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ABORIGINES OF THE NUCLEAR DESERT^{*)}

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ABSTRACT

The chart of "stable nuclides" extends from Hydrogen, to $Z \sim 98$, $A \sim 263$. It contains another island of stability - neutron stars - in a narrow range around $Z \sim 10^{56}$, $A \sim 10^{57}$. In between lies a supposedly barren region encompassing more than 50 orders of magnitude. This desert may be populated by strange quark balls: stable single bags containing similar proportions of u, d and s quarks. These balls are candidates for the constituency of the "dark mass" in galaxies and in the Universe. We describe seven ways to search for these possible inhabitants of the nuclear desert.

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1. THE INVISIBLE HALO OF GALAXIES

The Milky Way and scores of other galaxies have a distribution of mass that is not accounted for by stars and interstellar gas or dust. Galaxies have a massive halo of some other form of matter, extending well beyond their visible radius, R_{vis} , and having a gravitational mass five or more times superior to that of what is directly seen. This observation is based on the detection of Doppler-shifted characteristic emission lines from thin gas gravitating around a given galaxy. The data imply a mass density superior to that of the stars or the "test-particle" gas itself. From the Doppler shifts, one may extract the velocity $v(R)$ of the orbiting emitters, relative to the galactic centre, at a distance R from that point. A typical "velocity curve": $v(R)$ versus R is shown in Fig. 1a.

Let $M(R)$ denote the galactic mass within a centered sphere of radius R . Should the galactic mass be concentrated in the visible region, $M(R) = M(R_{\text{vis}})$ for $R > R_{\text{vis}}$. Newtonian mechanics ($GM/R^2 = v^2/R$) would then lead one to expect $v(R) \sim R^{-1/2}$ for $R > R_{\text{vis}}$. The observations give a completely different result: $v(R)$ stays approximately constant at 200 to 300 km/sec well beyond R_{vis} , up to a certain $R = R_H^{\text{min}}$, beyond which the signal is too weak to be observed. The minimum mass of the invisible halo $M(R_H^{\text{min}})$ is for some galaxies 5 or 10 times larger than $M(R_{\text{vis}})$.

FIGURE 1

The dark mass of galaxies and bigger beings. a) A galactic velocity curve. b) Velocities in the Sc galaxy NGC2998, deduced from Doppler shifts of optical lines. c) The mass of the Milky Way within centered spheres of increasing radius. d) Observations of M/L ratios for objects of increasing dimensions, in solar units. b), c) and d) are figures from Ref. 2.

The first observations¹ of the mysterious galactic halos were based on the analysis of the 21 cm line of electron spin flip in atomic Hydrogen. These results have recently been confirmed and strengthened for a considerable number of spiral galaxies by observations of H, He and ionized N and S lines in the optical domain². The technique and a typical result are shown in Fig. 1b. Monochromatic lines are observed through the slit of a spectrometer, placed in this case along or across the plane of an Sc galaxy (NGC2998). The lines seen with the slit in the vertical position just show the Doppler shift from the recession of the Galaxy at 4800 km/sec. The lines seen with the slit along the plane of the Galaxy show a differential shift corresponding to the rotation of the emitter atoms around the galactic axis. The deduced velocity curve (relative to the observer) is shown in the lower part of Fig. 1b. A few specific velocity curves (relative to the galactic centers) are shown in Fig. 2, in order of increasing galactic luminosity. For the cases at the bottom of the figure, the velocity curves extend to distances well beyond R_{vis} .

FIGURE 2
Rotation curves of Sc galaxies
of increasing luminosity, also
copied from Ref. 2.

A flat velocity curve corresponds to a linearly increasing galactic mass $M(R)$ within a radius R , $M(R) \sim R$. Figure 1c, from observations of a variety of "satellites" of our own galaxy, shows that the Milky Way has a dark halo similar to that of other observed galaxies. The halo extends well beyond the position of the Sun, once thought to be in the outskirts of our galaxy.

To summarize, *there is more to a galaxy than meets the eye* (stars and dust). Galaxies are a few times more massive and extensive than their star population. What is the stuff of the dark mass? It may be ordinary matter in the form of Jupiters or golf-balls: objects that would not emit or scatter much visible light. In the next chapter, I review an argument to the effect that this boring possibility is not tenable: to the extent to which

cosmological syllogisms are convincing, one may be convinced that the dark mass of galaxies, or bigger objects, cannot consist of ordinary matter.

