Ultra High Energy Cosmic Rays

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Cosmic rays with energies above 1 EeV are currently of considerable interest in astrophysics and are to be further studied in a number of projects which are either currently under construction or the subject of well-developed proposals. This paper aims to discuss some of the physics of such particles in terms of current knowledge and information from particle astrophysics at other energies. Included is an argument that the role of galactic sources at these ultra high energies should not be ignored. Also, the key role of the unknown structure and magnitude of the intergalactic magnetic field is emphasised.

§1. Introduction

Cosmic rays of the highest energies are currently of considerable interest. Spectral data at energies above 1 EeV (10^{18}eV) and directional results, notably from the AGASA project, are very suggestive of fascinating, unexpected physics.1) Further, this field of research is experimentally challenging and there is controversy in discrepancies between experimental data from experiments currently operational or recently discontinued. A new era in the field will soon begin with the commissioning of the Pierre Auger Project2) and then possible large-scale Japanese projects plus a space-based system.

At the present time, our ideas concerning cosmic rays at the very highest energies are predominantly based on the idea that such particles are likely to be of extragalactic origin. Their sources are presumed to be found in some extreme astrophysical environment such as the most energetic radio or gamma-ray sources. We have been forced to these ideas by our failure to identify any models for galactic objects capable of accelerating particles to within one thousandth of the required energies, and by the failure of our galactic source models to reproduce the directional isotropy of the observed beam. Nonetheless, extragalactic scenarios have their own problems. The intergalactic magnetic field has largely unknown properties. It could be strong enough, with a structure which makes it impenetrable to particles from nearby clusters of galaxies in realistic periods of time. Also, intracluster magnetic fields may limit the ability of particles even to leave galactic clusters. Finally, we still do not have a defined source model even with extreme astrophysical extragalactic objects.

This paper aims to describe some of the fundamental measurements of the highest energy cosmic rays and to indicate some possibly alternative interpretations of their results.

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§2. The cosmic ray energy spectrum

The cosmic ray energy spectrum is shown in Fig. 1. It is remarkable both in its range of energies and in its range of fluxes. It covers over ten decades of energy and thirty decades of flux in a form close to a power law with an index of about −2.7. Deviations from that power law are relatively small but are generally regarded as physically significant. There is a steepening at about 10^{16}eV, known as the knee, and a flattening at about 10^{18}eV known as the ankle. The knee is often argued to be associated with an energy limit of acceleration from supernova remnant sources although we will present an argument below that is primarily associated with a loss of ability for the galaxy to retain (and build up internally) its cosmic ray flux. The ankle is usually associated with the onset of a dominant, flatter, extra-galactic cosmic ray spectrum. Again, we will later propose an alternative scenario for consideration which will point to a more local source. It is important to note that in the conventional model described above, our galaxy produces particles with energies up to the ankle of the spectrum. That is already above 10^{18}eV, and is above

