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NUCLEARITES: A NOVEL FORM OF COSMIC RADIATION*

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ABSTRACT

We consider the possible existence of aggregates of stable nuclear matter betwixt nuclei and neutron stars in mass: nuclearites. If such entities inhabit galaxies, they may ccomprise their non-luminous mass. We suggest experiments that can detect the encounters of cosmic nuclearites with Earth or place significant limits upon their flux.

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Known forms of nuclear matter are atomic nuclei ($A \leq 263$) and neutron stars ($A \sim 10^{57}$). E. Witten[1] suggests that nuclear matter consisting of an agglomeration of up, down, and strange quarks in roughly equal proportion may be less massive than ordinary nuclear matter with the same quark number. These entities would be absolutely stable for virtually any value of A.

Ordinary nuclear matter has an energy density of about 938 MeV/nucleon. Ordinary quark matter--a purely hypothetical form of matter in which the constituent up and down quarks and gluons are not confined within individual nucleons--evidently has a higher energy density, for otherwise nuclei would decay into quark matter. Strange quark matter (consisting of equal numbers of u, d, and s quarks) differs energetically from ordinary quark matter in two ways: Strange quarks are considerably heavier than ordinary quarks, and it is for this reason that strange baryons are ~200 MeV heavier than nucleons. On the other hand, the Pauli Exclusion Principle acts in such a fashion as to make strange quark matter stabler than ordinary quark matter. In a degenerate gas of massless quarks at zero temperature the energy per quark depends upon the number of quark species, and in a three-flavor system (strange quark matter) it is estimated[1] to be ~90% of what it is in a two-flavor system. This additional (negative) symmetry energy may more than compensate the positive energy penalty associated with the strange quark mass.

Farhi and Jaffe[2] have performed semiquantitative calculations on the basis of the MIT bag model. They find that single nuggets of strange quark matter are stable for a range of strange quark masses and strong QCD coupling constants which overlaps with phenomenological estimates of these parameters extracted from hadron spectroscopy. In short, they are unable to come to a rigorous decision as to whether strange quark matter

is stable or not. We may not conclude from the observed stability of nuclei that there does not exist a stabler form of nuclear matter. The transition of, say, ^{56}Fe into strange-quark matter containing 168 u, d and s quarks in equal proportions is a 56th order weak interaction. Even if strange quark matter were stable, the lifetime of ordinary matter would be essentially infinite on cosmological times scales.

Witten[1] offers a tentative early universe scenario in which a large fraction of the mass and baryon number of the universe has survived in the form of nuggets of strange quark matter with radii between $R = 10^{-1}$-10 cm. These nuggets appeared shortly after the Big Bang in the QCD transition from a quasi-free quark plasma to a cooler state in which quarks are confined. Strange quark matter is non-luminous (not the stuff of ordinary stars) and did not participate in primordial nucleosynthesis. Primordial nuggets of strange quark matter are evident candidates for the constituency of the dark missing mass of the Universe and of the Milky Way.

There may be more contemporary sources. What we regard as neutron stars may in fact consist of strange quark matter.[3] Collisions involving neutron stars, or supernovae themselves may liberate pieces of strange quark matter with a spectrum of sizes that is difficult to guess. Nuggets of strange quark matter, or of other unsuspected states of nuclear matter may exist in the Galaxy as remnants of the Big Bang or as debris of astrophysical catastrophes. We use the term "nuclearite" to describe such an object in collision with Earth, and we consider possible experiments to detect its passage.

Galaxies, our own included, contain significant non-luminous mass[4], possibly in the form of nuclearites. The local density of dark matter is estimated to be $\sim 10^{-14}$ g/cm^3. With chaotic velocities ~250 km/s characteristic of the sun's galactic rotation, the local flux of dark matter (an upper bound to the nuclearite mass flux) is $\sim 2.5 \times 10^{-17}$ g/cm^{2}s and the annual Earth infall is $\sim 10^9$g. We assume that 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

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

Equation (1) is plotted in Figure (1) along with regions excludable by experiments we shall consider.