2. THE DARK MASS OF THE UNIVERSE

Let H_0 denote the present value of Hubble's "constant" $H(t)$: the observed fixed ratio, $v(D)/D$, of the velocity upon the distance of other galaxies, relative to ours. The value of H_0 is controversial, in the range of 50 to 100 km/s Mpc $\sim (20 \text{ to } 10 \text{ G years})^{-1}$. In the standard Friedman-Einstein cosmology, the Universe is flat (zero curvature: neither open nor closed) provided its present average energy density takes the critical value $\rho = \rho_c = 3H_0^2/4\pi G \sim 10^{-29}(H_0/50)^2 \text{ gr/cm}^3$. [Here and in what follows the cosmological constant is assumed to vanish.] Figure 1d displays observations² of the average energy density of cosmological objects of increasing dimensions, in terms of mass over luminosity M/L , rather than ρ . The data for objects bigger than single galaxies stems from statistical analysis of the motions of their constituents³. The same figure shows that the largest observable objects come tantalizingly close to the M/L value corresponding to $\rho = \rho_c$, $M/L \sim 700 \text{ solar units}^*$). Why should the Universe choose to be flat and have the critical energy density? There are two lines of theoretical argument in favour of $\rho \equiv \rho_c$, that I proceed to outline.

The general relativistic equation governing the evolution of the Universe is

$$3H^2(t) = 3\left(\frac{\dot{R}}{R}\right)^2 = 8\pi G\rho - k \frac{3c^2}{R^2} \quad (1)$$

with R a scale parameter of the Universe and $k = 1, 0, -1$ for a closed, flat or open Universe, respectively. The term proportional to $(\dot{R}/R)^2$ is a kinetic energy term, the one proportional to ρ is a gravitational potential energy term, the term behaving as R^{-2} is a "curvature" term. For our present Universe, the gravitational term is known to be not less than a few per cent of the curvature term. As one runs Eq. (1) backwards in time, R diminishes and the gravitational term increases with ρ as R^{-3} or faster. The curvature term increases more slowly, as R^{-2} . At $t \sim \text{few seconds}$, the time of onset of primordial nucleosynthesis (a subject that, as we shall see, seems to be well understood) the gravitational term is some 14 orders of magnitude bigger than the curvature term. To have the two terms be not so different at present, the curvature term must have been "tuned" to the 10^{-14} level at $t \sim 1 \text{ sec}$.

^{*}) It may be cogently argued that the data fall a little short of $\rho = \rho_c$, as done by A. Sandage and G.A. Tamman in the ESO/CERN proceedings of Ref. 2).

The necessary fine-tuning becomes increasingly precise as Eq. (1) is followed to earlier times. This is the "cosmological naturalness" problem, and the only reasonable way out of it seems to be to have $k = 0$, a flat Universe and no fine dialing problem⁴. This would be automatically set $\rho = \rho_c$.

Big bang cosmology is not without mystery. The observable Universe and its 2.7 °K background radiation are remarkably uniform and isotropic. In the standard cosmology, regions of space that we view in different directions, but that cannot have been in causal contact in the past, are surprisingly similar. This is the "cosmological causality" problem⁵. There is also a "GUT-monopole" problem⁶ encountered if one bravely runs the cosmological equations back to times when the prevailing temperature was high enough to produce the monopoles that necessarily exist in simple grand unified theories. The predicted abundance of primordial monopoles is well above the observational limits. These and other problems are solved in the "inflationary" and "neoinflationary" models of cosmology⁷. In these models the universal energy density is automatically the critical one.

Suppose the previous paragraphs have convinced you that $\rho = \rho_c$. In that case you face a new and fascinating problem, in connection with the primordial nucleosynthesis of D, ³He, ⁴He and ⁷Li. These, unlike the heavier elements, are not thought to be just fusion-cooked by the stars. The lighter elements are generated minutes after the big bang, when the prevailing temperature was such that the "right" fraction of ambient photons had energies comparable to nuclear binding energies⁸. That fraction is "right" in the sense of allowing the primary nucleosynthesis reaction $n+p \leftrightarrow D+\gamma$ to be temporarily in equilibrium. The primordial elements are fossil remnants of reactions such as

The reactions on the left column provide the ambient neutrons, most of which end up as ⁴He as the temperature drops to a level where fusion freezes. The calculated abundances depend weakly on the number N_ν of neutrino generations, and more steeply on the ratio $\eta = n_B/n_\gamma$ of (present) photon to baryon universal number densities. Recent results of Yang et al.⁹ are shown in Fig. 3. Amazingly enough, the observations are consistent with the predictions, in

FIGURE 3
The primordial abundance of elements as a function of $\eta = n_B/n_\gamma$, a figure from Ref. 9. Y_p is ${}^4\text{He}$ abundance by weight, relative to Hydrogen. The other abundances are by number, relative to H. The dotted domain is the allowed region for η , compatible with all observations.

