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Dedicated to Prof. Dorin N. Poenaru's 70th Anniversary

COSMIC RAYS OF THE HIGHEST ENERGIES

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Abstract. The origin and mode of propagation of cosmic rays of the highest energies is examined. Particular reference is made to a contemporary problem: at what energy is there a transition from mainly Galactic to mainly Extragalactic origin?

Key words: energy spectrum, composition, origin Galactic/Extragalactic, netra-high energies.

1. INTRODUCTION

It is appropriate that this contribution on cosmic rays of the **highest** energies should be offered to help celebrate the 70th birthday of a man of the **highest** intellectual calibre: Professor Dorin Poenaru. We wish him many more years of healthy and vigorous life.

2. AN OVERVIEW

'Cosmic rays' (CR) were discovered in 1912 by Victor Hess during perilous balloon ascents in which he had hoped to find out why ground-based electroscopes never maintained their charge. He correctly diagnosed a 'radiation' incident on the atmosphere from 'the Cosmos' and slowly attenuated with depth. The term 'radiation' was used because of the view that some form of ultra-energetic gamma radiation was responsible.

Later work showed that the bulk of the radiation was, in fact, composed of particles: protons, heavier nuclei and electrons. Interestingly, there is also a small fraction of gamma rays, present to the extent of some 10^{-6}, and these are helpful for elucidating at least the origin of the lowest energy CR.

The mass composition is not dramatically different from that of the general interstellar medium (with the exception of the 'secondary nuclei', Li, Be and B), although there is an increasing excess of heavier nuclei. In fact, as will be seen later, the identification of the primary masses becomes increasingly uncertain above about 10^{14} eV.

CR have been identified of energy as far as about 10^{20} eV, a truly gigantic value for a single atomic particle. Superficially, at least, the spectrum is characterised by only two features in an otherwise rapidly falling form: a 'knee' at about 3.10^{15} eV and an ankle at an energy approaching 10^{19}eV. These features loom large in attempts to find out where the particles are coming from, how they became accelerated and how they have propagated through space.

3. ENERGY DENSITIES

A perspective on CR can be achieved by examining the energy density of cosmic rays in comparison with that of other, potentially relevant, astronomical quantities. Table 1 shows the situation for Galactic CR (which carry

Table 1

Energy densities in the local Galaxy

Phenomenon	eV cm^{-3}
Cosmic rays	~ 0.5
$\left(\frac{4\pi}{c}\int E\, I(E) dE\right)$	
Magnetic field	~ 0.5
$(B^2/8\pi)$	
Starlight	~ 0.5
$\frac{4\pi}{c}\int hv\, I(hv)\, d\, hv$	
Cloud motion	~ 0.5
$\left\langle \sum \frac{1}{2} M v^2 \right\rangle / V$	

the bulk of the energy). It is fascinating that the values are essentially the same. It is presumed, however, that whereas the equality for magnetic fields is significant that for starlight is not – unless there is a phenomenon of some subtlety present.

Figure 1 shows the situation for extragalactic (EG) radiations and it will be noted that there are wide disparities. Some remarks are necessary about the value for UHECR, and this relates to much of the rest of this article.

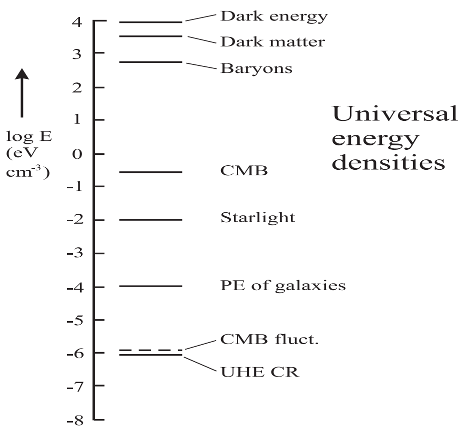

Fig. 1 – Universal energy densities.

The question concerns the demarkation energy below which the particles are Galactic (G) in origin and above which they are EG.

A variety of models have been put forward and Fig. 2 shows the results of different analyses. It will be noted that in our work the EG fraction is a minimum. Thus, the 'UHECR' value shown in Fig. 1 should be regarded as a minimum.

