of the events at $10^{19}$ eV are photon-initiated. This limit has been set in two ways. Taking the energy spectrum as measured by Flys Eye as being independent of the mass of the incoming particles, the rate of showers coming at large angles to the vertical can be calculated. Using Haverah Park data, it has been found that the observed rate of inclined showers is much higher than would be expected if the primary particles were mainly photons [10]. A more traditional attack on the problem by the AGASA group, searching for showers which have significantly fewer muons than normal, has given the same upper limit [19]. It is unlikely that many events are created by neutrinos as the
distribution of zenith angles would be different from that observed. Indeed, in all aspects so far measured, events of $10^{20}$ eV look like events of $10^{19}$ eV, but ten times larger, and this can be reiterated as we go to lower and lower energies were nuclei seem certain to be the progenitors of showers.

### 0.4 Theoretical Interpretations

The UHECR enigma is attracting significant theoretical attention. Some ideas suppose a form of electromagnetic acceleration while others invoke new physics.

Currently it is popularly believed that cosmic rays with energies up to about $10^{15}$ eV are energised by a process known as ‘diffusive shock acceleration’. Supernovae explosions are identified as the likely sites, although so far there is no direct evidence for acceleration of nuclei by supernova remnants at any energy. The diffusive shock process, which has its roots in some early ideas of Fermi, has been extensively studied since its conception in the late 1970s. In 

$$E = kZeBR\beta c,$$

where $B$ is the magnetic field in the region of the shock, $R$ is the size of the shock region and $k$ is a constant less than 1. The same result has been obtained by a number of people, e.g., 

$$E = kZeBR\beta c,$$

and most authors agree upon it. However, some claim that the diffusive shock acceleration process can be modified to give much higher energies than indicated by the equation and that radio galaxy lobes, in particular, are probable acceleration sites. It is difficult to see how an energy of $3 \times 10^{20}$ eV can be accounted for if the size of the shock region is 10 kpc and the magnetic field is 10 $\mu$G (values thought typical of lobes of radio galaxies), as even the optimum estimate of the energy is lower by a factor of 3 than the observational upper limit. It could be that the magnetic fields are stronger than is usually supposed, a line of argument that also comes from the arrival direction work mentioned above.

Proposals have been made which dispense with the need for electromagnetic acceleration. Attention has usually been focused on the highest energy events ($> 10^{20}$ eV). However, it is my view that proposers of some of the more exotic mechanisms often overlook one or more important points. Any mechanism able to explain the highest energy events must also explain those above about $3 \times 10^{18}$ eV, where the galactic component possibly disappears. The spectrum above this point is possibly too smooth to imagine that there are two or more radically different components — although this might be seen as an almost philosophical argument, particularly in the light of figure 1! In addition, the solutions proposed must produce particles at the top of the atmosphere that can generate showers of the type we see and now understand rather well. Finally, source energetics cannot be ignored: there seems little point in inventing a mechanism to ‘solve’ the GZK cut-off problem that requires a source region that is unrealistically energetic.

An overview of the various non-electromagnetic processes proposed can be found in 

$$E = kZeBR\beta c,$$

and I will only discuss one of these here. It has been suggested that UHECR arise from the decay of super-heavy relic particles. In this picture, the cold dark matter is supposed to contain a small admixture of long-lived super-heavy particles with a mass $> 10^{12}$ GeV and a lifetime greater than the age of the Universe. It is argued that such particles can be produced during reheating following inflation or through the decay of hybrid topological defects such as monopoles connected by strings. I find it hard to judge how realistic these ideas are but the decay cascade from a particular candidate has been studied in some detail and . A feature of the decay cascade is that
an accompanying flux of photons and neutrinos is predicted which may be detectable with a large enough installation. In particular photons are expected to be between 2 and 10 times as numerous as protons above $10^{19}$ eV. The anisotropy question has been examined and specific predictions have been made for the anisotropy that would be seen by a Southern Hemisphere observatory. Observation of the predicted anisotropy, plus the identification of appropriate numbers of neutrinos and photons, would be suggestive of a super-heavy relic origin. However, the experimental results on the photon/proton ratio at $10^{19}$ eV described above clearly do not support it.

