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THE ORIGIN OF ULTRA-HIGH-ENERGY COSMIC RAYS

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1. WHY BOTHER WITH ULTRA-HIGH-ENERGY COSMIC RAYS?

Protons, nuclei, and electrons in the energy range 10^9–10^{12} eV account for most of the energy of the cosmic-ray flux and have attracted most attention. Plausible models have been proposed for their acceleration (popularly in supernovae), of their entanglement by galactic magnetic fields, and of their eventual escape from the Galaxy ("leaky box" models). However, the energy spectrum of cosmic rays extends to $\sim 10^{20}$ eV (and *smoothly* to 10^{19} eV). This poses a challenge to these models, because (*a*) the ultra-high energies of these particles rule out most of the accelerating mechanisms that have been discussed, and (*b*) such particles cannot be retained in the disk of our Galaxy by its magnetic fields. Regrettably, the observations also cast doubt on the importance of the most popular shock-wave process for accelerating particles to ultrarelativistic energies.

In most respects, a very firm body of data on these ultra-high-energy cosmic rays now exists, and so it may be hoped that more attention will be paid to its interpretation. However, there are many problems to be solved.

SIZE OF ACCELERATING REGION The Larmor radius of a relativistic particle of charge Ze in a magnetic field $B_{\mu G}$ (strictly the component of B normal to the particle's velocity) is $r_L = 1.08\ E_{15}/ZB_{\mu G}$ pc, where E_{15} is the particle's energy in units of 10^{15} eV, and $B_{\mu G}$ is in microgauss. Clearly, in gradual modes of acceleration, where the particle makes many irregular loops in the field while gaining energy, the size L of the essential part of the accelerating region containing the field must be much greater than $2r_L \sim 2E_{15}/B_{\mu G}$. In

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fact, a characteristic velocity βc of scattering centers is of vital importance, and it turns out (Section 3) that L has to be larger than $2r_L/\beta$, so

$$B_{\mu G} L_{pc} > 2E_{15}/Z\beta, \qquad 1.$$

where L_{pc} is in parsecs. This limitation arises also in one-shot acceleration schemes, where an emf $\sim LvB/c$ (cgs) arises from the motion of a conductor (speed $v = \beta c$) in a magnetic field and may be partly available for particle acceleration (L may be the diameter of a rotating neutron star, for instance).

In Figure 1 are plotted many sites where particle acceleration may occur, with sizes ranging from kilometers to megaparsecs. Sites lying below the diagonal line fail to satisfy condition (1.), even for $\beta = 1$, for 10^{20} eV protons (the dashed line refers to 10^{20} eV iron nuclei): for more reasonable plasma velocities in the range $c > v > 1000$ km s^{-1}, the line will lie even higher, somewhere within the stippled band. Clearly, very few sites remain as possibilities: either one wants highly condensed objects with huge B or enormously extended objects. In either case, very high speeds are required. Among the excluded sites are supernova remnant envelopes.

ARRIVAL DIRECTIONS Many particles having energy $>3 \times 10^{19}$ eV have been reported, and many of these arrive from directions very far from the galactic plane (30), as is shown in Figure 2, which depicts a section through the Galaxy. If these particles have been deflected from sources within the active regions of our Galaxy, we require a magnetic field of somewhat

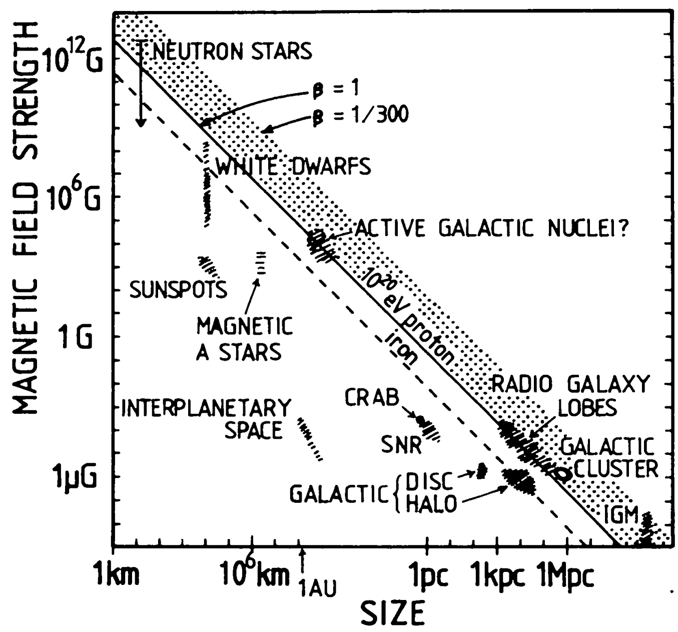

Figure 1 Size and magnetic field strength of possible sites of particle acceleration. Objects below the diagonal line cannot accelerate protons to 10^{20} eV.

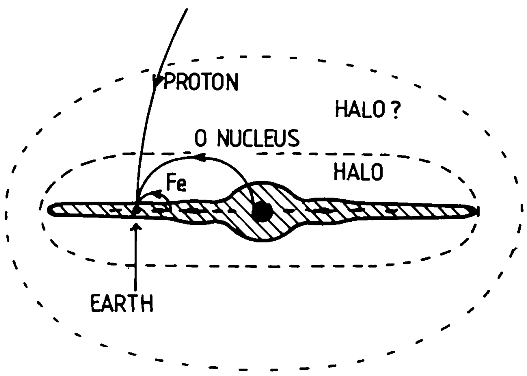

Figure 2 Size of the trajectories of 7×10^{19} eV cosmic-ray nuclei in relation to the Galaxy in a 2-μG magnetic field (assumed to be almost uniform).

implausibly constant direction over a large volume. This field could hardly be stronger than 2 μG (rather like that in the local galactic disk); in Figure 2, the typical energy of the sample is taken to be 7×10^{19} eV, and the trajectories of protons and oxygen and iron nuclei in such a field (normal to the diagram) are shown. Protons would clearly originate outside our Galaxy, and the arrival direction points roughly from the Virgo cluster of galaxies, 15–20 Mpc away (though Southern Hemisphere observers may not be much impressed by this remark). Only if the particles were all more highly charged nuclei and if the magnetic halo of our Galaxy extended to several kiloparsec (as shown) could the particles originate in our Galaxy. The evidence suggests that at least some of the particles are protons (97), but their identification is not easy. Such an identification is of critical importance. If they were to turn out to be entirely highly charged nuclei, we might consider whether young pulsarlike objects could possibly be sources; otherwise, we have to look outside the Galaxy.