the sense of being compatible with the calculated abundances for a certain range of η . This range: $3 \times 10^{-10} < \eta < 10^{-9}$, is shown as a dotted band in Fig. 3. And now for the conundrum. The photon number density $n_\gamma \sim 400/\text{cm}^3$ is well known from observations of the 2.7 °K background radiation⁸. The number density of baryons is $n_B = \eta n_\gamma$ and their contribution to the universal energy density is $\rho_B = m_p \eta n_\gamma < 7 \times 10^{-31} \text{ gr/cm}^3$. Stretching things around⁹, ρ_B cannot be bigger than 20% of the critical density ρ_c . Thus, if as indicated by experiment and strongly advocated by theory, the Universe is critical (flat), 80% of its energy density is contributed by something other than baryons. In other words, *more than eighty per cent of what there is, we do not know what it is*. To be precise, and to foretell our coming culprit, the dark mass may still be in baryons, provided they somehow managed to escape nucleosynthesis.

The stuff of the dark haloes of galaxies is not necessarily subject to the above argument: it may be ordinary matter (baryons). The reason is that galaxies fall short of providing all of the universal mass density: see Fig. 1d. The matter in halos, however, must be peculiarly distributed (dominant at the galactic outskirts, and not flattened into spiral discs, like the baryons that end up as stars). Moreover, halo-stuff of ordinary

matter must come in lumps of peculiar size (black holes, cool Jupiters, or "golf-balls" that do not scatter much light). While galactic haloes need not be made of something very weird, they may.

Many candidates for the constituency of the dark matter of the Universe have been proposed, among others massive neutrinos, axions, small primordial black holes, magnetic monopoles, the relativistic decay products of a variety of relic particles, gravitinos, photinos, you-name-it-inos ... In what follows, I shall concentrate on candidates for the constituency of the dark mass of the Universe that are closer than any of the above candidates to the heart of this audience, mainly composed of nuclear physicists.

3. STRANGE BALLS

Figure 4 is a more than usually complete chart of the nuclides, unusually drawn in the (Z,A) plane. In the lower left-hand corner lie the nuclei that are not very unstable against fission, a narrow band extending to $(Z,A) \sim (98,263)$. Higher up, in a small range around $A \sim 10^{57}$, there is an island of stability: neutron stars. These contain an equilibrium population¹⁰ of equal numbers of protons and electrons, their "Z" is a few per cent of A. "Nuclides" with ever larger A are unstable against gravitational collapse. The intermediate region $263 < A < 3 \times 10^{56}$ is traditionally thought to be a barren land where no nuclei are stable. Compared with this 54 orders of magnitude *nuclear desert*, the much publicized particle physics desert is a miserable grain of sand: it encompasses a mere 13 orders of magnitude: from the 100 GeV unification scale to the 10^{15} GeV grand unification scale. Witten¹¹ has recently argued that the nuclear desert may be inhabited, essentially for any A, by strange quark matter.

FIGURE 4
Chart of nuclides, hopefully incomplete.

Nuclei, we are told, are made of protons and neutrons and are not a single bag of u and d quarks. For the same value of A, a (p,n) ensemble is lighter than a hypothetical state wherein the nuclear constituents are dissolved and held in a single bag. At first sight, this fixed-A relation $M(p+n) < M(u+d)$ should be even more of an inequality, should some of the quarks in the hypothetical bag be replaced by strange ones, since $m_s > m_u, m_d$. But there is an effect, the Pauli exclusion principle, fighting in the opposite direction of making a bag with a strange quark contamination be lighter than one without it. It is more favourable to fill quantum states with three, rather than with two, different quark types. [In a degenerate gas of massless quarks at zero temperature¹¹, the energy per quark for three types of quarks is $[3/(1+2^{4/3})]^{3/4} \sim 0.9$ of what it is for two quark types.] Whether at fixed A, $M(p+n)$ is bigger or smaller than $M(u+d+s)$ is a delicate question of competition between Pauli and m_s . Should Pauli win, the ground state of nuclear matter may be single bags with approximately equal numbers of u, d and s quarks, and not what we were taught in school. Farhi and Jaffe¹² have done careful calculations regarding the issue of stability of strange quark bags in the context of the MIT bag model, and of a Fermi gas model. Their results are functions of m_s , α_s and B; the strange quark mass excess, the QCD fine structure constant and the bag parameter, respectively. They conclude that within the allowed range of these parameters, it is impossible to decide whether strange quark balls are more or less stable than ordinary nuclei. There are acceptable regions in the (B, α_s, m_s) plane for which strange quark matter is absolutely stable for essentially any value of A between "a few" and the black hole limit. They estimate the density of this hypothetical new ground state of nuclear matter to be

$$\rho_N \sim 3.6 \times 10^{14} \text{ gr/cm}^3, \quad (2)$$

not so different from the density of ordinary nuclear matter.