0.5 Detectors of the Future

The Pierre Auger Observatory was conceived to measure the properties of the highest energy cosmic rays with unprecedented statistical precision. When completed, it will consist of two instruments, in the Northern and Southern Hemispheres, each covering 3000 km$^2$. The design calls for a hybrid system with 1600 particle detectors and three or four fluorescence detectors at each of the sites. The particle detectors will be deep water-Cherenkov tanks arranged on a 1.5 km hexagonal grid. These detectors have been selected because water acts as a very effective absorber of the multitude of low energy electrons and photons found at distances of about 1 km from the shower axis.

At the Southern site fluorescence detectors will be set up at four locations, one near the centre of the particle array with the others on small promontories at the array edge: the site is close to the town of Malargüe in Mendoza Province, Argentina. During clear moonless nights, signals will be recorded in both the fluorescence detectors and the particle detectors, while for roughly 90% of the time only particle detector data will be available. Construction of an engineering array containing 40 water tanks and a section of a fluorescence detector has been completed (September 2001) and all of the sub-systems of the Observatory have been demonstrated. The first ‘hybrid’ events were recorded in December 2001 and there is great confidence that the Observatory will work as designed. When the Auger Observatory at Malargüe has operated for 10 years, we would expect to have recorded over 300 events above $10^{20}$ eV.

Achieving an exposure greater than that targeted by the Auger Observatory is a formidable challenge. A promising line is the development of an idea due to Linsley. The concept is to observe fluorescence light produced by showers from space with satellite-borne equipment. It is proposed to monitor $\sim 10^5$ km$^2$ sr (after allowing for an estimated 8% on-time). Preliminary design studies have been carried out in Italy and the USA. An Italian-led collaboration has proposed a design that is under study for flight in the International Space Station. This is known as EUSO (the Extreme Universe Space Observatory), and has the potential to detect neutrinos in large numbers as well as UHECRs. Observations are scheduled to start in 2008. This type of project requires considerable technological development but may be the only way to push to energies beyond whatever energy limits are found with the Auger instruments.

Acknowledgements: I am grateful to the organisers for inviting me to the Blois meeting. On-going support of PPARC to work on ultra high-energy cosmic rays at the University of Leeds is gratefully acknowledged. I also thank my many colleagues in the Pierre Auger project for helping to make a 10-year-old dream become a reality.
Bibliography

[1] Ave, M., et al., 2001, Proc 27th Int. Conf. on Cosmic Rays (Hamburg) 1 381
[2] Ave, M., et al., 2001, Proc 27th Int. Conf. on Cosmic Rays (Hamburg) 1 385
[3] Ave, M., et al., 2000, Phys Rev Letters 85 2244
[4] Benakli, K., Ellis, J. and Nanopolous, D.V., 1999, Phys Rev D 59 047301
[5] Berezinsky, V., Kachelreiss, M. and Vilenkin, A., 1997, Phys Rev Lett 22 4302
[6] Bird, D., et al., 1995, Astrophys J 441 144
[7] Birkel, M and Sarkar, S., 1998, Astroparticle Physics 9 297
[8] Drury, L. O’C., 1994, Contemporary Physics 35 232
[9] Farrar, G.R. and Piran, T., 2000, Phys Rev Letters 84, 3527
[10] Halzen, F., et al., 1995, Astroparticle Physics 3 151
[11] Hillas, A. M., 1984, Ann. Rev. Astronomy & Astrophysics 22, 425
[12] Kakimoto, F., et al., 1996, Nucl Inst and Methods A372 527
[13] Kronberg, P.P., 1994, Rep Prog Phys 57 325
[14] Nagano, M. et al., 2000, Astroparticle Physics 13 277
[15] Nagano, M. and A. A. Watson, 2000, Rev Mod Phys 27 689
[16] Nagano, M., et al., 2001, Proc 27th Int. Conf. on Cosmic Rays (Hamburg) 2 675
[17] Nagano, M., private communication, September 2001
[18] Rubin, N. A., 1999, M Phil Thesis, University of Cambridge
[19] Shinosaki, K, et al.,2001, Proc 27th Int. Conf. on Cosmic Rays (Hamburg) 1 346
[20] Takeda, M, et al., 2001, Proc 27th Int. Conf. on Cosmic Rays (Hamburg) 1 341