ACCELERATION PROCESSES IN THE UNIVERSE

by

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1. INTRODUCTION

Cosmic rays — energetic particles accelerated by natural extra-terrestrial processes — owe their discovery to the intrepid balloon experiments of Hess in 1912. They played a crucial part in high energy physics at least until the 1950s. Subsequently, they have been eclipsed as a research tool by the dramatic advances in accelerator technology. The emphasis in cosmic ray studies has shifted towards astrophysics: one is interested in trying to infer how and where the particles are accelerated, and in their propagation to the Earth. There is still no detailed understanding of cosmic ray origins (see [1] for a selection of "classic" papers on this theme). Part of the problem is that one has no directional information - only knowledge of the spectrum and composition of an almost isotropic background. It is as though we "smell" rather than "see" the sources. This talk (of which the present written text is just a summary) will deal with the various acceleration mechanisms that may be relevant; with some recent, and rather direct, observational evidence that some compact cosmic objects are exceedingly efficient accelerators of relativistic particles; and with the novel prospect that we can learn about the physics of ultra-high energies from cosmological evidence. Some cosmic acceleration mechanisms are genuinely analogous to what might be done artificially on Earth; others, however, depend on the availability of cosmic lengthscales and timespans.

The cosmic rays reaching the Earth have an energy spectrum which is roughly a power-law. The flux at energy > E is $N(> E) \propto E^{-n}$ where $n \simeq 1.6$. Although this spectrum extends up to energies of 10^{20} ev, the ultra high energy flux is exceedingly low. To illustrate this, one might note that at > 10^6 Gev (the highest centre-of-mass energy achievable by technically feasible $p - \bar{p}$ colliders) the "cosmic ray beam" amounts to only $(10^{-5} - 10^{-6})$ particles m^{-2} s^{-1}. Cosmic rays therefore can offer only rather secondary evidence (e.g. the content of extensive air showers initiated by ultrahigh energy primaries) on the physics of particle collisions above the energy range that is accessible by experimental techniques. Discrete radio sources (see Figure 1) emit by the synchrotron process: this indicates that they contain freshly accelerated relativistic electrons. Moreover, the energy spectrum of the electrons, which can be inferred from the frequency spectrum of the emitted synchrotron radiation, is generally close to $N(> E) \propto E^{-1.6}$, implying that there is something special about a power-law spectrum with this particular slope.

Despite continuing perplexity about the details, there is a general consensus that supernovae are implicated in the production of cosmic rays - either via the compact spinning neutron stars which are sometimes formed in the explosion, or via the ejecta which are blown off at speeds up to 10^4 km s^{-1} and eventually are decelerated by sweeping up interstellar matter. In this connection, I should like to recall the extraordinarily prescient 1934 paper by W. Baade and F. Zwicky (Proc. Nat. Acad. Sci. 20, 259), reprinted in ref [1], in which the authors said the following:

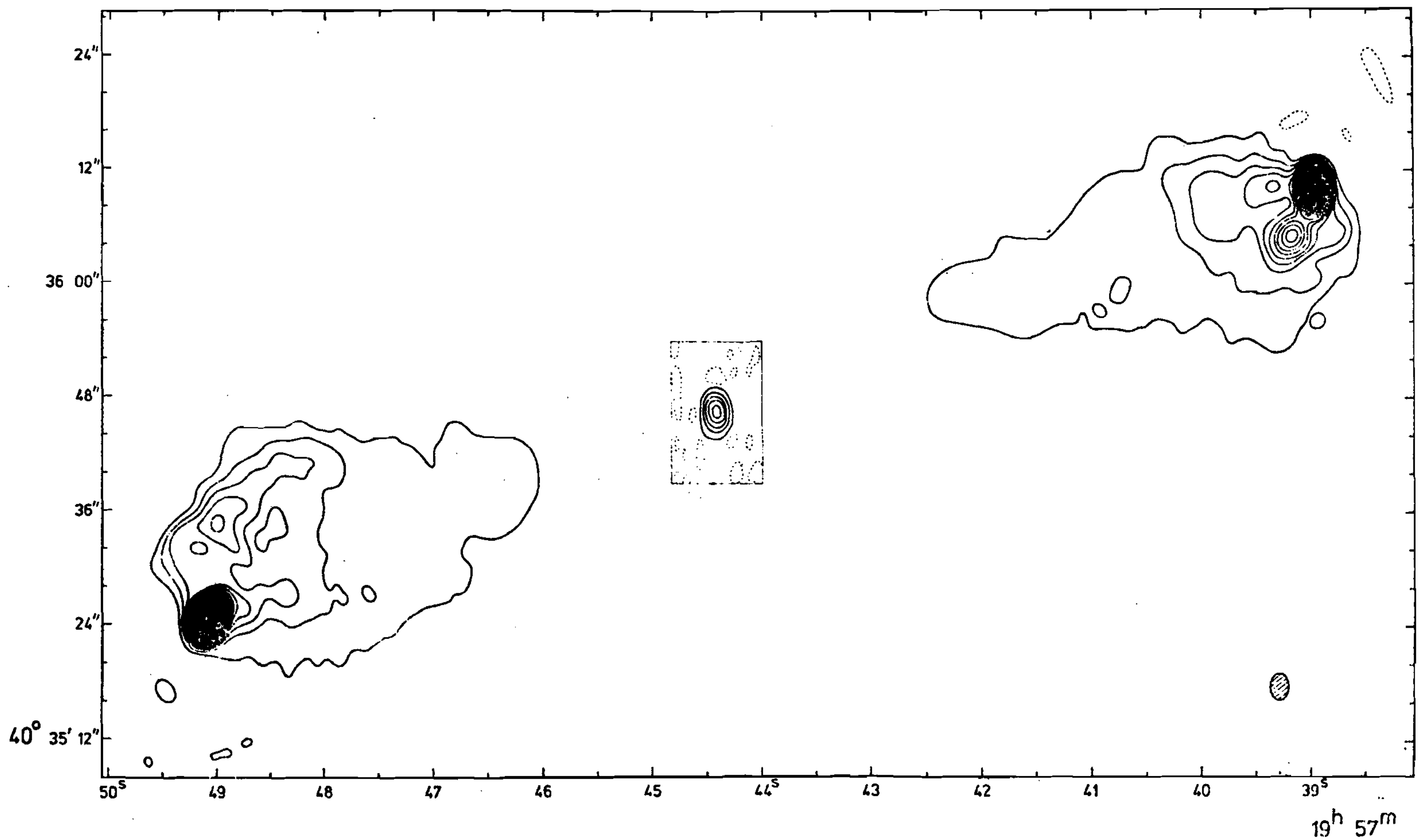


Figure 1. The 5 GHz radio map of the "archetype" strong extragalactic radio source Cygnus A (From Hargrave and Ryle MNRAS, 166, 305 (1974)). The synchrotron radio emission comes from 2 "lobes" symmetrically located on either side of the optical galaxy. Energy is fed into the lobes via collimated "beams" of hot (perhaps relativistic) plasma. The overall dimensions of the source are about half a million light years.

"With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such."

"The hypotheses that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays".

2. STOCHASTIC ACCELERATION MECHANISMS

The most familiar proposal for cosmic-ray acceleration is the "Fermi process". The acceleration was originally conceived as resulting from collisions with moving interstellar clouds, but many variants have subsequently been considered. The rate of energy gain is proportional to energy, and (subject to certain assumptions about escape probabilities, etc.) all particles injected with an energy exceeding the "threshold" below which ionisation losses are important would establish a power-law spectrum. The proportions of different charges accelerated depend on the injection and the fact that the threshold energy may not be the same for all species.

If the particles are scattered off randomly-moving fluctuations, the acceleration is a second-order effect. A more efficient variant of the Fermi mechanism, which has recently been investigated in some detail, involves shock waves [2 - 7] . If material flows through a stationary shock with upstream velocity v_1 and downstream velocity v_2 (when $v_1, v_2 \ll c$) then a relativistic particle coupled magnetically to the mean flow, but able to diffuse, may cross the shock $\sim (c/v_1)$ times; on each passage back and forth, its momentum is boosted by a fraction $\sim \left(\frac{v_1 - v_2}{c}\right)$. It behaves as though it were bouncing repeatedly off two approaching mirrors, the cumulative fractional change in its momentum being of order unity. A more detailed investigation of the diffusion process enables one to calculate the probability of different numbers of "bounces"; this work shows that a power law spectrum can be generated, whose slope depends primarily on the compression factor across the shock (v_1/v_2). This type of mechanism may well be highly efficient in many cosmic contexts - it may, in particular, accelerate the relativistic electrons whose synchrotron emission is observed in cosmic radio sources. The bulk of the cosmic rays at the Earth could have been accelerated by shock waves in the interstellar medium generated by expanding supernova remnants (see references [6] and [7] for reviews of this topic).