The hypothetical reader that has come so far must be fearing immediate and catastrophic extinction, for, if there is a state of nuclear matter lighter than ordinary nuclei, ordinary nuclei must decay into it. The weak interactions $[ud \rightarrow su, u \rightarrow se^+ \nu]$ of the quarks in, say, ^{56}Fe , should allow the nucleus to decay into a bag containing up to 56 strange quarks, with the emission of photons and maybe a few protons, α 's or $(e^+ \nu)$ pairs. Fortunately, this threatening decay is ~ 56 th order in the weak interactions and should take for ever to happen, even on a cosmological time scale. The reader may continue breathing normally.

The customary cosmological wisdom asserts that once upon a time the Universe was filled with a plasma of ν 's, γ 's, e 's, and quasi-free quarks and gluons. As it expanded and cooled below a temperature of a few hundred MeV, a phase transition took place, wherein all quarks ended up as ordinary protons and neutrons. But, if there is a more stable form of baryonic conglomerates - strange quark matter - much of the baryon number of the Universe may have ended up in the form of strange balls. Witten¹¹ proposes a controversial scenario in which this is indeed the fate of some 90% of the universal baryon number. Since the transition from the quark plasma to a cooler nuclear state occurred at a higher temperature (earlier time) than primordial nucleosynthesis, the baryon number hidden away in strange quark balls is not subject to the arguments of the previous chapter on primordial abundances in a flat critical Universe. In other words, *strange quark balls are candidate constituents of the dark mass of the Universe*. There may be other more contemporary sources of a strange quark ball contamination in our neighbourhood. As early as 1971, Chin and Kerman¹³ argued that the interior, or even most of a neutron star, may be made of strange quark matter. Collisions between neutron stars are not as infrequent as one may feel¹¹, and could be a cosmic source of strange quark matter, in lumps whose spectrum of sizes is not easy to predict.

Strange quark balls are but an explicit example of conceivable islands of nuclear stability within or beyond the A-values of the conventional nuclear table. In what follows, we shall refer to strange balls or other unusual lumps of nuclear matter as "*nuclearites*", when referring to past or present collisions of these peculiar nuclear meteorites with planet Earth¹⁴.

Since $m_s > m_{u,d}$, we expect strange quark balls to have fewer strange quarks than down quarks. This is explicitly shown¹²⁾ in Fig. 5a, a plot of strangeness over baryon number versus m_s , in strange balls large enough for surface effects to be negligible. The numbering of the different curves refers to values of α_s , the other parameters are chosen so that the energy per baryon is kept fixed at ~ 900 MeV. For $m_s = 0$, $-S = A$, and one third of the quarks are strange. As m_s increases the strange quark constituency is disfavoured. Similarly, Fig. 5b displays a calculation¹² of $Z/A^{1/3}$ versus A , with $m_s = 150$ MeV. For $m_s = 0$, Z would vanish. For $m_s \neq 0$, Z grows as $A^{1/3}$ for large A . Strange balls are more neutral than ordinary nuclear matter, for which $Z \sim A/2$; this is what makes them stable against Coulomb-induced fission. Being likely to have a net positive charge, strange balls will be neutralized by electrons and appear as nuclearites that in a sense are atom-like.

FIGURE 5

a) Fractional strangeness of bulk strange matter, as a function of m_s , for an energy of 900 MeV/baryon. b) $Z/A^{1/3}$ versus A for $m_s = 150$ MeV. Both from Ref. 12.

If the size of the nuclearite's nucleus is smaller than a typical $\sim 1\text{\AA}$ atomic size, the complete neutral nuclearite would have a radius $R \sim 1\text{\AA}$. A bigger nuclearite would be more akin to a neutron star and have its electron constituency distributed within its nuclear body, just sticking out a bit as an electronic atmosphere. The area α of the object, a quantity of interest in what follows, is therefore¹⁴

$$\alpha = \begin{cases} \pi A^2 & ; R_N \lesssim 1\text{\AA} \quad (M < 1.5 \text{ ng}) \\ \pi [3M/4\pi\rho_N]^{2/3} & ; R_N \gtrsim 1\text{\AA} \quad (M \gtrsim 1.5 \text{ ng}) \end{cases}$$

where we have used the ρ_N value of Eq. (1). The radii R_N in the above expressions may range from a few fermis to a few kilometers, corresponding to masses from that of a light nucleus to that of the Sun.