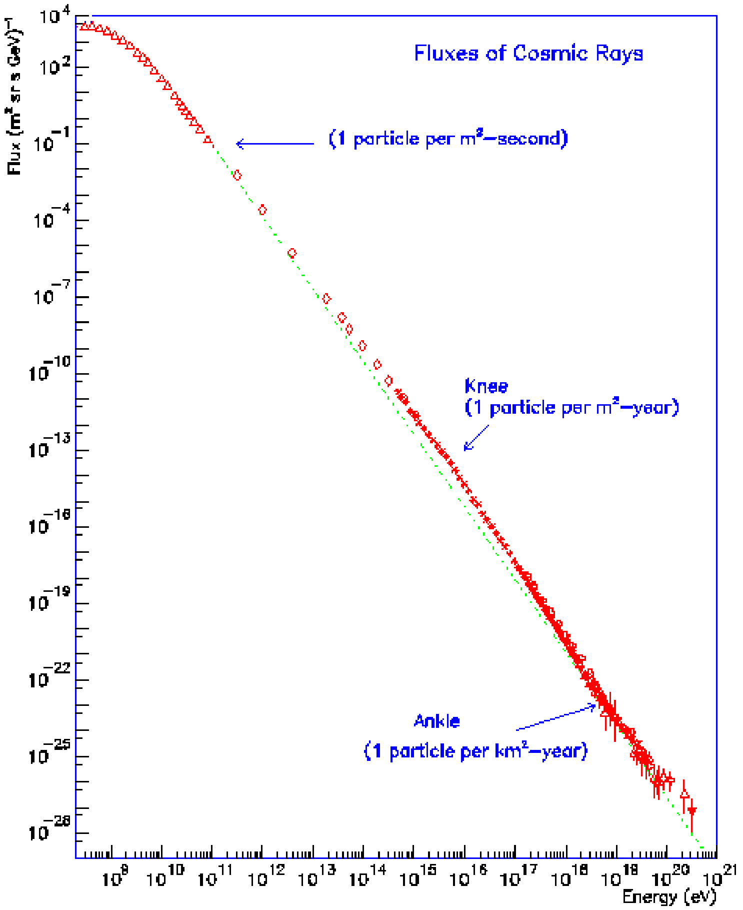

Fig. 1. The cosmic ray energy spectrum as measured from the Earth.[3)]

energies which are accessible for any present galactic acceleration models.

A key region of the spectrum is its very highest energies. The flux here is so low that the low event statistics in our observations to date leave us uncertain of the spectral structure above the key energy of 6×10^{19}eV. Above this threshold, there is a predicted spectral downturn (the GZK cut-off) for particles which have travelled more than a few tens of Mpc, due to interactions with the 2.7 K cosmological microwave background.[4)−6)] That distance is significant, happening to be the characteristic distance to any astrophysical object which differs significantly from those found in our own galaxy.

The remaining spectral feature is the flattening below 10^{10}eV which is certainly associated with heliospheric physics since these low energy cosmic rays have to reach us through the outflowing solar wind plasma and magnetic field. The spectrum outside the heliosphere is not known well at these energies. The total energy density above 1 GeV is about 1 eV/cc but this is arbitrary, depending as it does on the energy limit set by the solar wind. Since there is no evidence for a true flattening of the galactic spectrum, it is interesting to note that a galactic-wide cosmic ray proton flux which extended only a few decades down in energy could provide the energy/mass density to explain the galactic rotation curve. If universal, it could contribute significantly to the total universal dark matter. The arguments against such a cosmic ray dark matter component are currently rather weak.

§3. Arrival directions

A key observation in cosmic ray astrophysics is the directional distribution of the particles. That distribution will depend on any galactic magnetic fields and hence will be energy (rigidity) dependent. However, with very limited exceptions, which are not individually statistically significant, there is no observed deviation from isotropy above the knee of the energy spectrum (see Fig. 2). Any anisotropies at lower energies are themselves very small.[8)] Figure 2 is interesting in itself. It may appear that the amplitude of the first harmonic of the anisotropy (the broad-scale anisotropy on the sky in right ascension at the declination of the observing array) increases with energy. Whilst this may seem to be physically reasonable with the particles travelling in straighter lines as their rigidity increases, to a good approximation there is truly no significant anisotropy in the data. The amplitude data in the figure are almost all limits set by statistical limitations in the total numbers of recorded events. The increase in apparent amplitude is due to the precipitous decrease in the flux as a function of energy. However, Linsley[9)] has shown that the phase of the anisotropy may be sensitive even when the amplitude is not, and there may well be interesting data in the consistency of the phases below 10^{17}eV which is associated with galactic magnetic field effects.

The lack of any visible ‘Milky Way’ in the cosmic ray sky (the lack of any galactic plane anisotropy), tells us that the sources are distributed in some more uniform way than the optically visible galaxy. Liouville’s theorem tells us this, provided that the cosmic rays do not suffer energy loss whilst propagating in astrophysical magnetic fields. However, those same magnetic fields almost certainly remove any possibility