The great virtue of the shock-acceleration process is that it generates a power law spectrum with a fairly standardised slope. The problem with the Fermi mechanism in its original form was that the slope of the power law depended on the ratio of two timescales - the energy-doubling timescale and the timescale for escape from the region where acceleration occurs - which are, *prima facie*, quite unrelated.

3. "ONE STEP" NON STOCHASTIC PROCESSES

The statistical processes are probably the dominant ones for cosmic ray acceleration, and for the production of the relativistic electrons whose synchrotron emission provides the radiative output in most cosmic radio sources. There are, however, many contexts where systematic processes more analogous to a linear accelerator may be operative.

(1) Acceleration of bulk matter by a relativistic shock

The first-order Fermi process discussed in § 2 operates on a small number of particles moving faster than a (non-relativistic) shock. A different (and conceptually even simpler) possibility is that a relativistic shock accelerates bulk matter to speeds $\sim$ c.

Colgate and his collaborators [8] argued that the collapse of a stellar core would initiate an outward-propagating shock wave which blows off the stellar envelope, giving rise to a supernova. This shock would speed up as it penetrated into the tenuous outer layers of the star, eventually becoming relativistic. The layer with density ρ gets accelerated to $\gamma \propto \rho^{-\frac{1}{2}(3-\sqrt{3})}$ The energy spectrum of the resulting cosmic rays depends on the density profile in the stellar atmosphere, but could be a power law with about the right slope $n \sim 1.6$ if the mass fraction of atmosphere with density $< \rho$ scales roughly as ρ^{-1}. The chemical composition would be more or less that of the original unprocessed stellar material. However, the shock would impart equal velocities (i.e. equal Lorentz factors) to electrons and protons, so the electron/proton ratio at a given energy would be $(m_e/m_p)^n$ unless subsequent effects behind the shock front (e.g. plasma oscillations) could transfer energy from nucleons to electrons. The efficiency of this mechanism (i.e. the energy per supernova transformed by the shock into relativistic particles) is a complex and still disputed question.

This type of bulk acceleration could in principle result from explosive outbursts on white dwarfs or neutron stars. It now, however, seems unlikely that this process plays much part in the acceleration of the observed cosmic rays.

Recently, however, clear evidence that relativistic shocks exist has emerged in a different context. Very long baseline interferometry (VLBI) techniques have shown that the (milli-arc-second) radio structure of some quasars exhibits jet-like features whose structure changes so rapidly that these sources must involve bulk flows at speeds close to c — bulk Lorentz factors $\gamma_b \gtrsim 5$. The jets consist of plasma (conceivably $e^+ - e^-$ plasma) which could have acquired relativistic thermal energies in the deep potential well near a collapsed massive object, the thermal energies being converted into directed kinetic energy by expansion through a nozzle. (Alternative models involve pulsar-like electrodynamic processes near a massive black hole.) The radio-emitting moving features revealed by VLBI measurements would be places where the bulk flow is being re-randomised by passage through a relativistic shock (see Figure [2]).