4. NUCLEARITES ABOUT US¹⁴

An optimistic assumption on the maximum abundance of nuclearites close to Earth would be to ascribe to them all of the local dark matter density of our galaxy, estimated to be some 10^{-24} gr/cm³ in our neighbourhood. With galactic velocities of ~ 250 km/s, characteristic of the solar system's orbital rotation, the local flux of dark matter (an upper bound to the nuclearite mass flux) is $\sim 2.5 \times 10^{-17}$ g/cm²s and the annual Earth infall is $\sim 10^9$ g. We assume the whole of this flux consists of nuclearites only to set minimal useful sensitivities to experiments designed to discover cosmic nuclearites. If the mean mass of a cosmic nuclearite is M , the maximal cosmic flux is given by

$$F = 7.8 (1g/M) \text{ nuclearites/km}^2 \text{ y } 2\pi \text{ stere,} \quad (3)$$

Equation (3) is plotted in Fig. 6 along with regions excludable by experiments we shall proceed to discuss. Equation (3) is an overestimate if the mass distribution of nuclearites is not fairly peaked around a central value M .

FIGURE 6
Limits¹⁴ on the flux of nuclearites of fixed mass M , as a function of M . All limits but the "Mica" one¹⁵ are from possible but hypothetical searches.

Nuclearites with galactic velocities are protected by the Coulomb nuclear repulsion from direct nuclear interactions with the atoms they may hit. The same is true of nuclearites that have come to rest in matter. The principal energy-loss mechanism for a nuclearite passing through matter is by atomic collisions. As it traverses the medium, as in Fig. 7a, it displaces all the matter in its path by collisions with the ambient atoms. At relative velocities as small as $\sim 10^{-3}c$, these collisions are mainly elastic and quasi-elastic. For a massive nuclearite, as for meteorites¹⁶, the rate of energy loss is

$$\frac{dE}{dx} = -a\rho v^2, \quad (4)$$

where a is the effective cross-sectional area of the nuclearite, given by Eq. (2), v is its velocity, and ρ is the density of the medium. Thus, v decreases exponentially with distance L according to

$$v(L) = v(0)\exp - \left\{ \frac{a}{M} \int_0^L \rho \, dx \right\} \quad (5)$$

where M is the mass of the nuclearite.

FIGURE 7

a) A nuclearite travelling through matter. b) A meteorite at rest in a solid.

Equation (5) breaks down at low velocity when the retarding force does not vanish but becomes equal (in a solid) to the force by which the confining material resists interpenetration. The integrity of rock persists up to pressures of 1000 atmospheres, corresponding to a structural energy density $\epsilon \approx 10^9$ ergs/cm³, or ~ 0.1 eV per molecular bond. For subsonic velocities, $v(L) < v_c = \sqrt{\epsilon/\rho}$, the right-hand side of Eq. (4) must be replaced by the constant force $-\epsilon A$, and from this point the nuclearite is rather quickly brought to rest.

From Eq. (5) and the subsequent discussion, we compute the range of a nuclearite as a function of its mass

$$\int_0^L \rho dx = (M/\alpha) \ln(v(0)/v_c) = \begin{cases} 3 \times 10^7 [M/1 \text{ ng}]^{1/3} \text{ g/cm}^2 & M > 1.5 \text{ ng} \\ 2.3 \times 10^7 [M/1 \text{ ng}] \text{ g/cm}^2 & M < 1.5 \text{ ng} \end{cases} \quad (6)$$

Equation (6) is plotted in Fig. 8, where one can see that nuclearites heavier than 4×10^{-14} g penetrate the atmosphere while maintaining cosmic velocities, and those heavier than 0.1 g pass freely through an Earth diameter whose column density¹⁷ is 1.1×10^{10} g/cm².

Cosmic nuclearites which are sufficiently light will come to rest in the Earth's crust and accumulate therein, see Fig. 7b. The effect of gravity cannot be neglected. If the Earth's pull Mg exceeds the maximum static retarding force ϵA , a nuclearite cannot come to rest but will fall through the Earth. Nuclearites lighter than 0.3 ng will stop in the crust and can have developed an observable concentration. The maximal cosmic nuclearite flux Eq. (3), over the course of the Earth's 4.6 Gy history will have produced a crustal concentration of 10^{-7} by mass. Searches for these ambient nuclearites require judicious choice of materials (deep sea sediments, oysters, excreta, ...), methods of concentration (distillation, centrifugation, chromatography, ...), and detection techniques (proton X-ray activation, mass spectroscopy, Rutherford scattering¹⁸ with U, ...). The masses of accumulated nuclearites can range from those of atomic nuclei to the upper limit of 0.3 ng or $A \sim 2 \times 10^{14}$. A complete search probably requires the use of a variety of experimental approaches. In Fig. 6, we show the excluded region that would result from a negative search for crustal nuclearities to a concentration of 10^{-13} , a feasible experiment but one not yet done.