2. OBSERVATIONAL DATA

Particles of energy $> 10^{15}$ eV are detected through the extensive cascades of secondary particles that they generate in the atmosphere ("extensive air showers"). These are observed by large arrays of particle detectors on the ground. The largest of these arrays viewing the northern sky have been at Volcano Ranch (USA), Haverah Park (England), and Yakutsk (USSR); another array, Chacaltaya (Bolivia), operates near the equator. The southern sky has as usual been somewhat neglected, but the observers at Sydney (Australia) had the largest exposure of all at the highest energies. In the effort to gather statistics on 10^{20} eV particles, the global exposure to date is ~ 500 km^2 yr.

2.1 *Energy Spectrum and Composition of High-Energy Particles*

ENERGY SPECTRUM Figure 3 shows how the particle flux at very high energies continues the spectrum that has been well explored below 10^{12} eV. The differential flux $J(E)$ (particles m^{-2} s^{-1} sr^{-1} GeV^{-1}) is plotted as a function of energy E, with J multiplied by $E^{2.5}$ (E in GeV), thus disguising a very steeply falling spectrum. Particle species are not distinguished, as only the total energy given to the shower can be estimated. A few experiments spanning a broad energy range have been selected, and a critical assessment of the data is not attempted. (Some other data suggest that the flux may be slightly higher than shown near 10^{15} eV.) The low Sydney flux does not indicate a real difference in the southern sky, but reflects instead their use of the number of muons (N_μ) to measure shower size. Conversion from N_μ to E is strongly sensitive to the poorly known charge-retention features of high-energy pion interactions; other evidence on E/N_μ from Yakutsk (37) would about double the Sydney energies (see the upper dotted curve in Figure 3). The derivation of E from shower size is usually not a trivial matter, but

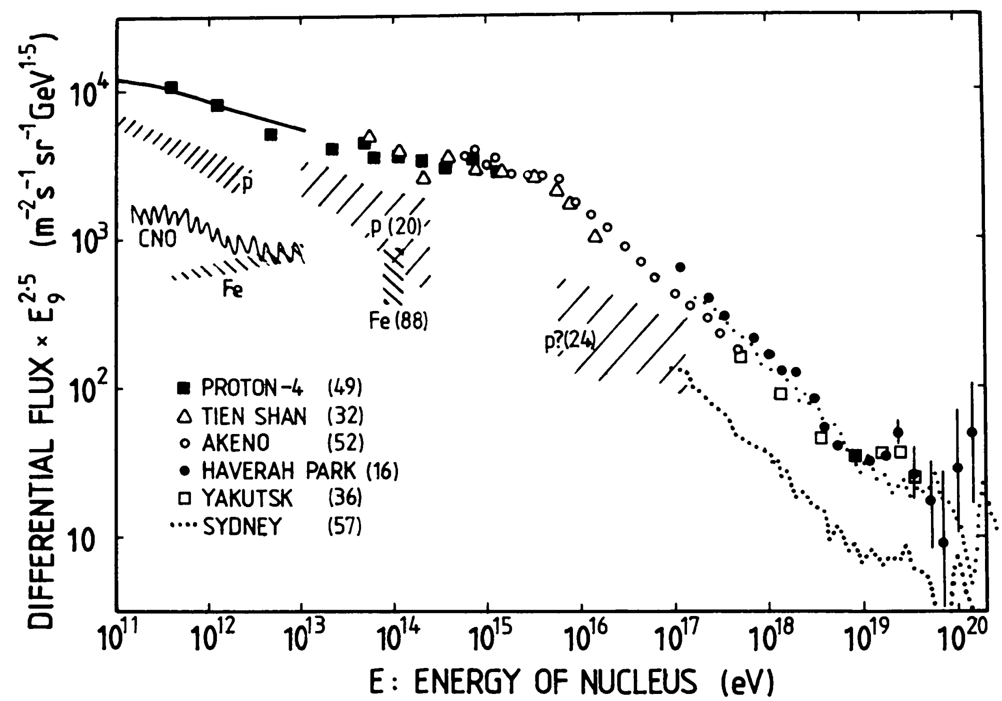

Figure 3 Energy spectrum of cosmic-ray particles from a few selected experiments (references given on diagram). A second version of the Sydney spectrum is also shown, with energies doubled. Shaded bands refer to particular nuclear species or groups. [The Akeno report (52) used two alternative energy conversion factors: the data plotted here are interpolated between these, guided by a shower model.]

three different methods—used at Volcano Ranch, Haverah Park, and Yakutsk—have been shown (17) to agree to within $\sim 20\%$ when applied to individual showers. (The error may nevertheless turn out to be somewhat larger than this.)

The energy spectrum presents the following main features. After J has varied as $E^{-\gamma}$ for many decades, it falls somewhat more steeply above 5×10^{15} eV—the well-known "knee" of the spectrum—and then continues smoothly to 10^{19} eV, beyond which Volcano Ranch, Haverah Park, and Sydney (to a lesser extent) find that it falls less rapidly. A hypothesis blessed by long tradition is that the more-energetic particles above the knee are able to leak out of the Galaxy more rapidly (assuming their sources to be within it). Probably, particles with a galactic origin end near 10^{19} eV (as Figure 2 might suggest), and above that a different source is active (most plausibly in the nearby supercluster of galaxies). However, the maximum energy of cosmic rays is disputed, as a reanalysis of the Yakutsk showers [internal report (36) and informal discussions] indicates an end to the spectrum near 5×10^{19} eV, beyond which they have no data points in Figure 3. The reason for this disagreement with the other three experiments is not at present understood. If the Yakutsk results are vindicated, they could alter considerably our view of cosmic rays, as they might demonstrate the predicted effect of long exposure to interactions with the primeval 2.7 K radiation (48,100), expected if particles have traveled >50 Mpc.

