Since Witten's seminal 1984 paper on the subject, searches for evidence of strange quark nuggets (SQNs) have proven unsuccessful. In the absence of experimental evidence ruling out SQNs, the validity of theories introducing mechanisms that increase their stability should continue to be tested. To stimulate electromagnetic SQN searches, particularly space searches, we estimate the net charge that would develop on an SQN in space exposed to various radiation baths (and showers) capable of liberating their less strongly bound electrons, taking into account recombination with ambient electrons. We consider, in particular, the cosmic background radiation, radiation from the sun, and diffuse galactic and extragalactic γ-ray backgrounds. A possible dramatic signal of SQNs in explosive astrophysical events is noted.

I. INTRODUCTION

A generation has passed since Witten [1] suggested that strange quark matter (SQM) might be the ground state of all familiar matter and de Rujula and Glashow [2] set down a list of methods to search for strange quark nuggets (SQNs) in various mass ranges. There have been significant efforts using most of those methods, but no SQNs have been found. An area that has received little attention is the possibility of exploiting the charge on SQNs in space that should be caused by radiation baths liberating electrons from SQNs. How challenging such exploration would be depends on how large such charges might be. We estimate those charges under various conditions, including those at the time of cosmic recombination, those in today's cosmic background radiation (CBR), those in the solar neighborhood from the quiet sun and from an X-ray flare, and those in the diffuse galactic and extragalactic (gamma ray) radiation backgrounds.

We begin, in this section, with a brief review of SQN basics. In Sec. II, we give the equations on which our numerical estimates are based and the approximations that go into deriving them. We make simple, conservative approximations in estimating electron wave functions and cross sections for large and small SQN masses and radii. In a separate publication, we will show, in more detail than needed for the first estimates here, the wave functions in the transition between these two regions [3]. In Sec. III we give the numerical results, and then conclude, in Sec. IV, with brief discussion of the results and their implications for the feasibility of space-based or space-directed electromagnetic SQN searches.

In 1984, Witten [1] considered systems of up, down and "strange" quarks, pointing out that they would have the same attractive potential energy as systems of just up and down because the force between two quarks does not depend on their flavor. They would, however, have about 10 percent less kinetic energy because the Pauli exclusion principle would not force them into as high kinetic energy states as in the case with just two kinds of quarks.

Soon after this seminal work suggesting that SQM might be the lowest energy state of familiar, baryonic matter, Farhi & Jaffe [4] worked out the basic nuclear physics of strange quark matter (SQM) within the MIT bag model [5], and de Rujula & Glashow [2] identified several observations that might lead to discovery of SQNs. The latter proceeded from the basic relation for energy loss

\[ dE/dt = -\pi r_N^2 \rho_M v_N^3 \]  

where \( v_N \) is the speed of the (spherical) nugget, \( r_N \) its radius, and \( \rho_M \) the density of the material through which it is passing. Equation (1) just says that the SQN must lose the energy needed to make the stuff in its way move as fast as it, the SQN, is moving. They estimated SQN mass ranges to which various sensors might be sensitive, for example the Earth network of seismometers being sensitive to masses over a ton. They estimated the upper boundary of mass regions by computing the mass \( M \) at which events would become too rare for the detector system if the galactic dark matter (DM) density, \( \rho_{DM} \), were all in the form of SQNs of mass \( M \). Roughly, we have, for events per unit time,

\[ dN/dt = v_N (\rho_{DM}/M) \pi r_d^2 \]  

where \( v_N \) is again the speed of the SQN, \( \rho_{DM} = 5 \times 10^{-25} \) g cm\(^{-3} \) and \( r_d \) is the radius of the detector system through which it is passing. Equation (2) gives minimum detectable mass or speed in terms of the dark matter density limit on the abundance of SQNs of some one single mass.

An important recent development is work by Alford et al. [6] showing that, for SQM in bulk, Cooper pairing, the basic phenomenon of superconductivity, of quarks should occur. The pairing could take different forms. Most likely at high density, perhaps, would be pairs of...
TABLE I: Some Strange Quark Nugget Searches.