The density of strange quark matter is estimated[2] to be $\rho_N = 3.6 \times 10^{14}$g/cm^3, somewhat larger than the density of atomic nuclei or neutron stars. Because strange quarks are heavier than the others and thereby disfavored, the net quark charge is positive and is compensated by electrons. Nuclearites small compared to the Bohr radius resemble superheavy nuclear atoms with $A < 10^{15}$ and Z well beyond any published periodic table. The electron distribution of larger nuclearites extends beyond the nuclear boundary by at least an electron Compton wavelength. Nuclearites with galactic velocities are protected by their electron "atmosphere" 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, it displaces all the matter in its path by elastic or quasi-elastic collisons with the ambient atoms. For a massive nuclearite, as for meteorites[5], the rate of energy loss is

$$\frac{dE}{dx} = -A\rho v^2, \qquad (2)$$

where A is the effective cross-sectional area of the nuclearite, v is its

velocity, and ρ is the density of the medium. Thus, v decreases exponentially with distance L according to

$$v(L) = v(0)\exp - \left\{\frac{A}{M}\int_0^L \rho\, dx\right\} \qquad (3)$$

where M is the mass of the nuclearite. In the case of a nuclearite larger than an atom ($R_0 \gtrsim 1$Å), its cross-sectional area is simply πR_0^2. On the other hand, the effective area of a smaller nuclearite is controlled by its electronic atmosphere which is never smaller than ~ 1Å. Thus, we take

$$A = \begin{cases} \pi(3M/4\pi\rho_N)^{2/3} & M \geq 1.5\text{ ng.} \\ \pi \times 10^{-16}\text{ cm}^2 & M < 1.5\text{ ng.} \end{cases} \qquad (4)$$

Equation (2) 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 to 1000 atmospheres, corresponding to a structural energy density $\epsilon \approx 10^9$ ergs/cm^3, or $\sim .1$ eV per molecular bond. For subsonic velocities, $v(L) < v_c = \sqrt{\epsilon/\rho}$, the r.h.s. of Eq. (2) must be replaced by the constant force $-\epsilon A$, and from this point the nuclearite is rather quickly brought to rest.

From Eq. (2) and the subsequent discussion, we compute the range of a nuclearite as a function of its mass

$$\int_0^L \rho dx = (M/A)\ln(v(0)/v_c) = \begin{cases} 3 \times 10^7[M/1\text{ ng}]^{1/3}\text{g/cm}^2 & M \geq 1.5\text{ ng} \\ 2.3 \times 10^7[M/1\text{ ng}]\text{g/cm}^2 & M < 1.5\text{ ng.} \end{cases} \qquad (5)$$

From Figure (2), we see that nuclearites heavier than 4×10^{-14}g penetrate the atmosphere while maintaining cosmic velocities. and those heavier than 0.1g pass freely through an Earth diameter whose column density[6] is 1.1×10^{10} g/cm^2.

Cosmic nuclearites which are sufficiently light will come to rest in the Earth's crust and accumulate therein. 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. (1), 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, excreta,...), methods of concentration (distillation, centrifugation,...), and detection techniques (proton X-ray activation, mass spectroscopy,...). 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 Figure (1), we show the excluded region that would result from a negative search for crustal nuclearites to a concentration of 10^{-13}, a feasible experiment but one not yet done.

Cosmic nuclearites, in traversing a transparent medium like water or air will deposit some of their energy in the form of visible light. The fraction of dissipated energy appearing as light is called the luminous efficiency η. A lower bound upon η can be deduced from simple thermodynamical arguments in which light is emitted as black-body radiation from an expanding cylindrical thermal shock wave. The

effective temperature of the shock depends upon its radius R according to

$$T(t) = \frac{mv^2}{n}(R_0/R(t))^2 \quad (6)$$

where m is molecular mass of the medium and n is the effective number of submolecular species which are excited. For this calculation, we use natural units where $\hbar = c = k = 1$. The rate of expansion of the shock is given by

$$\dot{R}(t) = \sqrt{\frac{2Tn}{m}} \quad (7)$$

characteristic of molecular velocities. From (6) and (7), we deduce

$$R^2(t) = (8)^{1/2}\, vt\, R_0$$

$$T(t) = (8)^{-1/2}\, mv R_0/nt \quad (8)$$

for the time evolution of the radius and the temperature of the shock. The integration constant is chosen in such a fashion that the passage of the nucleorite takes place at the time $t_0 = R_0/v\sqrt{8}$. The thermodynamic description of the event is valid when R exceeds the mean free path ℓ in the medium, corresponding to the time $t_1 = (\ell/R_0)^2 t_0$.