NATURE OF THE PRIMARY PARTICLES The fine detail of nuclear composition obtained below 10^{11} eV is not available at much higher energies. According to the "leakage" interpretation of the knee in the spectrum, the spectrum of each nucleus should exhibit a "knee" at the same magnetic rigidity (i.e. at $E_{\rm knee} \propto Z$). Protons would fall away first, iron nuclei last. Some factor appears to complicate this picture, however, as only a single step is apparent in the spectrum; and although many authors claim indirect evidence exists that very heavy nuclei predominate in the flux just above 10^{15} eV, the evidence is far from convincing, and such a dominance is not yet evident in the few top-of-atmosphere observations (21, 88). At 10^{17}–10^{19} eV, the fluctuations in the depth of maximum development of showers indicate that there must be an appreciable proportion of protons among the incoming particles (24, 97); and the few showers of energies $>10^{19}$ eV measured in detail look no different from 10^{18} eV showers. This has an important bearing on trajectories (Figure 2); and the presence of protons raises severe difficulties in acceleration models (Section 3). Charged dust particles have been dismissed as possible primaries in this energy range (69), as the depth of shower development clearly puts the particle mass $\ll 10^4$ amu.

2.2 *Observed Anisotropy of High-Energy Cosmic Rays*

IS THERE REALLY A SIGNIFICANT ANISOTROPY AT HIGH ENERGIES? This question is persistently raised by critics. Around 10^{13} eV, there is a clear but very small (0.06%) pattern of intensity variation (see, for example, 1)—but is this all? Until recently, the statistics at high energies have only justified the simplest measure of anisotropy [the first Fourier component (24-hr sidereal period) of the intensity variation as the sky passes overhead], and the reported amplitude A in many energy ranges has never been far above noise. The best test of whether these amplitudes are random noise is to compare the phases (time of maximum) reported in various energy ranges by Haverah Park (30, 41, 72, 73) and Yakutsk (42), which have both viewed the northern sky with good statistics. These are plotted in Figure 4, together with data from Chacaltaya (3)—although these have only ~60% overlap in the declination range—and from two less recent experiments near 10^{16} eV (29, 34). Apart from a region near 10^{19} eV where the direction is unclear, they do agree: the phases are not random, and there is a real anisotropy. For $E < 10^{14}$ eV the phase is ~1 h; this phase is altered above the knee and shows a new pattern above 5×10^{17} eV. Finally, above 10^{19} eV, there is a rapid change.

The magnitude A of the anisotropy provides a crude test of the "leakage" interpretation of the knee in the spectrum. If sources in the Galaxy produce $Q(E)$ ($\propto E^{-\gamma}$, say) cosmic rays of energy E per unit time, and if these move around for an average time $T(E)$ before escaping, then the number of

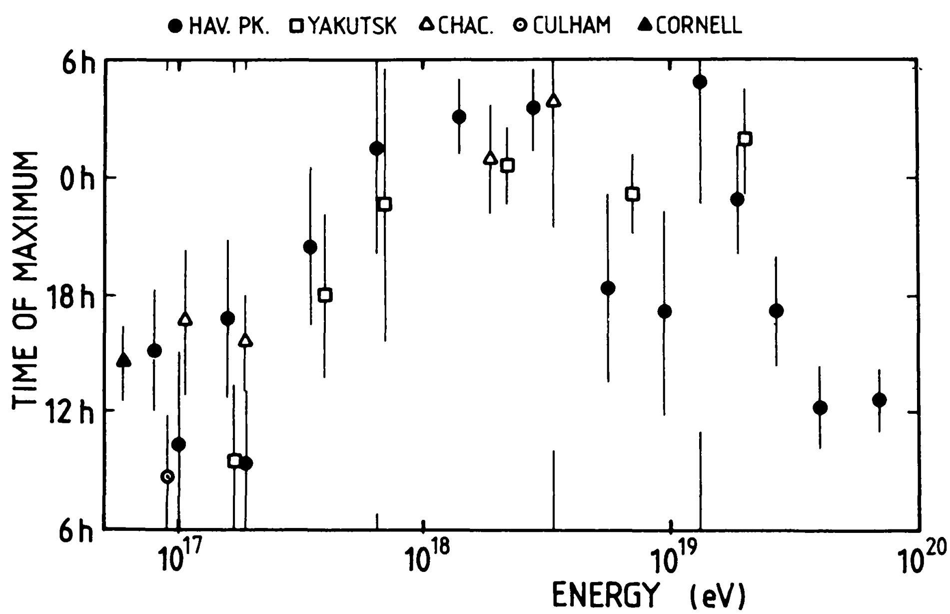

Figure 4 Comparison of phases (right ascension of maximum) of first harmonic anisotropy reported by different experiments.

particles in the Galactic box will be $N(E) = Q(E)T(E)$, and the spectrum falls off more if leakage becomes more rapid. If t is the average escape time under rectilinear propagation, an observer at a typical position in the box would see an anisotropy $A = kt/T$ very roughly: thus $A \propto 1/T$, and

$$T(E) = N(E)/Q(E) = E^{\gamma}N(E) \propto 1/A. \qquad 2.$$

In Figure 5, the observed values of A (1, 31, 41, 42, 70, 72, 73; with noise subtracted in quadrature, and values corrected for solar motion below 10^{15} eV) are plotted inversely and compared with the curve $E^{2.47}J(E)$ (i.e. we postulate a production spectrum $E^{-2.47}$ arbitrarily). Of course, there may be local eddies in the flow of cosmic rays, and we have plotted only one component A of a vector flow, but the observations are at least consistent with the model. Even the low-A point at 3×10^{14} eV may be associated with a proton "knee" (56). Most remarkably, the model suggests a power-law spectrum extending to $\sim 10^{19}$ eV (if the final decade were considered to be extragalactic). For comparison, the source spectrum deduced below 10^{11} eV from other data is $\sim E^{-2.4}$. If, instead, the knee is due to features of the accelerating region, the anisotropy would have to reflect very local, rather than global, flow patterns.