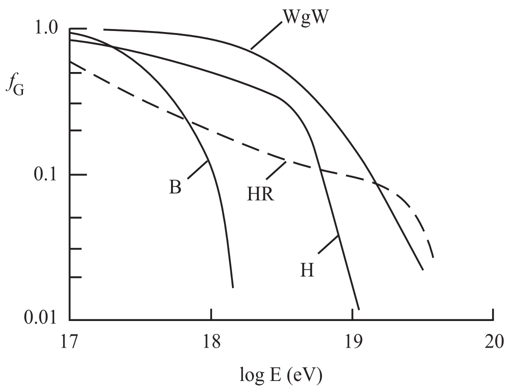

Fig. 2 – Galactic fractions (from Wibig and Wolfendale, 2005). WgW – present work. B – Berezinsky *et al.*, (2004). HR – High Res. – private communication. H – Hillas (2004).

Considering Fig. 1, it is interesting to note that the UHECR energy density is much less than that in the cosmic microwave background (CMB), showing that the particles are not of cosmological origin in the true sense. However, the energy density in the fluctuating part of the CMB is similar to that in the UHECR, although it is unlikely that UHECR themselves have any effect, at the detectable level, on the CMB. What is likely, however, is that Galactic CR are relevant to the CMB fluctuations, in the sense that there are correlations between GCR effects (as evinced by radio and gamma ray observations) and the CMB fluctuations (eg Wibig and Wolfendale, 2005).

Of some relevance in Fig. 1 is the fact that the energy density of UHECR is about 1% of the 'PE of galaxies'; this quantity is the energy available from the collapse of matter to form galaxies in the first place. It might have been expected that one way or another CR would participate in this energy release: 1% seems a not unreasonable fraction. It should be noted that the relatively higher energy density for GCR is because of the large trapping factor for the Galaxy caused by the Galactic magnetic field.

4. THE SPECTRAL SHAPE

In a number of publications (e.g. Szabelski *et al.*, 2002) we have collated the data on the primary energy spectrum of UHECR. The latest compilation is given in Fig. 3. Systematic errors are removed by normalization but

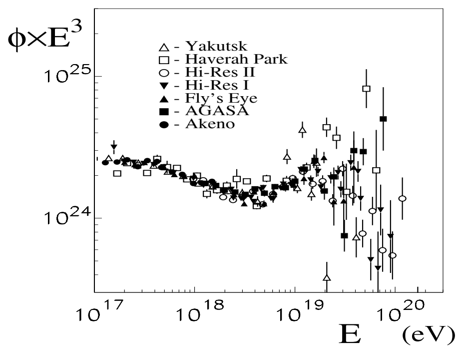

Fig. 3 – The best combined UHECR data (see the earlier version by Szabelski *et al.*, 2002 for the key). Intensity units: eV^2 m^{-2} s^{-1} sr^{-1}.

unidentified errors remain, particularly in the most important region above $\sim 3 \times 10^{19}$ eV. It will be remembered that the results come from measurements made on the 'extensive air showers' generated by the impact of the UHECR on air nuclei. There are many steps from the observed quantities, by way of assumptions about the physics of nuclear interactions, to the end product: the energy spectrum.

What can be said, without fear of contradiction, is that there is an 'ankle' at about 10^{19} eV. Whether there is evidence for the famed GZK – 'cut-off' (actually a predicted turn over of intensity) is still debatable.

5. THE MASS COMPOSITION

The usual method of determining primary mass is by way of the 'depth of maximum', X_{max}, ie the depth in the atmosphere at which the number of particles in the shower is greatest.