FIGURE 8
Range of nuclearites impinging on matter with galactic velocities, as a function of their mass.

As a nuclearite traverses a medium at $v \sim 250$ km/sec, it collides elastically or quasi-elastically with the ambient atoms, giving them velocities of $O(v)$. The temperature of the medium is risen by the struck atoms to $T \sim O(\text{keV})$ and a hot plasma is generated that travels outwards as a shock wave, as in Fig. 7a. If the medium, like air or water, is transparent to light in a certain frequency domain $(\omega_{\text{MIN}}, \omega_{\text{MAX}})$, some of the deposited energy will radiate in the form of visible light. The fraction of dissipated energy appearing as light is called the luminous efficiency η_L . A lower bound upon η_L can be deduced from simple thermodynamical arguments in which light is emitted as black-body radiation from an expanding cylindrical thermal shock wave. Let $\rho(\text{MW})$ be the density (molecular weight) of the medium and $\rho_W(18)$ be the same parameters for water. The luminous efficiency can be estimated to be¹⁴

$$\eta_L \sim 2 \times 10^{-5} (\omega_{\text{MAX}}/\pi \text{ eV})^{5/2} (\text{MW}/18)^{3/2} (3/n)^{3/2} (\rho_W/\rho) \quad (7)$$

where " π eV" is a typical visible photon energy and $n \sim 0(3)$ is an estimate of the relevant number of excited subnuclear degrees of freedom (the temperatures in the heated medium are sufficient to break air or water molecules into their constituents). In highly purified water $\omega_{\text{MAX}} \sim 3.75$ eV and $\eta_L \sim 3 \times 10^{-5}$, while in air at atmospheric pressure $\eta_L \sim 4\%$.

Some recent attempts to search for proton decay can as well search for cosmic nuclearites. For example, the Irvine-Michigan-Brookhaven (IMB) proton decay detector¹⁹ consists of 80 kilotons of purified water surrounded by phototubes at a depth of 1.7×10^5 g/cm². It detects the Čerenkov light produced by relativistic charged particles as they traverse the detector. The water is very transparent to visible photons with energies between 2.25 and 3.75 eV, and the device can detect events involving the production of at least 3×10^4 photons. From Fig. 8, it follows that only nuclearites heavier than 10^{-11} g reach the IMB detector. However, the nuclearite must not only reach the detector, but do it with a velocity greater than 30 km/s, corresponding to a water temperature of several thousand °K. Thus, to be detected at IMB, nuclearities must be heavier than $\sim 2 \times 10^{-11}$ g. On the other hand, to produce an event rate within the detector of more than one per year, the nuclearite flux must satisfy $F > 3 \times 10^{-5}$, with units (hereafter suppressed) km⁻²y⁻¹ (2 π ster)⁻¹. Were the IMB detector programmed to detect slow moving nuclearites (30-300 km/s), the region displayed in Fig. 6 could be explored and perhaps excluded in one year's operation.

Some experiments designed to search for cosmic magnetic monopoles consist of large surfaces of scintillator placed near the Earth's surface. Scintillating material is even more sensitive to the passage of nuclearites than water is. Unshielded scintillators at sea level can detect nuclearites with masses as small as 10^{-13} g. The region explorable with a planned detector²⁰ of area 1500 m² is shown in Fig. 6.

Nuclearites produce visible light as they traverse the atmosphere, like meteors (a meteor is a meteorite that has not made it to the Earth's surface, and vice-versa). The rate of power dissipation of a nuclearite, from Eq. (4), is $\alpha \rho v^3$. Using the luminous efficiency Eq. (7), we deduce an altitude independent expression for the atmospheric luminosity of a nuclearite as a function of its mass

$$L = 1.5 \times 10^{-3} (M/1\mu\text{g}) \text{ watts}, \quad (8)$$

This expression is not applicable to nuclearites lighter than 10^{-5} g: they would not make hot air at a temperature high enough to emit visible light¹⁴. The visual magnitude of an atmospheric nuclearite at a distance h from an observer is computed from Eq. (8) to be

$$m = 10.8 - 1.67 \log_{10}(M/1\mu\text{g}) + 5 \log_{10}(h/10 \text{ km}). \quad (9)$$

For example, the apparent magnitude of a 20g nuclearite at a distance of 10 km is $m = -1.4$, equal to that of the brightest star, Sirius.