ARRIVAL DIRECTIONS IN RELATION TO GALACTIC COORDINATES The Haverah Park group have found that in the energy range 2×10^{17}–10^{19} eV there is an intensity gradient in galactic latitude (5), with a deficit of flux from the north; this result has now been fully confirmed at Yakutsk (42). At 4×10^{18} eV, for example, the gradient is 0.2% per degree of latitude.

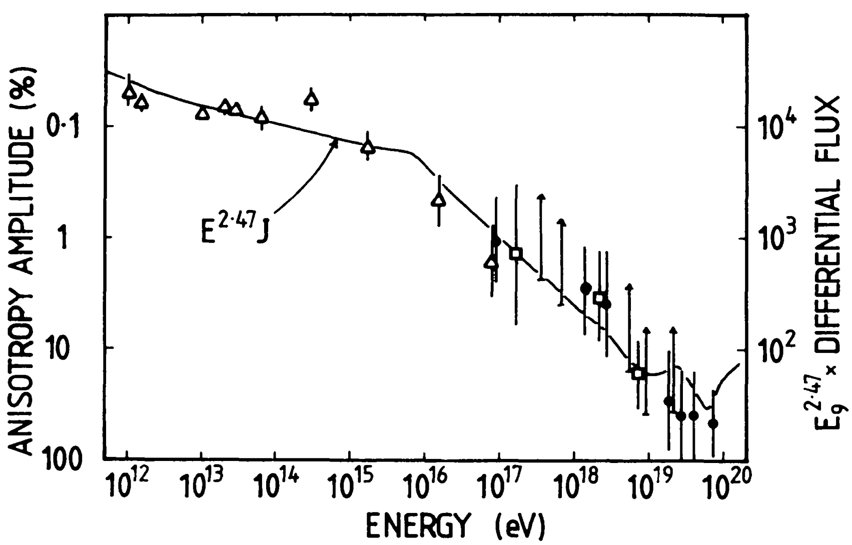

Figure 5 Amplitude of first harmonic as a measure of residence time: variation in A compared with variation in flux (cf. Equation 2).

Above 10^{19} eV, the pattern of arrival directions changes rapidly with energy. Haverah Park finds that above $\sim 3 \times 10^{19}$ eV there is a large excess of particles from high northern galactic latitudes, and Watson (98) considers the most likely explanation for this to be a large contribution from the Virgo supercluster. The Sydney group, though, find no north/south (N/S) anisotropy above 2×10^{19} eV in the part of the sky they see (58), and 8 out of 10 particles above $\sim 8 \times 10^{19}$ eV (doubling their quoted energies again) are within 30° of the galactic plane. Krasilnikov et al. (63) believe, in fact, that the strong northern excess occurs in a limited energy region, and that taken as a whole, the pattern bears a strong relationship to galactic features; thus, we must be seeing trajectories in a large-scale galactic field. A global view of the sky is needed to decide between these viewpoints.

2.3 *Specific Identified Sources of Cosmic Rays*

A new field is opening up here, with the direct identification of one or two specific sources of very energetic particles. Dzikowski et al. at Lodz (39, 40) reported an excess of air showers detected from the general direction of the Crab Nebula at $>10^{15}$ eV (about 10^3 times the energy of previously known gamma-ray sources); however, the Akeno and Haverah Park experiments have failed to see such an excess [Hayashida et al. (53) and Lambert et al. (68) appear to set a limit a factor of ~ 50 lower], although the Fly's Eye optical detector may have seen it (15). Thus the present position is unclear. However, Samorski & Stamm at Kiel (84) discovered that the X-ray binary Cygnus X-3 emits 10^{16} eV particles, presumably gamma-rays, which are detected at one point of the 4.8-hr binary period. This has since been confirmed (74): the "pulse" is narrow (duty cycle 2%) and occurs at a phase 0.25 after the X-ray minimum. Near 10^{12} eV, pulses have been reported at a similar phase (90), and also about 0.4 later. The differential spectrum seems to extend as $\sim E^{-2}$ from lower energies but falls off sharply above 10^{16} eV. Presumably a compact object (neutron star? black hole?) accelerates electrons or protons to energies above 10^{16} eV, and the 4.8-hr period is attributed either to interactions with the surroundings of a companion (89, 96) or to precession of a relativistic jet (50). This identified source is of the greatest importance and is a challenge to theorists, as it is hard enough to see how 10^{12} eV electrons or photons get out of a pulsar magnetosphere (see, for example, 4).

3. ACCELERATION MECHANISMS

Attention focuses here on mechanisms for achieving energies of 10^{20} eV (since this is seen by several observers) or 10^{19} eV (approximately the end of that part of the spectrum that extends back smoothly to 10^{15} eV). All the proposed acceleration processes are problematical, however, and new ideas are needed.

STATISTICAL OR DIRECT ACCELERATION? Figure 1 focused attention on a few plausible acceleration sites, but the question remains as to what mechanism is at work.