Figure 4 shows the results from one early analysis (by Wibig and Wolfendale, 1999; the measurements being by Bird *et al.*, 1993). The main problem

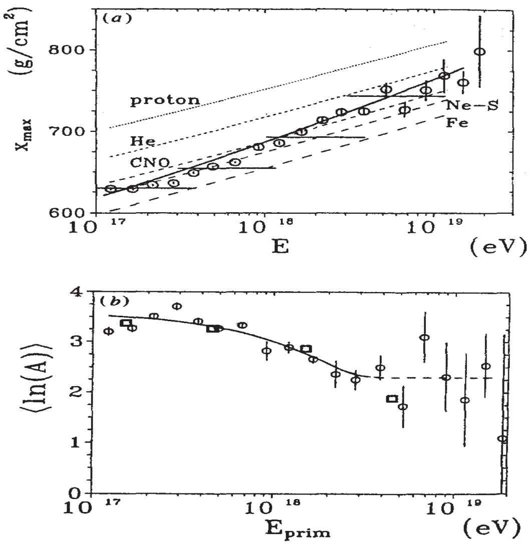

Fig. 4 – a) Depth of maximum (X_{max}) versus primary energy, E_{prim}. The lines are from 'our' calculations (1) and the points are from the Fly's Eye experiment (Bird *et al.*, 1993); b) (in A) *versus E* derived from (a) by linear interpolation. The curve is simply to guide the eye (from Wibig and Wolfendale, 1999).

in determining the primary mass is in knowing the exact position of the theoretical lines, for protons, He ... Fe, in view of the uncertainty about the interaction model. Figure 5 shows the results of a recent compilation of the estimated fraction of primary Fe in the CR beam.

Taken at its face value, Fig. 5 indicates about 20% Fe at 3.10^{19} eV. In view of the fact that if these particles were Galactic in origin we would expect a marked anisotropy in arrival directions – a 'Galactic Plane Enhancement' (Chi *et al.*, 1993, 1994) – and only a very small one is seen, we consider that the EG flux is 'mixed' unlike the common view that protons alone constitute the EG beam.

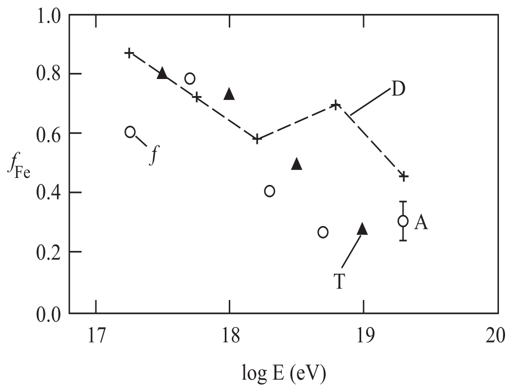

Fig. 5 – Fraction of iron in the primary beam. T – trajectories for Galactic particles: Chi *et al.*, (1994). f – frequency of shower maxima: Wibig and Wolfendale (1999). A – Akeno: Shinosaki *et al.*, (2003). D – Dova *et al.*, (2003). The summary is from Wibig and Wolfendale, 2005).

In what follows, we consider alternatively the EG beam being mixed and the EG beam being overwhelmingly protonic. In the first case the ankle marks the cross-over point for G and EG; in the second case there is an alternative explanation and that most of the CR are EG down to about 5.10^{17} eV (or even 1.10^{17} eV).

6. THE ANKLE AS THE G/EG INTERFACE

An example of this situation is shown in Fig. 6, for the stylized case where the EG spectrum has a constant slope (of -2.37) and the smoothly falling G-spectrum is chosen to provide the rest of the total.

Modifications to the EG spectrum are necessary to allow for CR propagation through the CMB and these can be seen by reference to Fig. 7 which shows the relevant energy losses. Of particular importance is the rapid rise in losses at about $6 \cdot 10^{19}$ eV due to pion production and this quickly distorts the EG spectrum shown in Fig. 6. The actual distortion depends on the manner in which the particles are 'produced' in the sense of spatial distribution of the sources and their intensity.