Atmospheric nuclearites may easily be distinguished from ordinary meteors. Travelling at galactic velocities ($v \sim 250\text{km/s}$), they are much speedier than meteors, which move no faster than 72 km/s relative to Earth, as every night-sky lover knows. Why? Ordinary meteors are in orbits bound to the Sun. Consequently their velocity relative to the Sun, v_{MS} , at a position in the orbit of the Earth, cannot be bigger than the escape velocity from the Sun at that position: $v_{\text{MS}} \lesssim 40 \text{ km/s}$. The velocity of the Earth in its orbit is $v_{\text{ES}} \sim 30 \text{ km/s}$. Finally, the escape velocity from Earth is a mere 10 km/s, the gravitational effect of our planet on the kinetic energy of a meteorite is not big. These facts are somehow reflected in Fig. 9, at the top of which observations²¹ of the percentage of meteorites of different velocities are shown. The two peaks in the distribution correspond to "head on" and "catch up" meteor arrivals. Another difference between meteors and nuclearites concerns the altitude at which their luminosity is maximal. As Fig. 10 shows, meteors generally emit light²² in the upper atmosphere ($h > 60 \text{ km}$) where they ablate and disintegrate. The condition that air be dense enough for a nuclearite to heat it locally to visible-light-emitting temperatures can be translated¹⁴ into a maximum height for light production, $h_{\text{MAX}} \sim 2.7 \text{ km} \ln(M/12 \text{ mg})$. Thus, nuclearites with a mass of 10^{-4}g produce their light at altitudes less than 6 km while those with a mass of 10^4g shine below 60 km. Evidently, the meteoric behaviour of nuclearites is essentially a phenomenon of the lower atmosphere.

FIGURE 9
Observed²¹ percentages of
meteors of different velocities
at atmospheric touch-down.

FIGURE 10
Observed²² distributions for meteors of height of maximum luminosity versus
velocity. The uniformly shaded area would be populated by galactic nuclearites.

From a point on the Earth, the flux corresponding to one annual atmospheric event is given by $F = 2/\pi h_{\text{MAX}}^2$ at zenith angle smaller than $\pi/4$. (The factor of 2 reflects the difficulty of daytime observations.) For a large domain of nuclearite masses this expression is less than the maximum cosmic flux of nuclearites of Eq. (3). This defines the excludable region shown in Fig. 6. To what extent searches already performed have actually excluded the excludable region is obscure to us. The largest nuclearite compatible with the cosmic limit that is likely to be detected from one location over the course of 365 nights of observation has a mass of 4×10^4 grams. The apparent magnitudes of hypothetical cosmic nuclearites range from $m = +6$ for nuclearites near 10^{-4} g to $m = -3$ for those with masses near the upper mass cut-off.

Nuclearites may inflict star wounds (*astroblems*) and leave scars on the face of Earth. In a recent publication¹⁵, Price et al. present results to a negative search for magnetic monopoles. They examine ancient mica for etchable trails of lattice defects produced by cosmic monopoles, as in Fig. 11a. Their data provide our sole example of an established limit on the cosmic nuclearite flux. They argue that an energy loss $dE/\rho dx > 2.5 \text{ GeV cm}^2/\text{g}$, in the form of nuclear recoil suffices to produce an etchable track. In the case of nuclearites, virtually all of the energy loss is of this kind. With their assumed mean burial depth of the mica of 5 km, we compute from Eq. (4) that an etchable track is produced by any cosmic nuclearite with mass greater than 2.4×10^{-10} g. The mica sample has an area of 13.5 cm^2 and an estimated age of 0.5 Gy. Thus, the minimal measurable nuclearite flux to which this experiment is sensitive is $F = 1.5$, and the excluded region is shown in Fig. 6.

Etchable tracks in mica are but one example of fossil traces that may be produced by nuclearites in rock. Any nuclearite more massive than 2.4×10^{-10} g can leave an observable track at great depth - an otherwise inexplicable linear astroblem. Neither meteorites, micrometeorites, natural radioactivity nor conventional cosmic radiation can produce such an effect. The tracks produced by nuclearites lighter than $\sim 1 \text{ g}$ are microscopic, and require, for their detection, sophisticated searches upon well-chosen materials in the spirit of the Price et al. mica experiment²². Larger nuclearites can produce visible astroblems, as in Fig. 11b. The energy dissipated by a cosmic nuclearite, Eq. (4), is sufficient to melt a cylinder of rock with a radius $R_M = v\beta^{-1/2}$ where $\beta \sim 800 \text{ J/g}$ is the energy required to heat and fuse a gram

FIGURE 11

a) and b) Small and large nuclearite-induced astroblems. c) Nuclearite origin of an epilnear earthquake.