1. Particles may gain energy gradually by numerous encounters with regions of changing (moving) magnetic field; such processes are variants of Fermi's mechanism (43). Their advantage is that the energy is spread over many decades, and in the shock-wave variant (7, 8, 12, 64) the spectrum very convincingly emerges as $\sim E^{-2}$. Their disadvantages are that they are slow, and that it is hard to keep up with energy losses at the highest energies.
2. Particles may be accelerated directly to high energy by an extended electric field (e.g. emf arising in rapidly rotating magnetized conductors, such as neutron stars or supermassive objects). Such a mechanism has the advantage of being fast, but it suffers from the circumstance that the acceleration occurs in an environment of very high energy density, where new opportunities for energy loss exist. In addition, the complexity of such an analysis is daunting: and it is usually not obvious how to get a power-law spectrum to emerge.

3.1 *Problems Associated with Statistical Acceleration*

FERMI ACCELERATION Cavallo (22) has summarized many of these problems [though Greisen (47) had raised the basic issues before]. Following the same path, we find that the acceptable sites for acceleration are very few indeed. The results here largely carry over to the shock acceleration models.

Statistical acceleration is characterized by an effectively continuous gain of energy with an acceleration time t_A (i.e. $dE/dt = E/t_A$) competing with a possibility that the particle escapes from the system, with mean escape time t_E. Particles emerge with an energy spectrum $J \propto E^{-\gamma}$, where $\gamma = 1 + t_A/t_E$, so we need $t_A \sim t_E$. Apart from the problem that t_A probably rises and t_E falls with increasing E, energy gain will stop if any steady energy loss sets in that cancels the gain. The energy gain may occur by reflection of charged particles from distinct magnetized "clouds" moving randomly with velocity βc in a very inhomogeneous medium, as in the models of supernova remnants proposed by Scott & Chevalier (85) and others; in such a case (43), we have $t_A^{-1} = 2c\beta^2/\lambda$, where λ is the particle's mean free path for scattering from clouds (assuming the motion approximates to a random walk). In a less inhomogeneous medium, particles can be scattered by Alfvén and similar waves moving with speed $\sim v_A$ in the plasma, and the acceleration rate (based on 66) is $t_A^{-1} \sim 3c\beta^2/2\lambda$, where $\beta = v_A/c$. Scattering is now effected by field perturbations of wavelength $\sim 2\pi r_L$, where r_L is the Larmor radius of the particle in the overall field B. In somewhat turbulent conditions, we may assume $\lambda \sim$ 4–25 r_L; i.e. $\lambda = \eta r_L$, where (say) $\eta \sim 10$. (The rough lower limit to λ arises because much of the field energy will lie in nonresonant long wavelengths.)

In a strong magnetic field of B gauss, synchrotron radiation causes an energy loss with a time scale $t_S = 1.4/E_{20}B^2$ yr for protons, where E_{20} is the particle energy in 10^{20} eV units. [The value of t_S is increased by a factor of $(A/Z)^4$ for a heavy nucleus.] In a weak field, interactions with low-energy photons provide a more serious energy loss. As a minimum, there are always the primeval 2.7 K photons, and for protons the energy loss time scale t_P is $\sim 7 \times 10^8$ yr at 10^{20} eV (with t_P falling rapidly as E rises) and $\sim 5 \times 10^9$ yr at 10^{19} eV, although t_P will be much reduced near a luminous source. Figure 6 shows the range of Alfvén speeds βc that are required to make $t_A < t_{loss}$ so that an energy of 10^{20} or 10^{19} eV can be reached: the shaded regions are excluded by one or the other of the two losses. If the ratio $\eta = \lambda/r_L$ is reduced from 10 to 4, the effect on the boundary of the allowed

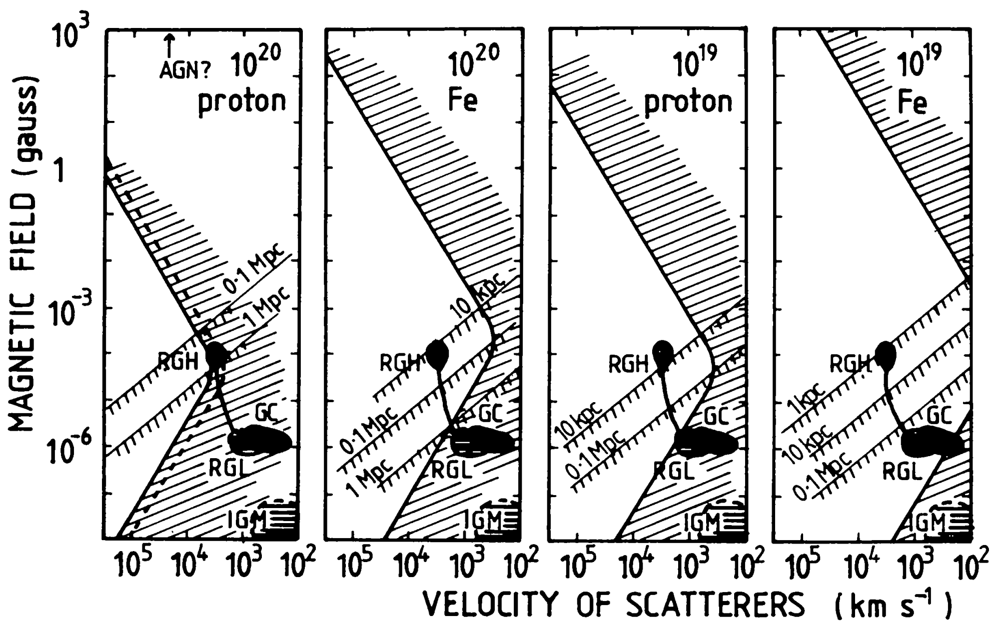

Figure 6 Combinations of magnetic field strength and velocity of scattering centers that allow Fermi acceleration to reach 10^{20} or 10^{19} eV for protons or for iron nuclei. Only the unshaded triangular region at the left in each diagram beats synchrotron losses (above the upper leg of the triangle) and photoreactions (below the lower leg). Any candidates must also lie above the diagonal line appropriate to their radius or diffusive escape will be too rapid. Positions of galactic clusters (GC), radio galaxy lobes (RGL), radio galaxy hotspots (RGH), and the intergalactic medium (IGM) are indicated.