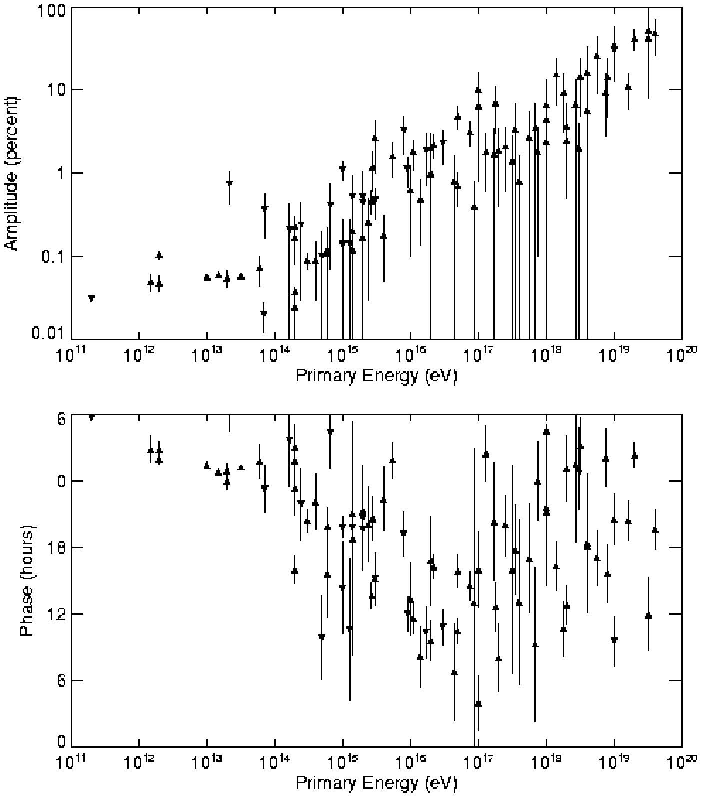

Fig. 2. The anisotropy of cosmic rays. 7)

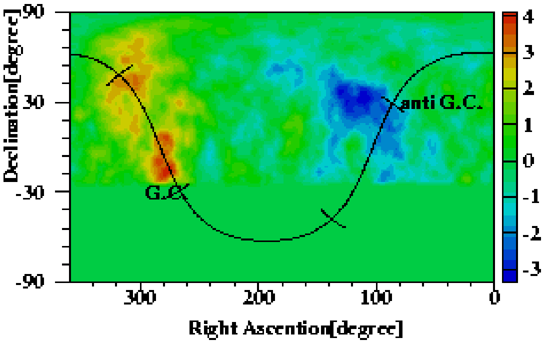

Fig. 3. The statistical significance of deviations from the expected event distribution for AGASA events. The energy range is $10^{18.0}$eV to $10^{18.4}$eV. 1)

of directional charged cosmic ray astronomy below 10^{19}eV. 10), 11)

Recently, the AGASA experiment 1) found a non-uniform distribution of arrival directions in the energy range $10^{18.0}$eV to $10^{18.4}$eV (Fig. 3). That observation is potentially very important, particularly as there is supporting evidence in data from the SUGAR array.[12)] However, neither of those observations on their own is clearly statistically significant. Those data are regarded by many as the possible beginning of a new era in cosmic ray astrophysics in which we can begin cosmic ray astronomy. The possibility of having a source to observe may indeed open up new frontiers. Already, interpretations of the data (see below) may be giving us new and important information on the structure and extent of the galactic magnetic field.

§4. Cosmic ray sources

Cosmic rays are accelerated within our galaxy. It is possible that the highest energy ones come from elsewhere or that some are produced by the decay of exotic particles, but the fact that radio astronomers detect galactic synchrotron emission from high energy cosmic ray electrons in plausible acceleration sources makes it certain that our galaxy is capable of accelerating high energy nuclei. Radio measurements often indicate that the electrons have a power law spectrum and that spectrum often exhibits a spectral break due to electron synchrotron losses. These limit the electron energies which are achieved. It is reasonable to believe that such sources accelerate nuclei. Synchrotron losses are suppressed for the massive nuclei, hence we expect that radio sources are also sources of highly energetic cosmic ray nuclei.