The expanding hot cylinder emits black-body radiation with a spectrum

$$\frac{dp}{d\omega da} = \frac{\omega^3}{(2\pi)^2}\, \frac{1}{e^{\omega/T}-1}\,, \quad (9)$$

of power radiated per unit frequency and per unit area. The total luminous energy radiated by the nuclearite per unit length of its trajectory is

$$\frac{dE_\gamma}{dx} = \int_{\omega_{MIN}}^{\omega_{MAX}} d\omega \int_{t_{MIN}}^{\infty} dt\, 2\pi R(t)\, \frac{dp}{d\omega da}. \quad (10)$$

The limits on frequency correspond to the window of transparency of the medium, and t_{MIN} is the greater of t_0 and t_1. For a wide window of transparency, and under circumstances such that

$$T(\ell) >> \omega_{MAX}, \qquad (11)$$

a condition which is satisfied for the cases we consider, Eq. (10) may be approximated by

$$\frac{dE_\gamma}{dx} \simeq (6\pi^2\sqrt{2})^{-1}\, \omega_{MAX}^{5/2}(m/n)^{3/2}\, \pi R_0^2\, v^2. \qquad (12)$$

The luminous efficiency is obtained through the comparison of Eq. (2) and (12),

$$\eta \cong (6\pi^2\sqrt{2})^{-1}\, \omega_{MAX}^{5/2}(m/n)^{3/2}\rho^{-1}$$

$$\cong 2\times10^{-5}(\hbar\omega_{MAX}/\pi eV)^{5/2}(MW/18)^{3/2}(3/n)^{3/2}(\rho_W/\rho), \qquad (13)$$

where πeV is a typical visible photon energy, MW is the mean molecular weight of the medium, n=3 is an estimate of the relevant number of excited subnuclear degrees of freedom and ρ_W is the density of water. In highly purified water ($\hbar\omega_{MAX}$ = 3.75 eV[7]) we obtain $\eta \cong 3\times10^{-5}$, while in air at atmospheric pressure $\eta \cong$ 4%.

Note that Eq. (13) depends neither upon the size R_0 of the nuclearite nor upon its velocity provided that Eq. (11) which may be written

$$\frac{mv^2}{n} >> (\ell/R_0)^2\, \omega_{MAX}, \qquad (14)$$

is valid. Recalling that the effective radius of a nuclearite is never less than 1Å, we find that Eq. (14) is satisfied in water for any nuclearite whose velocity has not been severely degraded. In air at sea level, Eq. (14) is satisfied by cosmic nuclearites exceeding a radius of 2×10^{-7} cm corresponding to a minimum mass of 10^{-5}g. Incidentally, Eq. (13) does not apply to ordinary meteors which ablate and are

consumed before Eq. (12) is satisfied.

Some recent attempts to search for proton decay can as well search for cosmic nuclearites. For example, the Irvine-Michigan-Brookhaven (IMB) proton decay detector[7] consists of 80 kilotons of purified water surrounded by phototubes at a depth of 1.7×10^5 g/cm^2. It detects the Cerenkov 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 Figure (2), it follows that only nuclearites heavier than 10^{-11}g reach the IMB detector. However, the nuclearite must not only reach the detector, but reach it with a velocity greater than 30 km/s corresponding to a temperature of several thousand °K. Thus, to be detected at IMB, nuclearites must be heavier than $\sim2\times10^{-11}$g. On the other hand, to produce an event rate within the detector of more than one per year, the nuclearite flux must satisfy $F \geq 3\times10^{-5}$, with units (hereafter suppressed) km^{-2}y^{-1}(2π stere)$^{-1}$. Were the IMB detector programmed to detect slower moving nuclearites (30-300 km/s), the region displayed in Figure (1) 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. Such devices can detect nuclearites with masses as small as 10^{-13}g, in the case of an unshielded detector at sea level. The region explorable with a planned detector[8] of area 1500 m^2 is shown in Figure (1).