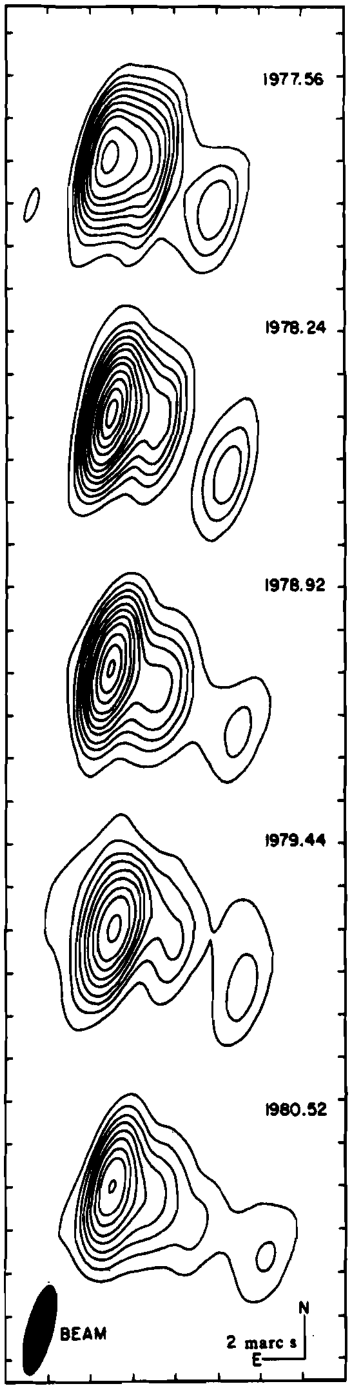
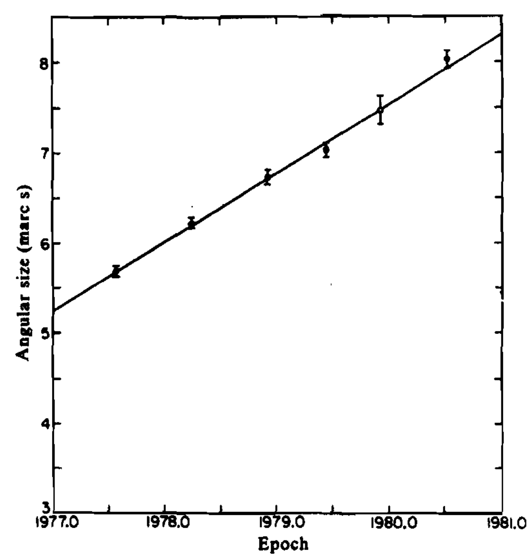
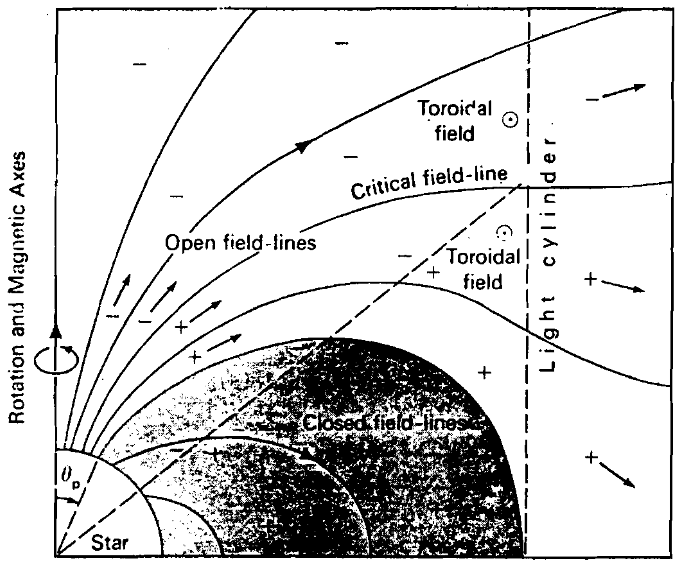


Figure 2. This diagram taken from Pearson et al. (Nature 290, 365 (1981)) shows VLBI maps of 3C273 at 5 epochs. The observing frequency is 10.65 GHz. The high-surface-brightness feature on the left hand side is probably identifiable with the optical nucleus. The "blob" on the right hand side has moved with an apparent speed of $5(H_0/100\ km\ s^{-1}\ Mpc^{-1})^{-1}c$, and points in the direction of the optical jet in 3C273. These observations imply bulk motions with a Lorentz factor $\gtrsim 5$. The material involved may be electron-positron plasma rather than "ordinary" plasma.





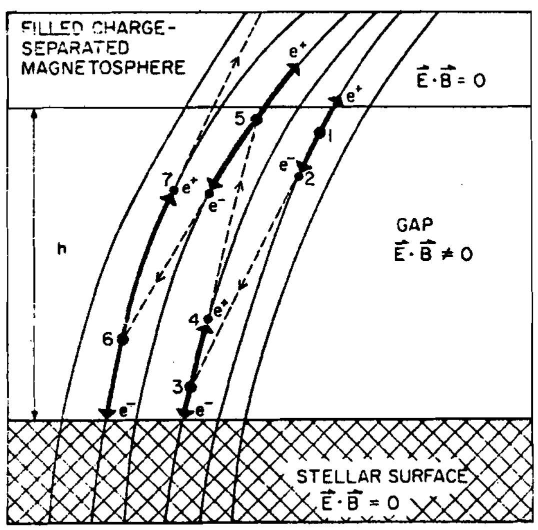


Figure 3. The upper figure shows the field structure expected around a neutron star spinning around its magnetic axis (after Goldreich and Julian (Astrophys.J., 157, 869 (1969)). The lower figure, from ref [10], shows how $e^+ - e^-$ plasma may be generated in a gap near the polar caps where $\underline{E}.\underline{B}$ is very large.

(2) Pulsars - linear accelerators?