The simplest situation is where there is uniform production in a Euclidian universe out to the Hubble radius. Here, the modified spectral form will be simply the power law multiplied by the inverse of Fig. 7. It will be apparent that there is an experimental excess of particles, although it must be admitted that the residual presence of systematic errors (Fig. 3) is a worry. Figure 8 shows the situation in more detail, where the pion losses are included. Results are given for different spectra (above 10^{19} eV). A 'flat' production spectrum is

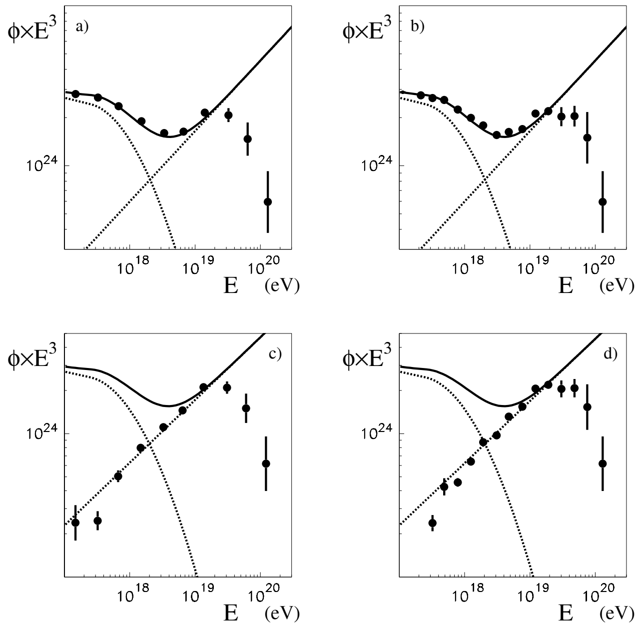

Fig. 6 – a), b) A world summary of the UHECR with different binning (left and right). Galactic and EG spectra (the latter with slope −2.37) are indicated, as is their sum; c), d) the world average data after subtraction of the galactic component. The line corresponds to a spectrum with slope −2.37. It is evident that a smoothly falling Galactic spectrum results in an EG spectrum that is a simple power law for energies below log $E \sim 19.4$ (from Wibig and Wolfendale, 2005).

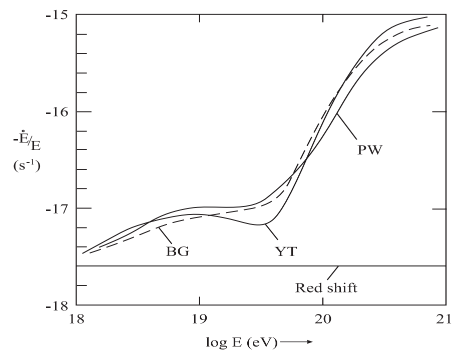

Fig. 7 – Range of energy loss of protons on the CMB from various authors. PW – ‘present work’ (Wibig and Wolfendale, 2005). BG – Berezinsky, Vs and Grigor’eva, Astron. Astrophys., **199**, 1 (1988). YT – Yoshida and Teshima, M. Prog. Theor. Phys., **89**, 833 (1993).

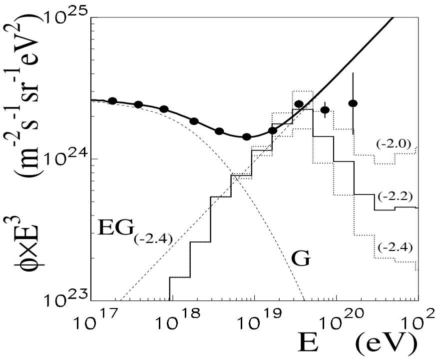

Fig. 8 – Primary energy spectrum of ultra-high energy cosmic rays. The points represent the summary of the world's data after normalization to the same 'ankle' position and using the scale for the Hi-Res experiment. The sharp minimum ('ankle') at log $(E)\sim 18.7$ is regarded by us as strong evident for a transition from Galactic (G) to Extragalactic (EG) particles; primary protons are assumed in the comparison of expectation with the points but the results for primary iron nuclei would be similar, in view of the normalization of the expectations to the EG line at 10^{19} eV (from Wibig and Wolfendale, 2004).

indicated (exponent $= -2.0$) but the inclusion of heavy nuclei (Fig. 3), which have a rapid intensity fall-off at a higher energy than for protons, would close the gap.

There seems little doubt that the explanation of the ankle as the site of the G/EG interface is in with a good chance.