Nuclearites, like meteors, produce visible light as they traverse the atmosphere. Their rate of power dissipation, from Eq. (2), is $A\rho v^3$.

Using the luminous efficiency Eq. (13), we deduce an altitude independent expression for their luminosity as a function of their mass

$$L = 1.5 \times 10^{-3} (M/1\mu g) \text{watts}, \tag{15}$$

which is valid provided that Eq. (13) is satisfied. Because of the latter constraint, our analysis does not apply to nuclearites lighter than 10^{-5}g. The visual magnitude of an atmospheric nuclearite at a distance h from an observer is computed from Eq. (15) to be

$$\mathcal{M} = 10.8 - 1.67 \log_{10}(M/1\mu g) + 5 \log_{10}(h/10 \text{ km}). \tag{16}$$

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

Atmospheric nuclearites may easily be distinguished from ordinary meteors. Travelling at galactic velocities ($v \sim 250$ km/s), they are much faster than meteors, which, being bound to the Solar System, move no faster than 72 km/s relative to Earth. Moreover, meteors generally emit light only in the upper atmosphere ($\gtrsim 100$ km) where they ablate and disintegrate. We show below that the production of light by nuclearites is essentially a low altitude phenomenon. Thus, the apparent angular velocity of a nuclearite is usually of order a hundred times that of a meteor.

The constraint given by Eq. (14) can be expressed as an upper limit to the altitude at which nuclearites effectively generate light. Using the fact that the scale height of the atmosphere is $\sim$8 km, we obtain

$$h_{MAX} = 2.7 \text{ km} \ln(M/1.2 \times 10^{-5} g). \tag{17}$$

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 behavior of nuclearites is essentially a phenomenon of the lower atmosphere.

From a point on the Earth, the flux corresponding to one annual atmospheric event is given by $F = 2/\pi h_{MAX}^2$ 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. (1). This defines the excludable region shown in Figure (1). 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 a year of observation has a mass of 4×10^4 grams. The apparent magnitudes of hypothetical cosmic nuclearites range from $\mathcal{M} = +6$ for nuclearites near 10^{-4}g to $\mathcal{M} = -3$ for those with masses near the upper mass cutoff.

In a recent publication[9], 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. Their data provide our sole example of an established limit on the cosmic nuclearite flux. They argue that an energy loss $dE/\rho dx \gtrsim 2.5$ GeV cm^2/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. (9) 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 region excluded by this experiment is shown in Figure 1.

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$1g are microscopic, and require, for their detection, sophisticated searches upon well-chosen materials in the spirit of the Price et al. mica experiment.[9] Larger nuclearites can produce visible astroblems. The energy dissipated by a cosmic nuclearite, Eq. (2), is sufficient to melt a cylinder of rock with a radius $R_M = v\beta^{-1/2}$ where $\beta \sim 800$ J/g is the energy required to heat and fuse a gram 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 ~ 1 cm^{-2} if the upper limit upon the cosmic nuclearite flux of Eq. (1) 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 granite produces a spherical crush zone of radius 30 m[10], we deduce that the radius of the crush zone associated with the passage of a large nuclearite is $\sim$2000 R. Thus, a nuclearite of one kiloton mass produces a linear astroblem 4m in diameter. The maximum possible frequency of such events is 10^{-2} km^{-2} per billion years. We show in Figure (1) the result to a hypothetical negative hunt for nuclearite fossils. It terminates at nuclearite mass of 1.5 10^{18}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 epilinear earthquakes. 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 teleseismic 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 granite.[11] 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 Figure (1) is bounded by $F \gtrsim 10^{-9}$ 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 are discussed in this paper, as well as others (acoustic detection at sea, 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 is a hypothesis that is subject to feasible (though highly interdisciplinary) experimental test.