Pulsars are spinning neutron stars whose surface magnetic fields are in many cases believed to exceed 10^{12} gauss. It is a general feature of all pulsar theories that large induced electric fields are unavoidable. In order of magnitude, the E-field along the magnetic field lines near the poles may be $> 10^{10}$ volts cm^{-1} for a typical ($\sim$ 1 second period) pulsar, and still more if the spin rate is faster. Thus, because of the ultra-strong fields, electrostatic acceleration can in principle achieve $> 10^{16}$ volts in regions no larger than a terrestrial accelerator (e.g. the region of dimensions $\sim$ 1 km around a neutron star's magnetic poles).

Although the available electric potential would suffice to accelerate individual charges to extremely high energies it is completely unclear what energies would actually be attained by particles escaping from the magnetic polar caps. Nor is it clear whether electrons or ions would be preferred. In early work [9] it was supposed that electrons emerge from some regions and that the circuits were completed by ions emerging from other parts of the star. Ruderman & Sutherland [10] have emphasised that the available electric fields may be unable to extract ions from the crust of a strongly magnetised neutron star, because the surface material forms into a tightly bound and very dense anisotropic lattice. To extract ions from this lattice would typically require $\sim 10^{12}$ V/cm, whereas the maximum field available is only $\sim 10^{11}(\Omega/2\pi)$ V/cm. Except for very young pulsars, the current circuit is then instead completed by an inward-flowing stream of electrons, electron-positron pairs being created in the magnetosphere by interaction of γ-rays with the 10^{12} gauss magnetic fields. The positrons stream outward and escape from the pulsar. (The γ-rays themselves result from curvature radiation by the electrons and positrons. Cascades of electron-positron pairs are produced in localised 'sparks', in terms of whose peculiar properties Ruderman & Sutherland try to explain several puzzling features of pulsar emission.) The main relevance of this work to cosmic rays is that it suggests a mechanism for primary positron production.

(3) Pulsars: strong e-m wave acceleration?

According to a popular class of models, pulsars resemble spinning magnetic dipoles to the extent that they emit electromagnetic waves at the rotation frequency. It is unclear whether it is realistic to envisage that these ultra-low-frequency waves propagate for many wavelengths, but if they did, they would be very effective in particle acceleration. This is because the "strength parameter" $eB/m_e c\omega$, where ω is the wave frequency, is $>> 1$. This parameter is a measure of the Lorentz factor which a test electron would acquire if exposed to the wave field for one half-cycle. The general motion of a test charge in a strong wave consists of a "guiding centre" motion together with a periodic component whose Lorentz factor (in the guiding centre frame) is of order the strength parameter. In terrestrial contexts, strength parameters $\gtrsim 1$ are attained only in extreme conditions involving focussed lasers; but for the ultra-low coherent emission that may come from pulsars, the energies attainable by test particles are as high as those that can arise from the large $\underline{E}.\underline{B}$ near the magnetic poles.

(4) SS433: radiation pressure acceleration?

A unique object in our Galaxy is SS433, [11] which expels two oppositely-directed jets whose orientation precesses on a 160 day timescale. The jet speeds can be directly measured, because the moving material emits spectral lines, and are steady, at ~ 0.27 c. There is no consensus about the precise nature of this object, nor about what drives the jets. However, there is a "coincidence", first pointed out by Milgrom [12] which suggests that radiation pressure may be the driving force. The redshift between the jet material and the central object which ejects it is close to $\lambda_{obs}/\lambda_{em} = 4/3$. This is the ratio which shifts the Lyman limit into coincidence with Lyman α. If the radiation causing the acceleration resembled the continuum from a hot star, it would cut off sharply. The main acceleration force would be due to absorption of this continuum by atomic hydrogen in the jets; the acceleration would then stop (and the material coast at a steady terminal velocity) when the redshift reached just this value. If this idea is correct, it is the most extreme instance of radiation pressure acceleration - a process which is widespread in other astrophysical contexts (e.g. the driving of winds from hot stars). Because the length scales are so large, radiation pressure can readily generate relativistic speeds even if the radiation flux is no more intense than purely thermal. To make a hydrogen atom move relativistically, it must absorb the momentum of $\sim 10^8$ Lyman α photons. This requires a path length $10^8 A_{21}^{-1}$ c. To achieve analogous acceleration on a terrestrial scale would require the use of a heavy hydrogenlike ion, for which the rate A_{21} and the momentum per relevant photon are both higher.