The mechanism for producing such high energies is generally believed to be some form of shock acceleration in which the repeated scattering of some particles backwards and forwards across a relativistic shock results in a progressive increase in particle energy. This process results in a small fractional energy increase per scat-

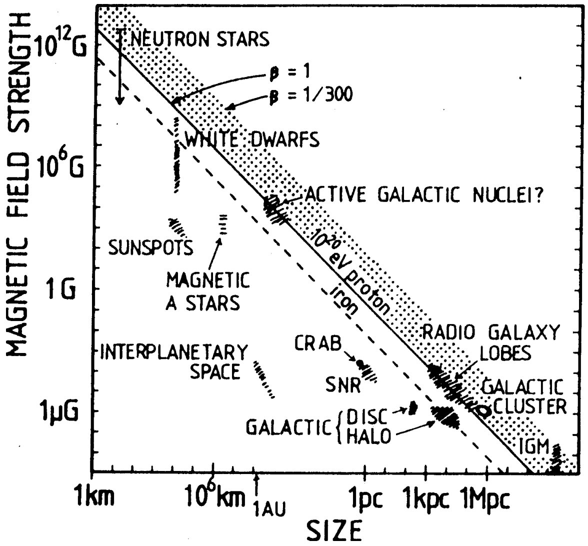

Fig. 4. Proposed sites for cosmic ray acceleration related to their likely dimensions and magnetic field strength. The lines represent plausible energy limits for cosmic ray containment in the sources.[13)]

tering cycle and requires a shock which has some stability over the total acceleration time. At much lower energies, Lim et al.[14)] studied heliospheric shock acceleration *in situ*. In the particular case which they studied, they noted a severe time constraint on the possible shock acceleration mechanisms. In that case, the acceleration time required for diffusive acceleration was four times the lifetime of the shock structure. The point of this comment here is merely to emphasise that the lifetime of a source may be an important factor for us to consider.

Figure 4 is a well known diagram first produced by Hillas.[13)] It reminds us that acceleration associated with magnetic structures requires the field and its dimensions to be sufficient to contain the accelerating particle through the acceleration process. This puts a limit on the product of the source field and its physical dimensions. Strong fields with large-scale structure are necessary for acceleration to the highest energies. An interpretation of Fig. 4 is that there are few (or no) suitable acceleration sites for the highest energy cosmic rays if a slow acceleration process is required. The problem is brought into clearer focus when one considers that real shocks are unlikely to be the simple structures often used in our models and may well be much more leaky than we assume. Further, as we noted above, we know that our galaxy is capable of accelerating particles above 1 EeV and yet we have no clear galactic sources even for those energies. It appears that shock acceleration may be what we need but that mechanism is at its limits for UHE cosmic rays.

We note that, since Hillas originally produced his diagram, new knowledge has been found on galactic objects which may reward further study as acceleration sites. For instance, in the direction of the SUGAR excess, there is a microquasar V4641 Sgr with superluminal radio jets. This would seem to be a scaled down version of popular AGN acceleration sites which are themselves too distant at energies for which the GZK cut off applies.

§5. Propagation

Cosmic rays reach us after travelling through the magnetic fields which pervade space. Details of the strength and structure of such fields are unknown but broad generalisations are possible within certain volumes of the Universe.

Our galaxy is of spiral structure and the galactic magnetic field has a regular component with a characteristic strength of the order of microgauss and which seems to be associated with the spiral arms. Additionally, there is a turbulent, random, component which is at least as strong as the regular component. This component is even less well known since measurements of Faraday rotation or other techniques tend to average out when the line of sight transits a number of turbulence cells. The spectrum of turbulence scales is often assumed to be of a Kolmogorov kind which has the important property of being dominated by the largest scale sizes. This means that the largest scale lengths in the turbulence tend to dominate the cosmic ray propagation. Within our galaxy, the largest internal structures tend to be of 100 pc scales (e.g. supernova remnants). With a field strength of a few microgauss, this means that significant scattering of cosmic rays will occur at least to a few times 10^{17}eV.

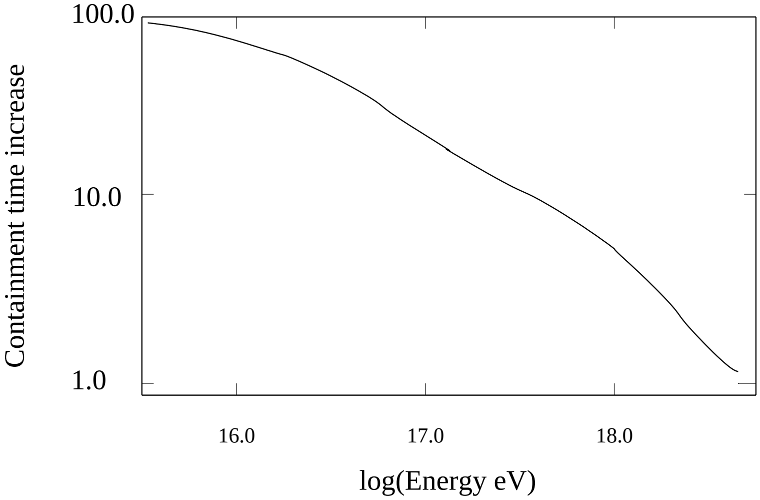

Fig. 5. The fractional increase in containment time (over their direct exit time) for cosmic rays in a model of our galaxy which includes both regular and random magnetic fields.[10)]