area is shown by the dashed line in the first diagram. Also, the accelerating region must be large enough to ensure that the escape time t_E is not much less than t_A. The diffusive escape time from a sphere of radius R is $\sim 1.5R^2/c\lambda$: this limit is also indicated on Figure 6, although a highly organized field could alter t_E. Among the candidate sources from Figure 1, clusters of galaxies, such as the Virgo or Coma clusters, may have $B \sim 2 \times 10^{-6}$ G (35, 82), $v_A \sim 1000$ km s^{-1} ($\sim$ random motion of the galaxies), and $R \sim 0.5$ Mpc. The lobes of very large radio galaxies (and also the local radio galaxies, Virgo A and Cen A) are probably little different. Hotspots in the very active lobes (such as Cyg A), where $B \sim 10^{-4}$ G, might be the only locations that approach our requirements. In the general intergalactic medium, one can only guess at conditions, but if v_A is a few hundred kilometers per second, as in galactic motions, and $B \sim 3 \times 10^{-8}$ G (or less), then $t_A \gg t_{\mathrm{Hubble}}$. For iron nuclei, the losses are smaller, and some of the illustrated sources may be large enough to attain energies $>10^{19}$ eV. Turning to the more compact (high-B) sources of Figure 1, we can see from Figure 6 that for any speed of scatterers ($<c$), the magnetic field B is <1 G for 10^{20} eV protons (50 G at 10^{19} eV); thus, this defeats Fermi acceleration at accretion disks around active galactic nuclei (proposed in 59), with the possible exception of acceleration of iron nuclei (but there are other photons around!). Furthermore, if the diffusive escape time $t_E > \frac{1}{2}t_A$, then this requires that $R_{pc}B > 0.5E_{20}/\beta$ (times $\eta/10$), and thus the total magnetic energy over a spherical volume is $>3.10^{54}E_{20}^5\beta^{-5}A^{-4}(\eta/10)^4$ erg (where A refers to heavy nuclei); this is more than $100/\beta^5$ times the energy available from collapse to a neutron star if $E_{20} = 1.5$.

ACCELERATION BY SHOCK WAVES Many readers will be familiar with this process, so only a brief introduction is given here. A collisionless shock front, propagating at a speed $v_S = \beta c$ through a plasma carrying a magnetic field, can reflect particles with a large gain in energy if the orientation of the field is just right; but practically all investigators have concentrated on "parallel shocks" (magnetic field parallel to gas flow), in which case the most important process for very-high-energy particles is closely related to Fermi acceleration. Behind the shock, the gas advances with speed $v_2 = \beta_2 c$ $(= \frac{3}{4}v_S$ for a strong shock—very high v_S—if gas pressure dominates), carrying with it magnetic irregularities that again act as scattering centers. These scatterers advance upon the motionless scattering centers in the unshocked gas (this time we neglect their individual motions), and particles crossing the shock front encounter oncoming scatterers, on average gaining energy $4E\beta_2/3$ per back-and-forth crossing. As it diffuses around, a particle makes on average $1/4(\beta-\beta_2)$ cycles of crossing before eventually being left behind by the front (8), and the statistics of crossings yield an energy spectrum E^{-2}

for strong shocks ($\gamma > 2$ as the shock weakens). (For an enthusiastic review, see 6; see also 38, 95.) The initial applications of shock-wave theories were greeted with enthusiasm, since supernovae certainly produce strong shocks that seemed almost inevitably to lead to about the right intensity and spectrum of cosmic rays generated in the Galaxy [Krymsky & Petukhov (65), Blandford & Ostriker (13)].

There have been doubts, however, about the spectrum generated (e.g. 46): most seriously, the spectrum generated in this way by supernova shocks would terminate much too soon. Lagage & Cesarsky (67) have made a detailed study of the limitations imposed by the size and duration of the shock and find that the known scattering mechanisms would yield E_{max} a few times 10^{13} eV for protons, above which the spectrum would fall very steeply. They find, too, that an ensemble of shocks does not extend this limit much. How do shocks improve on normal Fermi acceleration in other sites? Clearly β is greater ($v_S > v_A$), and for various reasons (8, 38) turbulence should ensure a short λ, but that is all. [Axford (6) suggested that shocks might speed up on entering the galactic halo, but this is unlikely to be so (67).] Lagage & Cesarsky find an effective acceleration rate of $t_A^{-1} = c\beta^2/(\lambda_1 + 4\lambda_2) \sim c\beta^2/2\lambda_1$, where λ_1, λ_2 refer to upstream and downstream scattering mean free paths—this is very similar in form to Fermi acceleration, except that β has to be $\sqrt{3}$ times as large for the same effect, so virtually the same diagram as Figure 6 applies in this case too. Shock waves do not rescue the galactic cluster site from the effect of energy losses, since $v_S < 3000$ km s^{-1} for bow shocks of galaxies; nor, by a larger margin, does the intergalactic medium in general appear to be a possible location for the origin of these high-energy particles. The diffusive motion needs a very large space L on either side of the shock: $L \sim \lambda/\beta$, a value of, say, 300 mean free paths or $\gg 300 r_L$. (If $v_S = 1000$ km s^{-1}, a particle makes 4×10^5 scatterings in gaining one decade of energy: is this really the most efficient process?)

From Figure 6, it appears that acceleration should be far easier if $v_S \sim c$, and although this would give a notably flatter spectrum (77), the effect has not been fully explored. The fast-moving "knots" in radio galaxies may be unusually effective shock waves (87) if they are large enough. But the radio galaxies in our vicinity are not so active. So, iron nuclei might possibly be accelerated to 10^{19} eV, but not protons.