4. THE HIGHEST ENERGY COSMIC RAYS

Stochastic or shock wave acceleration of 10^{20} ev protons (the highest cosmic ray primaries observed) in a region of mean field B and length scale ℓ is possible only if $B_{gauss}\, \ell_{light\ years} \gg 10^{-2}$. This rules out supernova remnants, whose scale is much smaller than the gyroradii of such particles. The high-B regions associated with galactic nuclei and pulsars are also unpromising, because of the high radiation density. The prime sites for the acceleration of these ultra-high energy particles are the "lobes" of large extragalactic radio sources.

The most energetic elementary particle reactions occurring on earth are collisions between very highly energetic cosmic rays and nucleons in the upper atmosphere. A collision of a 10^{11} GeV primary with a nucleon has a center of mass energy of $10^{5.5}$ GeV. There may not be any reactions in the atmosphere at energies significantly higher than this, because the spectrum of very high energy cosmic ray primaries is expected to drop steeply above the observed 10^{11} GeV, because of interactions with the 3K background photons (c.o.m. energies > 0.1 GeV, high enough for photopion interactions) [13, 14]. It is not yet clear whether the primaries of giant air showers are single protons or heavier ions, possibly even iron nuclei [15]. In the latter case the highest observed energy per nucleon will be only 10^9 GeV, or $10^{4.5}$ GeV in the c.o.m. frame of atmospheric collisions. Even $10^{4.5}$ GeV exceeds the highest energies attainable with present-day accelerators by more than an order of magnitude. However, if (in the next century) new types of accelerators would reach this energy, they could trigger reactions more energetic than ever before occurred on Earth.

Collisions of two ultra-energetic cosmic rays with each other could yield c.o.m. energies above 10^{11} GeV. Such events are incredibly rare, but it is interesting to ask whether they would be likely to have occurred anywhere — in our Galaxy or beyond. P. Hut and I have tried to make such an estimate. The flux of > 10^{11} GeV particles is $\sim 4 \times 10^{-16}$ m^{-2} s^{-1} sr^{-1}, corresponding to density $n(E > 10^{11}$ GeV$) = 1.7 \times 10^{-29}$ cm^{-3}. For an order of magnitude estimate we can take all particles to have the same energy $E = 10^{11}$ GeV, with density $n = 10^{-29}$ cm^{-3}. The appropriate cross section for (nearly) head-on collisions, the square of the Compton wavelength, is $\sigma \approx 1/E^2 \approx 10^{-48}$ cm^2. This leads to a collision rate per particle of $n\sigma c = 3.10^{-67}$ s^{-1}. The total collision rate per space-time.volume is then $n^2\sigma c = 3.10^{-96}$ s^{-1} cm^{-3}. Our past light cone has a space-time volume of order c^3T^4, where $T \approx 10^{10}$y is the Hubble Time. Therefore, the expected number of collisions between ultra-energetic cosmic ray primaries with a c.o.m. energy $E > 10^{11}$ GeV inside our causally connected past is $n^2\sigma c^4 T^4_{Hubble} \approx 10^5$.

For higher energies, $E > 10^{12}$ GeV, probably not even one collision has taken place in the history of the observable Universe: even an optimistic extrapolation of the ultra high energy cosmic ray flux, neglecting any 3K attenuation, gives $\Phi(E > E_0) \propto E_0^{-1.5}$, leading to an expected number of collisions at energies above E_0 which drops off as E_0^{-5} (taking $\sigma \propto E^{-2}$).

This derivation has assumed a homogeneous distribution of ultra high energy particles. If these particles are clumped on, say, the scales of galaxy clusters then the effective volume for collisions is smaller than c^3T^4 by a factor of $\sim 10^{-2}$. This could reduce the normalization of the energy scale in the previous formula by a factor 2 or 3. But at the place of production of ultra high energy particles the collision probability will have been higher than measured at the Earth, counteracting the effect of the smaller space-time volume available.

The most energetic collision in the Universe (which we can say with confidence must have occurred) had a center of mass energy of order $10^{11} - 10^{12}$GeV. This limit, directly deduced from observations of ultra high energy cosmic ray showers, puts the most stringent limits on the existence of other vacuum states lower than the one we presently inhabit. In some field theories, the Universe might have supercooled in a local minimum of the effective potential [16]. The metastable false vacuum must be very stable against a spontaneous transition via tunnelling, but it is interesting to ask whether high-energy collisions could trigger the formation of a "bubble" of true vacuum, which would then expand at $\sim$ c to destroy the Universe as we know it. How seriously the above result constrains a specific spontaneously broken field theory, depends on its parameters such as barrier height and potential drop between true and false vacuum. But at least we can be reassured that no particle accelerator in the foreseeable future will pose any threat to our vacuum - vastly greater local concentrations of energy have been repeatedly produced by collisions of cosmic ray particles with each other.