The particles follow paths rather like random walks, with a scattering length of the order of a gyroradius (up to the scale size of the turbulence). A first approximation to galactic propagation is then diffusion. Honda[15)] has given an excellent discussion of extensions to make the simple picture more realistic. That work, and similar propagation modelling by Clay,[10)] gives us some understanding of resulting measurable properties of the cosmic ray beam. Since the propagation is diffusive, the time for a particle to leave the galaxy is greater than the simple direct transit time. Figure 5 shows the results of calculations by Clay which indicate the level of this increase. Cosmic ray particles travel essentially at the speed of light and so this containment time increase results in an increase in flux over that which would have been observed had there only been straight line propagation from galactic sources. Figure 6 shows the result of allowing for that increase. It allows us to crudely determine a ‘source flux’. That source flux, or source energy spectrum, shows no knee and, possibly, no ankle. It may be that both those features (and certainly the knee) are consistent with purely propagation effects. The resulting source spectrum is now a power law with an index of -2, the limit of physically acceptable indices. There is a problem with such an explanation of the ankle since particles above that energy travel in rather straight lines and a ‘Milky Way’ perhaps ought to be visible in the anisotropy data. However, data at these energies are somewhat sparse and, of course, the AGASA/SUGAR source could be just such an effect. It would seem that there is an argument for suspecting that the observed cosmic rays all come from our galaxy but that there is a strong counter argument in terms of the isotropy at the highest energies (e.g. Ref. 16)).

Cosmic rays from extragalactic sources also propagate to us through astrophysical fields. As we noted above, the GZK effect of progressive photopion production energy losses in the 2.7 K cosmological background limits the plausible source distance at the highest energies to a few tens of Mpc. However, in reality this means the

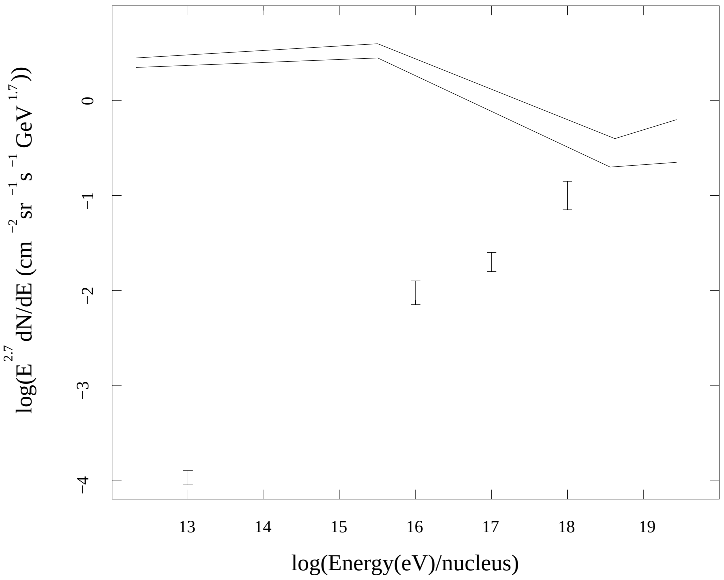

Fig. 6. The cosmic ray energy spectrum (points with error bars) with galactic containment time effects removed.$^{10)}$