3.2 *Direct Acceleration*

ELECTRICAL GENERATORS We now consider the high-B candidate sources of Figure 1. If a rotating neutron star has a surface field $\sim 10^{12}$ G, a radius $r \sim 10$ km, and a rotational frequency $\omega/2\pi \sim 30$ s^{-1} (like the Crab pulsar), a circuit connected between pole and equator would see an emf $\sim \omega B r^2/c$ (cgs units) $\sim 10^{18}$ V for an aligned or oblique dipole. If we assume, as is customary, that the part of the magnetosphere corotating within the light cylinder will fill with conducting plasma maintaining $\mathbf{E}\cdot\mathbf{B} = 0$ [although this has been questioned (2, 76)], the emf measured now from pole to the last open field line is reduced by the factor $r\omega/c$. (Note that **E** refers to electric field, E to particle energy.) Just where the main potential drop occurs in the external space, which contains current sources (pair production), is still unclear (4). This position affects acceleration of whatever nuclei are around, since the radiative energy loss $-dE/dx = 2\gamma^4 Z^2 e^2/3R_C^2$ (cgs) has to be overcome, where the particle of charge Ze and Lorentz factor γ follows a path of radius R_C. Berezinsky (10) suggests that the electrical potential $V = B\omega^2 r^3/4c^2$ becomes available for acceleration at a distance R very far from the pulsar, perhaps near the light cylinder, so that R_C may be large ($\sim R$); the Crab pulsar could then accelerate iron nuclei to 10^{18} eV (protons to 5×10^{16} eV). His expression varies weakly with ω. This model for a cosmic-ray source would imply that the most energetic nuclei were highly charged, unless there is a mechanism by which the paths could be even less curved by the field. Ferrari & Trussoni (43a) found that even the unrealistic vacuum fields around an oblique rotating dipole (emf $\sim 10^{20}$ V) resulted in virtually the same maximum energies as quoted above. Although it is not obvious that a power-law spectrum is likely, it may just possibly result from pulsar evolution. (According to observation, pulsars do generate electrons with power-law spectra.) It is very challenging to see that Cygnus X-3 accelerates particles to at least 10^{16} eV: if these are electrons, protons might reach a higher energy.

Lovelace (75) offered as another unipolar inductor the rotating accretion disk around a $10^8\ M_\odot$ black hole in the center of a radio galaxy; such a disk could draw in magnetic flux with the gas to give a magnetic field $B \sim 10^4$ G parallel to the rotation axis, generate 10^{19} V, and might fire out a beam of protons axially (if $\mathbf{B}\cdot\boldsymbol{\omega} < 0$). More recently, Rees et al. (81) have proposed that in a galactic nucleus, a $10^8\ M_\odot$ black hole may be spun up to near-maximum permissible angular momentum by accretion, after which rotational energy up to $0.29Mc^2$ may in principle be extracted by electrodynamic torques [Blandford & Znajek (14); see also 79]. They consider a magnetic field $B \sim 10^4$ G entering the hole's horizon: an emf $V = 10^{19}(B/10^4\,\mathrm{G})(M_H/10^8 M_\odot)^2$ volt is then available at maximum angular momentum (79). These later papers, however, do not suggest that 10^{19} eV protons will automatically be produced, for although efficient power extraction may be possible (79), there will be a dense positron-electron plasma generated by thermal gamma rays that will modify the electric field and also interact with very energetic protons. An important question again is, How far away does the main potential drop occur? Colgate (26) made a crude estimate of energy losses due to known photon fluxes from active galactic nuclear regions, and even in Cen A (luminosity 10^{-3} of Colgate's example), after correcting for a numerical error, the energy loss time scale is $\ll 1$ yr over a wide energy range; thus the electric fields would have to occur well away from the nucleus, where there were fewer photons. Otherwise, acceleration would be defeated above $\sim 10^{16}$ eV. But the environment of a galactic nucleus is likely to be more complex than imagined, and G. Lake & R. E. Pudritz (preprint) argue that its huge inductance makes the electric circuit outside the spinning nucleus unstable, with disruption of currents inducing large transient fields. They suggest that this should show up in unsteady production of high-energy gamma rays (and neutrinos?).

Potentials of 10^{21} V appear also in Fischhoff's electrostatic cosmology (44); but interactions with photons over 10^9 yr remain a problem.

MORE ABOUT PULSARS Gunn & Ostriker's proposal (51) that protons and nuclei could reach 10^{21} eV by riding in the outgoing strong wave field beyond the light cylinder of a pulsar has not been seriously considered since it was noted (61) that even a small contamination of plasma in the waves would destroy the necessary phase locking. However, few other schemes could produce the whole range of cosmic-ray energies in the same source, and any modification that made this process available again would have great attractions. Pulsar remnant disks might offer another way to subvert unproductive magnetospheres and regain very high voltages (76).

HYDRODYNAMIC SHOCKS The value of E_{max} seems much too small in Colgate & Johnson's scheme (27), where a shock wave emanating from the core of a collapsing supernova eventually attains ultrarelativistic speed in the steep density gradient of the stellar atmosphere, accelerating a small fraction of the local matter to cosmic-ray energies directly in the radiation-dominated shock. Colgate (25) has defended this scheme against arguments questioning whether the shock can form (see 86), but he still needs to find a way to propagate the shock beyond the point where $E \sim 3 \times 10^{14}$ eV per nucleon. In addition, evidence indicates that the relativistic particles in supernovae largely gain their energy after the initial outburst (e.g. 23, 85).

3.3 *Final Comments*

None of the schemes discussed above has really exploited first-order Fermi acceleration, which might be much faster than the other statistical processes. In a sense, shock waves involve first-order acceleration at the front itself, but almost all the scattering merely produces diffusion within the gas: one would like to find approaching mirrors with a higher reflection coefficient! M. E. Pesses (private communication) suggests that oblique shocks may play an important role.

4. PROPAGATION OF COSMIC RAYS

Great uncertainties about the configuration of the magnetic field both in the outer regions of our Galaxy and in metagalactic space have discouraged attempts to interpret the arrival directions in detail. The improved body of cosmic-ray data may now encourage further analysis. Since the present situation cannot be described profitably in the short space available, only the barest indication of some recent work is given here.