Besides the observed high energy cosmic rays, there might exist other objects which could place higher limits on the stability of our vacuum, such as monopoles or even small primordial black holes. The former might induce a transition to a lower vacuum state because of their high mass (of order 10^{17}GeV in most models) and small dimensions, while the latter could induce a transition at the moment of final explosion at the end of evaporation via Hawking radiation. However, so long as such objects remain conjectural, neither sets any firm limits on the stability of our vacuum.

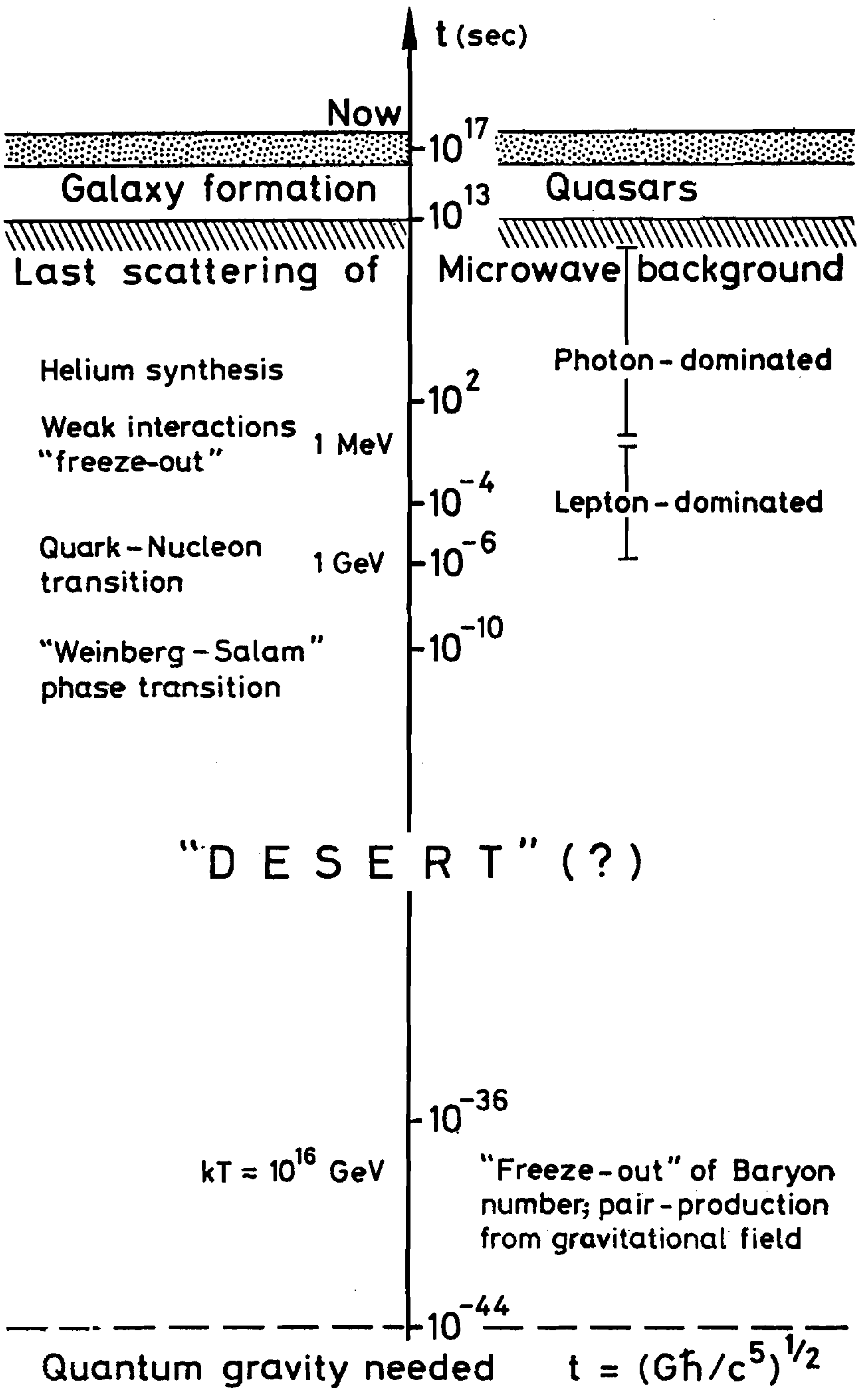


Figure 4. This diagram illustrates, in terms of logarithmic time, various key physical stages in the expansion of a standard Big Bang model. 60 "decades" separate us from the Planck time. Observations of individual sources permit us to probe only the last decade (stippled region of diagram); the last scattering of the microwave background may have occurred when the universe had only $\sim 10^{-4}$ of its present age: primordial nucleosynthesis yields evidence on physical conditions when $t \simeq 1$ sec. The crucial consequences of GUT's would be confined to still earlier stages: they involve extrapolating back in time by a further 36 orders of magnitude!