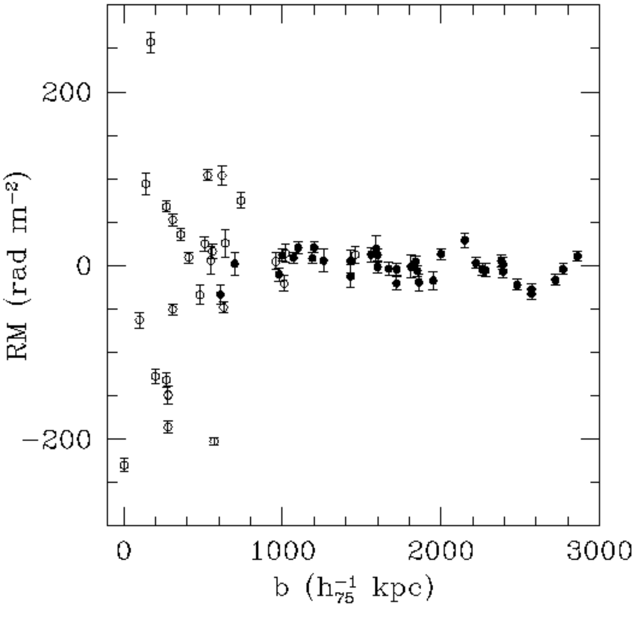

Fig. 7. The galaxy-corrected rotation measure as a function of source impact parameter for a sample of 16 Abell clusters.$^{17)}$

total transit time must be less than about 10^8yr and the source rectilinear distance limit will depend on the form of propagation.

In considering the propagation path, there are two environments to consider. They are the intra-cluster magnetic fields of both the source galaxy and our own galaxy, and the inter-cluster field. Clarke et al.[17)] have shown that, remarkably, a characteristic intra-cluster magnetic field strength in a rich galactic cluster fills the cluster and has microgauss strengths — maybe 5 μG in the inner 500 kpc (Fig. 7). If we make a simple first approximation to a diffusion coefficient as the speed of light (the cosmic rays)* the radius of gyration/3, we can assume diffusive propagation and derive an estimate of the time to reach a given root-mean-square displacement. If we consider a 10^{19}eV particle in the 5 μG field, we find a required time of 10^{8}yr just to leave the source cluster through 500 kpc. The GZK effect is clearly relevant here. If the source is in the Virgo Cluster of galaxies, it may have to travel through the remainder of the cluster to reach intercluster space and then reach us though our own cluster field. In fact, it may be that the intercluster field is also at microgauss levels. In this case, we are looking at tens of megaparsec from the nearest likely AGN source with a transit time, being dependent on the square of the distance, greater than the age of the Universe. This is clearly an issue which pushes us to a careful consideration of very local sources.

This argument is rather crude. Sigl[18)] has modelled time delays for particles travelling 10 Mpc in a turbulent 0.3 μG field. These are shown in Fig. 8. Even for that modest field strength, transit times of 10^{8}yr apply at 10-100 EeV. Apart from any concern about particles reaching us within the age of the Universe, our comments on diffusion times emphasise that it may not make sense to correlate cosmic ray observations with sources beyond 10 Mpc unless one can be sure that those sources have a lifetime for emission substantially greater than 10^{8}yr.

Let us reconsider the data from the AGASA array which suggests a cosmic ray source in the direction roughly of the galactic centre (Fig. 3). There is some excess from the inward spiral arm direction but the main excess (supported by SUGAR)

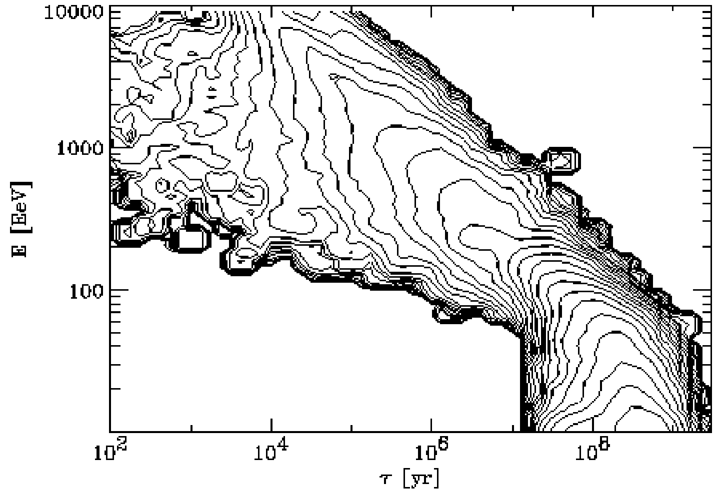

Fig. 8. The delay of particle arrival times for a source at a distance of 10 Mpc in a proposed supergalactic magnetic field of 0.3 μG. The delay is relative to the propagation time without any field.[18)]