7. THE ANKLE: A PROPERTY OF THE EG FLUX ITSELF?

7.1. GENERAL REMARKS

Insofar as a power law EG injection spectrum would itself give, after propagation through the CMB, a spectrum at earth having a distinct ankle (Fig. 7), serious attention must be given to the possibility. As shown in Fig. 2 a number of workers have adopted this idea, the EG flux then extending back to the range $10^{17} - 10^{18}$ eV.

We, ourselves, prefer the scenario in which the ankle corresponds to the intersection of the individual G- and EG- spectra. The reasons are as follows:

i) A 'sharp' crossing of the G- and EG- spectra guarantees a sharp knee, whatever the smearing effects experienced by the EG spectrum.
ii) The smearing effects on the latter are manifold and include:

∗ Variations in the temperature of the ambient space penetrated by the CR, particularly in the region of the sources (see Wibig and Wolfendale, 2005, for discussion of the effect of the IR 'background' near cluster sources).
∗ Non-smoothly varying spatial distributions of the sources/quasars, AGN, galaxy clusters ...)

iii) With the standard model (uniform production in a Euclidian Universe) there is a marked shortage of CR below $3 \cdot 10^{18}$ eV. Whilst it is possible to invoke an evolutionary increase in intensity, and to improve the fit below 10^{19} eV, the ankle position is displaced to much higher energy and the fit destroyed. A further problem is that the G-EG transition (Fig. 8), which would be at $\sim 10^{17}$ eV, would produce an ankle there, which is not observed.

iv) If, indeed, there is a mixture of masses in the primary EG beam (Fig. 5) then, as we have shown (Wibig and Wolfendale, 2005) only 10% of iron would smooth out the ankle and the model be ruled out.

7.2. SPECIFIC CALCULATIONS

As a check on the contention that the ankle is most unlikely to be due to EG protons we have embarked on calculations for specific situations.

The results so far are available for two cases: a uniform distribution of sources in a Euclidian Universe and a spatial distribution following that of Galaxy clusters (using the results of Bahcall *et al.*, 1988).

Figure 9 shows the results for the two cases, for the situation where the injection spectrum has a differential slope of −2.4. To provide an adequate

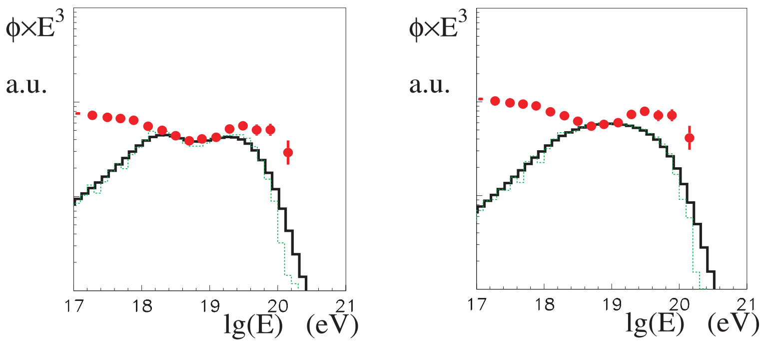

Fig. 9 – Primary spectra of UHE CR for two models for the spatial distribution of the sources. The injection spectrum has an exponent of −2.4. With a realistic modulated source distribution the predicted ankle is smeared out.

supply of particles below $\log E = 19.0$, an injection spectrum having such a slope would be needed. It is apparent that there is indeed an ankle just below $\log E = 19.0$ but it is not sufficiently sharp.

Turning to the galaxy cluster situation, there is no ankle at all, the ankle being smeared out by the non-uniform spatial distribution of CR sources. Calculations for other potential sources are on-going; these include quasars and AGN. We have no reason to believe that the ankle will be sharpened.

8. CONCLUSIONS

Although the problem of the origin of the highest energy particles, and their propagation through the Universe, is by no means solved, it looks as though the characteristic 'ankle' in the primary CR spectrum at $\log E \simeq 19.0$ is not an intrinsic property of the EG injection spectrum but that it marks the changeover from a Galactic to an Extragalactic Component.

The source of the EG particles is still obscure but AGN, quasars, galaxy clusters, colliding galaxies ... all have their adherents.

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