of rock. Thus, $R_M \sim 400 R$. A one-gram nuclearite produces a fossil track with a diameter of $\sim 10^{-2}$ cm. The incidence of such fossils in billion year old rock is $\sim 1 \text{ cm}^{-2}$ if the upper limit upon the cosmic nuclearite flux of Eq. (3) is attained. Still larger nuclearites may be associated with fossils consisting of crushed rock. From the fact that a one-kiloton (TNT equivalent) nuclear test in granite²³ produces a spherical crush zone of radius 30 m, we deduce that the radius R_C of the crush zone associated with the passage of a large nuclearite is $\sim 2000 R$. Thus, a nuclearite of one kiloton mass (radius $\sim 10^{-2}$ cm) produces a linear astroblem a few meters in diameter. The maximum possible frequency of such events is 10^{-2} km^{-2} per billion years. We show in Fig. 6 the result to a hypothetical negative hunt for nuclearite fossil tracks. It terminates at nuclearite mass of $1.5 \times 10^{18} \text{ g}$ or radius 10 cm beyond which the maximum cosmic flux corresponds to less than one collision with Earth in its lifetime.

The last effect of nuclearite passage that we consider is the possibility of nuclearite-induced epilnear earthquakes, depicted in Fig. 11c. Note that the diametric Earth passage of an $M = 1$ ton nuclearite releases a total energy equivalent to a 50-kt (TNT equivalent) nuclear weapon. (At 30° zenith angle this is reduced by a factor of 2, at 60° by a factor of 5.) Such nuclearites may collide with Earth no more than once per year. At tele-seismic distances, the seismic signal produced by a point source (weapons test or earthquake) is comparable in magnitude to that produced by a line source of the same total energy release. Indeed, the nuclearite may produce a larger signal since the seismic efficiency of a nuclearite passing through the dense mantle may be larger than the $\sim 10^{-2}$ efficiency of a well-tamped

nuclear shot in granite²³. Nuclearite seismic signals are readily distinguishable from other sources. The signal arrival times characteristic of a linear sonic antenna are vastly different from those of a point source. (Remember that the nuclearite traverses Earth in less than one minute.) Surface waves should be absent, since most of the energy loss takes place in the mantle. Similarly the production of shear waves is suppressed by a power of c/v where c is the local sound velocity. Large *epilinear* earthquakes (body magnitude >5) can perhaps be "discovered" in existing seismological data. Thus, the excluded domain shown in Fig. 3 is bounded by $F > 10^{-9}$ corresponding to one event in Earth per decade. The limit on signal size corresponds to an energy deposition equivalent to one kg TNT per kilometer, or a nuclearite mass of 1 kg.

The experiments that we have outlined, as well as others (acoustic or visual detection at sea or at lake Baikal, the effect of small nuclearites upon airglow, etc.) can severely constrain the hypothesis of a cosmic nuclearite flux. In particular, the explanation of the galactic missing mass problem in terms of nuclearites smaller in size than several centimeters in a hypothesis that is subject to feasible (though highly interdisciplinary) experimental test.

5. CONCLUSIONS AND HOMEWORK

It behooves the closing speaker in a conference on nuclear physics (or any other subject) to tell the audience that they do not know what they are doing. In this spirit, we have contemplated the outrageous possibility that the ground state of nuclear matter may not yet have been discovered (for $A > a$ few).

The search for nuclearites, it should by now be clear, is a vast subject and a large extra number of weird thoughts come to mind, that I shall leave as quizzes to the audience (or the readance). Among them, are nuclearites the source¹¹ of Centauros? Do they have anything to do with anomalous? Shouldn't nuclearites eat stars by accretion? And a long et coetera.....

I have mainly paid attention to relatively large nuggets of the hypothetical strange quark matter. To the experimenter on Earth who would rather make her own strange balls than, say, search for them in oysters (or excreta, depending on her budget) the question of very small A is more immediate. A case in point is the dihyperon with $A = -S = 2$, advocated by bag-modelists²⁴. Farhi and Jaffe¹² have also made a preliminary assault on the very difficult

problem of small strange nuggets, that they call *strangelets* (in a *trainlet*?). For certain choices of parameters they find that, with the possible exception of the dihyperon, the stability line starts at $A \gtrsim 70$. But this difficult estimate may well be wrong. Perhaps an isotope of Carbon with strangeness -3 or -4 is in fact stable or quasi-stable. Perhaps relatively light isotopes occasionally decay into strangelets. Hopes are often entertained that a quark-gluon plasma (*quagma*) containing many strange quarks may be made in heavy atom collisions, either in the lab or by medium- A , very energetic cosmic rays. If strange quark matter is stable or nearly so, the quagma may decay into strangelets, a signature that in a charge and mass-measuring detector, should be hard to miss.

To summarize, the QCD revamping of nuclear physics, though not yet extraordinarily successful, may hold surprises that are extraordinarily strange.

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