5. THE VERY EARLY UNIVERSE

According to the "big bang" theory, high thermal energies would have been attained in the initial instants of the universal expansion. The fact that the observed abundances of He, D and other light elements is consistent with what would be produced ∿ 1 - 100 seconds after the big bang has encouraged some authors to invert the line of argument and use astronomical data to constrain such things as the number of neutrino species, etc. on the assumption that there was a big bang. Moreover, the success of primordial nucleosynthesis has emboldened some physicists to extrapolate the hot big bang back to still earlier times, where the physics is more uncertain. The only mandatory stopping place for such extrapolations is the Planck time, where quantum gravity effects are crucial. If the expansion had indeed followed a Friedmann model ever since the threshold of classical cosmology, kT would exceed 1 GeV for the first microsecond. During the initial stages the particle energies would sweep down through the entire range of interest to theoretical high energy physicists, including of course the ultra-high energies unattainable by any feasible terrestrial accelerator. In effect the universe provides us with a giant but cheap accelerator (or at least one which is not being charged to us). However, it shut down ten billion years ago. The only surviving "fossils" of the high energy era will be related to processes which fell out of equilibrium at that stage. For the first 10^{-36} seconds, the thermal energies were high enough that the massive X-boson postulated in GUT theories would have existed. Many people have recently explored the exciting possibility that the ratio of the number of photons to the number of baryons can be explained in terms of GUT theories - in other words, that the baryons in the universe are themselves a "fossil" of the first 10^{-36} seconds, just as helium may be a fossil of the first few seconds after the big bang.

Extrapolation from the nucleosynthesis era ($t \simeq 1$ sec, $kT \simeq 1$ Mev) back to the GUT era involves more powers of ten than are involved on going from the present time ($t \simeq 10^{10}$ yrs) back to primordial nucleosynthesis. It is still very speculative - just as the ideas of Gamow and his collaborators about the "primordial fireball" were deemed highly speculative when first propounded more than 30 years ago. However, many cosmologists (as well as many particle physicists) suspect that processes occurring at the GUT era — baryon nonconservation, phase transitions, etc. — may hold clues to several key properties of the Universe such as its scale, particles content and degree of homogeneity. One hopes that these ideas will be placed on a firmer footing in the next few years, just as big bang nucleosynthesis was during the 1960s. One can perhaps be assertive enough to claim that cosmology may offer some of the few empirical tests of GUT models, where the crucial phenomena involve energies far beyond those which accelerators can ever probe directly.

REFERENCES

1. S. Rosen (ed) "Selected papers on cosmic ray origin theories" (Dover, N.Y. 1969)
2. G.F. Krymsky, Sov.Phys.Doklady, 23, 327 (1977).
3. A.R. Bell. MNRAS, 182, 147 & 443 (1978).
4. W.I. Axford, E. Leer and G. Skadron. Proc. 15th International Cosmic Ray Conference (Plovdiv) 11, 132 (1977).

5. R.D.Blandford and J.P. Ostriker. Astrophys.J., 221, L29 (1978).
6. W.I. Axford. Ann.N.Y. Acad. Sci., 375. 297.
7. L. O'C. Drury. Rep. Prog. Phys. (in press).
8. S.A.Colgate and M.H. Johnson. Phys. Rev. Lett., 5, 235 (1960).
9. P.A. Sturrock. Astrophys.J., 164, 529 (1971).
10. M.A. Ruderman and P.G. Sutherland. Astrophys.J., 196, 51 (1975).
11. B. Margon. Science 215, 247 (1982).
12. M. Milgrom. Astr. Astrophys., 78, L9 (1979).
13. R. Greisen. Phys. Rev. Letters, 16, 748 (1966).
14. G.T. Zatsepin and V.A. Kuzmin. JETP Letters, 4, 78 (1966).
15. G. Cunningham, J. Lloyd-Evans, A.M.T. Pollock, R.J.O. Reid and A.A. Watson. Astrophys.J. (Letters), 236, L71 (1980).
16. S. Coleman and F. DeLuccia. Phys. Rev. D.21, 3305 (1980).