4.1 *Propagation from Extragalactic Sources*

LOSSES DUE TO PHOTOREACTIONS Soon after Greisen (48) and Zatsepin & Kuzmin (100) pointed out the serious energy losses that protons must suffer as a result of interactions with the 2.7 K primeval radiation, and the consequent depletion of the flux expected above $\sim 4 \times 10^{19}$ eV, it was generally accepted that 10^{20} eV particles cannot come from sources distributed uniformly throughout the Universe. Instead, the Local supercluster (at 15–20 Mpc) must make a disproportionately strong contribution to any extragalactic component (99), regardless of whether protons or mixed nuclei made up the flux (55, 80, 91, 94). Even then, the flux would have to drop off a little above 10^{20} eV. We may indeed live near a local density node in a cellular pattern of voids in the Universe (101). If photon interactions have not resulted in flux losses, neither should they have removed very heavy nuclei from the flux; and since most potential sources are likely to contain synthesized elements, we do not expect just a proton flux. However, if the revised Yakutsk spectrum eventually prevails, the whole question may be reopened.

MOTION OF THE PARTICLES As mentioned above, the (by no means exclusive) tendency of particles above 3×10^{19} eV to arrive from high northern galactic latitudes also drew attention to the Virgo supercluster region. Giler et al. (45) have proposed modeling the motion through intergalactic space with a diffusion, the coefficient D rising with E. Then a rising anisotropy above 10^{19} eV could be expected, while D might be too small to allow space to fill with old particles from farther off. At a distance r from a source, the anisotropy amplitude is $A \sim \lambda/r$, so if $A \sim 0.6$ at $\sim 6 \times 10^{19}$ eV, the mean free path is $\lambda \sim 10$ Mpc if Virgo dominates the flux. The spectrum can flatten somewhat in the 10^{19} eV region in such models, but this depends on an interplay of several factors.

4.2 *Propagation from Galactic Sources*

What if the sources lie within the Galaxy? Are the observed cosmic rays too isotropic for this? Kiraly et al. (62) found that for energies up to 10^{17} eV, the anisotropy was consistent with galactic sources; and a measurement at 10^{17} eV that worried them has since been retracted (28). Figure 5 is certainly favorable. Such an origin for the cosmic rays requires a galactic halo extending many kiloparsecs (Figure 2), but an ordered field of $\sim 2\ \mu$G extending beyond 10 kpc is quite compatible with radio observations (33, 78), as B^2 must fall off more slowly than synchrotron emission. An ordered field confined to the disk, however, would guide a large concentration of cosmic rays above 10^{17} eV into directions along the galactic magnetic field lines (60, 92), contrary to observation; but Berezinsky & Mikhailov (11) find that a small B component normal to the disk destroys this pattern. They also find that the observed magnitude of the anisotropy is very reasonable for particles originating in the Galaxy (up to 10^{19} eV), even without the requirement of a very extensive halo. The striking tendency toward a southern excess below 10^{19} eV has been interpreted (56) as indicating a local density gradient of cosmic rays in this energy range ($\sim 15\%\ \mathrm{kpc}^{-1}$) increasing toward the Orion region. (Alternatively, we may live in a hole in the magnetic field, asymmetrically situated north of the central plane of the Galaxy.) Indeed, these energy-dependent anisotropies indicative of density variations on a kiloparsec scale are much more favorable to a galactic origin.

5. CONCLUSIONS

Where do cosmic rays originate?

Are they all extragalactic? Burbidge (18, 19) has pointed out the possibilities of such schemes. At low energies we really only have weak gamma-ray evidence against an extragalactic origin (83), and an earlier conclusion that cosmic-ray protons were less numerous in the outer parts of the Galaxy has now been overturned by observations from COS-B (54). There is, however, a consistent galactic picture, and near 10^{18} eV the 10–20% N/S asymmetries just alluded to speak against a very distant origin.

Are they all Galactic? This would seem possible only if (*a*) further evidence at 10^{19} eV and above becomes consistent with a composition that is principally carbon and heavier, and (*b*) there is the necessary very large halo with ordered fields $> 1\ \mu$G. (One might use the COS-B result to argue for the existence of a very large halo.) The irregular shape of the spectrum near 10^{19} eV—which is not really just a different slope—would probably then relate to large-scale looping of trajectories. The directions of the most energetic Sydney showers favor such an interpretation. A direct mode of acceleration by pulsars would probably be called for.

Do extragalactic particles take over for energies larger than 10^{19} eV? This is at present the most likely hypothesis [supported also in an earlier review by Berezinsky (9)], being more probable than the previous one because of Haverah Park's directions and the fluctuation measurements (though at somewhat lower energy) that favor protons as a large component. However, Virgo is not a particularly impressive source region.

Present Galactic acceleration models have difficulty in getting particles beyond 10^{15} eV, but Cygnus X-3 illustrates the shortcomings of such models (and this source points to the importance of direct rather than statistical acceleration). Do the principal (supernova?) accelerators really give out immediately above the knee of the spectrum, beyond which ($\sim 3 \times 10^{16}$ eV) a new proton-rich flux takes over, as is strongly advocated by some workers (e.g. 71, 93)? Most remarkably, experiments do not show a departure from a smooth spectrum here (there must be a very neat join!), and the smoothness of the spectrum from 10^{16} eV to near 10^{19} eV presents a great challenge to those who build accelerators in the sky. At any rate, this part of the spectrum cannot be a "universal" flux: this would be highly isotropic. The smooth one-bend spectrum and the clear anisotropies below 10^{19} eV are particularly interesting aspects of the present data.

When the methods of deducing composition near 10^{15} eV have been made consistent, we may be able to reduce the number of possibilities considerably. Meanwhile, it is very tantalizing that although progress in extending the upper limit of the spectrum has been very slow, it has shown that a global mapping of the sky just beyond the energy range now studied could make the Galactic versus Virgo choice clear.

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