appears to be a combination of a SUGAR point source and a diffuse halo. The halo is matched in the anticentre direction by a diffuse deficit which is the result one would have for a progressive diffusion past the observer — a so-called dipole anisotropy. This looks like a good scenario. A source produces both a charged and a neutral beam which results in a point source being observed plus a diffusive charged component. Clay 11) showed that this structure is plausible. However, the agreement is too good. Our galaxy has a rather thin disk-like structure and one might expect particles to leak out of the plane and produce a deficit for directions away from the plane. Such an out-of-plane deficit is not present in Fig. 3, suggesting that the galactic field extends well out of the galactic plane. An unknown quantity is then how far the galactic field extends and how it merges into any intracluster field for our own cluster, and then into any intercluster field which may exist. One can speculate that turbulence at the cluster boundary, such as is found at the edge of the Earth's magnetosphere, could act as a mirror for the highest energy cosmic rays to ensure that their anisotropy is below observed levels. Clay and Smith 19) showed that a radial distance of the turbulence mirror of 120 kpc from the galactic centre was sufficient to produce anisotropies consistent with present data.

We note that another significant unknown is the appropriate turbulence model for intra- and inter-cluster fields. It would seem plausible that the largest scale sizes are at least of galactic dimensions within clusters (100 kpc?) as the fields would be distorted by the passage of galaxies through them leaving turbulent wakes. Certainly, where clusters are visible through X-ray emission, such scales exist. Intercluster turbulence seems to be in the realm of speculation. Information on the strength and structure of magnetic fields in the galaxy, the intra cluster medium and the intercluster medium will clearly be a key to future understanding in this field.

§6. Conclusions

Cosmic ray astrophysics at the highest energies is entering a new era with major new facilities being proposed and developed. There are major questions remaining to be answered in terms of how nature produces such particles and what volume of the Universe they fill. Conventional wisdom suggests that the highest energy particles come from extragalactic sources but that scenario is not without inconsistencies. It is possible that we will have to reconsider the possibility that all the observed particles originate relatively locally in astrophysical terms.

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References

1) N. Hayashida et al., Astropart. Phys. **10** (1999), 303.
2) Auger Collaboration Contributions, Proc. 27th Int. Cosmic Ray Conf. (Hamburg) **2** (2001), 699.

3) P. Bhattacharjee and G. Sigl, Phys. Rep. **327** (2000), 109.
4) K. Greisen, Phys. Rev. Lett. **16** (1966), 748.
5) G. T. Zatsepin and V. A. Kuzmin, Sov. Phys. JETP Lett. **4** (1966), 78.
6) R. Lampard, R. W. Clay and B. R. Dawson, Pub. Astron. Soc. Aust. **14** (1997), 258.
7) A. G. K. Smith and R. W. Clay, Aust. J. Phys. **50** (1997), 827.
8) R. W. Clay, M.-A. McDonough and A. G. K. Smith, Pub. Astron. Soc. Aust. **15** (1998), 208.
9) J. Linsley, Phys. Rev. Lett. **34** (1975), 1530.
10) R. W. Clay, Pub. Astron. Soc. Aust. **17** (2000), 212.
11) R. W. Clay, Pub. Astron. Soc. Aust. **19** (2002), electronic.
12) J. A. Bellido, R. W. Clay, B. R. Dawson and M. Johnston-Hollitt, Astropart. Phys. **15** (2001), 167.
13) A. M. Hillas, Ann. Rev. Astron. Astrophys. **22** (1984), 425.
14) T. L. Lim et al., Ann. Geophysicae **14** (1996), 400.
15) M. Honda, Astrophys. J. **319** (1987), 836.
16) A. A. Lee and R. W. Clay, J. of Phys. G **21** (1995), 1743.
17) T. E. Clarke, P. P. Kronberg and H. Bohringer, Astrophys. J. **547** (2001), L111.
18) G. Sigl, *Lectutre Notes in Phys.* **556** (2000), 259.
19) R. W. Clay and A. G. K. Smith, Proc. 24th Int. Cosmic Ray Conf. (Rome) **2** (1995), 784.