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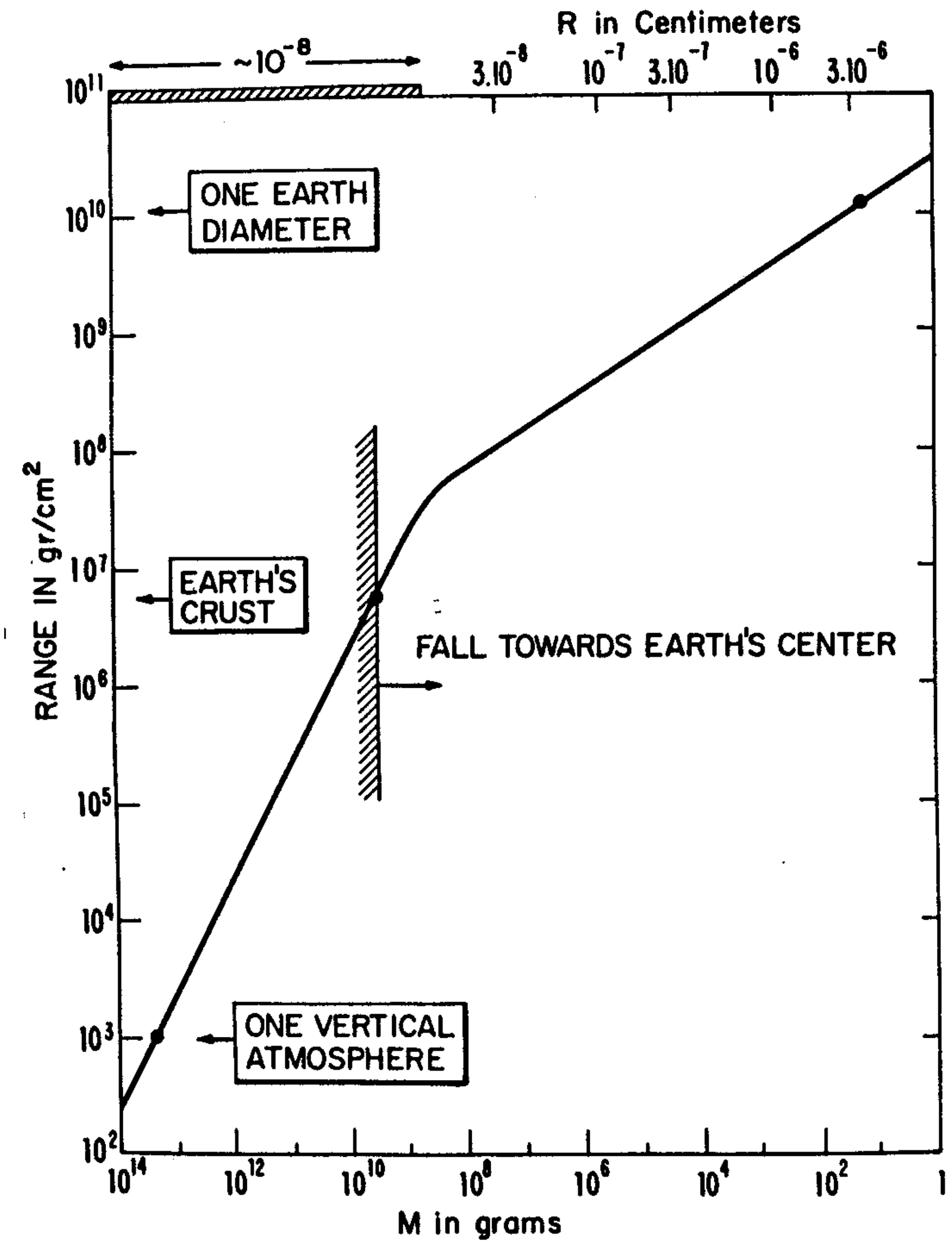
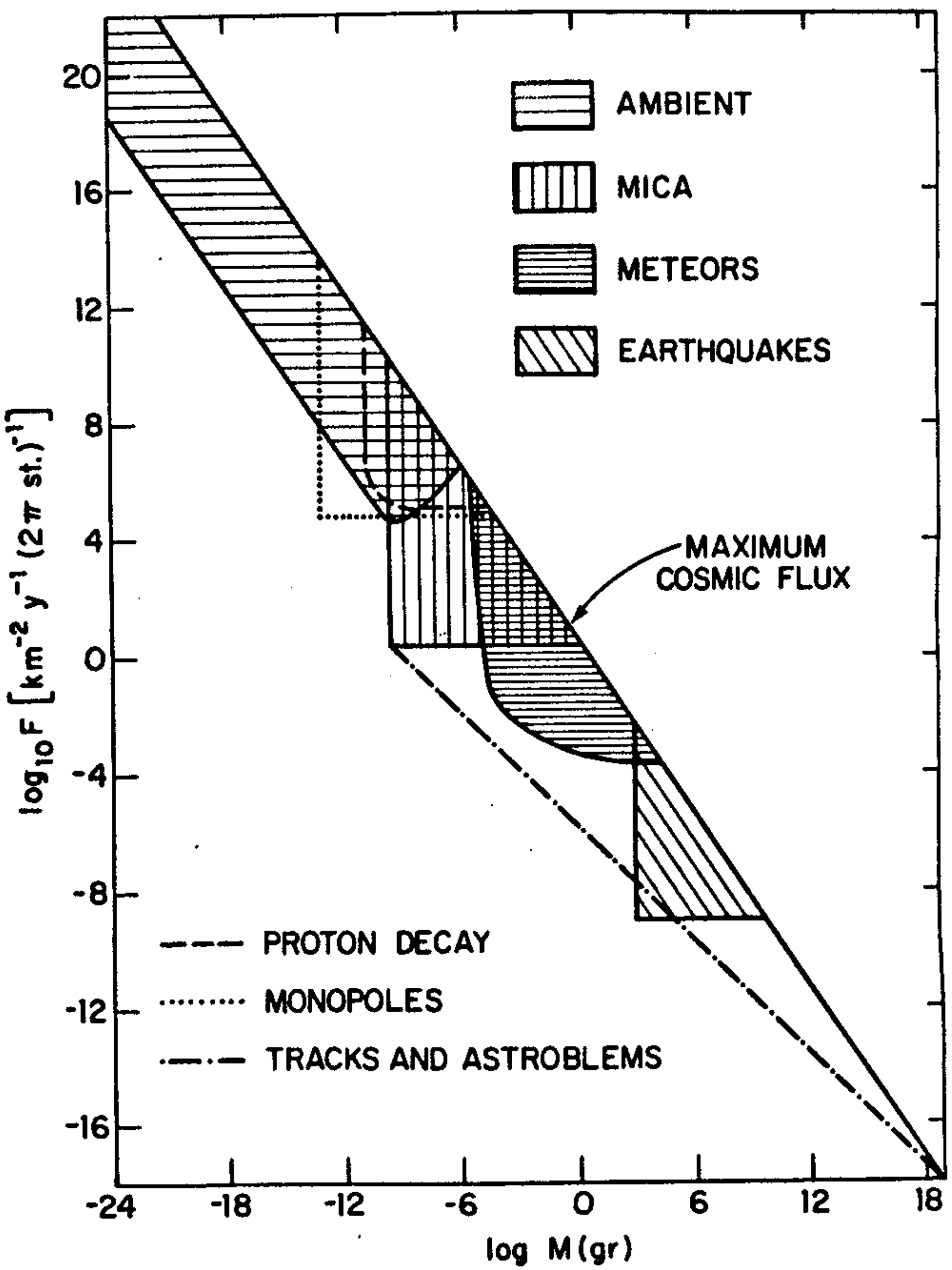
Figure Captions

Figure 1: The range of nuclearites as a function of their mass, as predicted by Eq. (5).

Figure 2: The maximum possible cosmic flux of nuclearites is shown as a function of their mass. Also shown are regions that would be excluded by the several experiments discussed in the text. (of these, only the "mica" limit corresponds to an experiment actually performed.)


R in Centimeters
~10^{-8}
3.10^{-8}
10^{-7}
3.10^{-7}
10^{-6}
3.10^{-6}
ONE EARTH DIAMETER
EARTH'S CRUST
FALL TOWARDS EARTH'S CENTER
ONE VERTICAL ATMOSPHERE
RANGE IN gr/cm^2
M in grams


AMBIENT
MICA
METEORS
EARTHQUAKES
MAXIMUM COSMIC FLUX
PROTON DECAY
MONOPOLES
TRACKS AND ASTROBLEMS
$\log_{10} F \left[km^{-2}\, y^{-1}\, (2\pi\ st.)^{-1}\right]$
log M(gr)