<table>
<thead>
<tr>
<th>Experiment/Observation</th>
<th>Mass Range (g)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS\textsuperscript{a}</td>
<td>$10^{-24} - 10^{-22}$</td>
<td>not done</td>
</tr>
<tr>
<td>RHIC\textsuperscript{a}</td>
<td>$&lt; 3 \times 10^{-21}$</td>
<td>not found</td>
</tr>
<tr>
<td>Mica Tracks\textsuperscript{b}</td>
<td>$10^{-20} - 10^{-14}$</td>
<td>$&lt;&lt; \rho_{DM}$</td>
</tr>
<tr>
<td>ICE CUBE\textsuperscript{c}</td>
<td>$10^{-3} - 10^{-2}$</td>
<td>not done</td>
</tr>
<tr>
<td>Seismometers:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Future Lunar \textsuperscript{d}</td>
<td>$10^3 - 10^6$</td>
<td>not done</td>
</tr>
<tr>
<td>Apollo\textsuperscript{e}</td>
<td>$10^4 - 10^6$</td>
<td>$&lt; \rho_{DM}/10$</td>
</tr>
<tr>
<td>USGS Reports\textsuperscript{f}</td>
<td>$10^6 - 10^8$</td>
<td>$&lt; \rho_{DM}$</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Sandweiss[7].
\textsuperscript{b}Price[10].
\textsuperscript{c}Price[9].
\textsuperscript{d}Herrin et al.[11].
\textsuperscript{e}Herrin et al.[12].

quarks with equal and opposite momentum, antisymmetric in spin, flavor and color, color-flavor locked (CFL) pairing. The quark matter of such a SQN would be electrically neutral in its interior, but would have net positive charge on its surface, with the total (quark) surface charge proportional to the area. It would have quark charge $Z_Q = 0.3 A^{2/3}$ (where $A$ is one third the number of quarks), balanced by electrons feeling a potential that is a step function at the SQN radial boundary and Coulomb beyond it. We will discuss this model further below.

There are two potential sources for SQM. It might have been produced primordially, in particular in a phase transition in the early stages of the big bang. That was Witten’s original thought, but it is, at best, controversial. The issue is that a SQN formed at high temperature needs to cool. If it does that by evaporation, the SQN disappears - quark by quark. Alternatively, it might cool by neutrino emission in which case it survives. There are experts on both sides. The second potential source is “neutron stars (NS).” If SQM is the lowest energy state of matter, it is expected that Type II supernovae would likely rise to high enough temperature to cool into SQM. If one did not, local quantum fluctuations would likely soon cause a global transition of the NS to an SQS. Binary strange quark star (SQS) systems would in time spin down, collide, and the galaxy would gain a population of SQNs of varying masses from the fragments.

There is significant, ongoing activity in searching for SQNs in various mass ranges. One important effort is the Alpha Mass Spectrometer experiment [7] which was due to be flown by the space shuttle to the space station in a couple of years. It would have been able to detect, and to distinguish from cosmic rays, light SQNs that would not penetrate the atmosphere. However, the Columbia accident and the need to retire the shuttle fleet and to complete the space station have prevented AMS launch as scheduled [8]. A second is the ICE CUBE neutrino detector [9] being installed in Antarctica. It will have phototubes to detect the products from collisions of (weakly interacting) neutrinos with the electrons and nuclei of the ice. It will also have seismometers to be able to identify tracks made by SQNs. It should be able to detect SQN masses up to as much as about a gram. This is the highest mass for which Eq. (2) gives a dozen or more events per year in a kilometer-sized region.

Past searches have included examination of tracks in mica by Price at Berkeley [10]. They have also included two cases of NASA work, in 2002, with evidence that two neutron stars were actually strange quark stars [13]. However, it was later concluded that alternate explanations for the observations were more likely [14]. Looking for evidence of SNQs was a prime objective of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Since RHIC collides gold nuclei with gold nuclei, SQN masses up to two gold nuclei could, in principle, be produced. The experiment found none [16]. However, the binding energy per quark of SQM would increase with increasing numbers of quarks [4], so it would not be surprising if systems with hundreds or even many thousands of quarks did not exist, but larger assemblies (than thousands) were found.

Selected past searches are summarized in Table I. In the table, a few major searches are listed (we modestly include ours [11, 12]), along with the mass range to which they will be sensitive and the result, where there is one, in terms of the inferred SQN density in our region of the galaxy.

Our goal is electromagnetic space tests, in several different settings, designed to discover SQNs or to falsify current SQN models. Each setting is characterized by a photon distribution and an ambient electron distribution. In the next section we discuss the settings, models of SQN structure, and the formulary. In the following section we present our results. In the concluding section, we day dream of possible electromagnetic detection schemes.

II. THE FORMULARY AND ITS APPROXIMATIONS

A. Settings

We consider extragalactic, galactic and solar system SQNs. In each case, we specify photon and electron energy and angle (radiation bath - isotropic, or unidirectional shower) distributions. We go back in red shift $z$ to recombination at $z = 1089$ to raise the question of whether today’s cosmic microwave background (CMB) might have some imprint from a component of primordial, charged SQNs contributing to the dark matter.

In Table II we summarize these settings. $r_{ac}$ is the distance from the sun to the center of the galaxy, $r_{bh}$ is
the radius of the supermassive black hole there, and $r_S$ is the solar radius. For the cosmic background radiation (CBR) we take just blackbody radiation at temperature $(1+z)T_0 = T$ where $T_0 = 2.75K$, today's temperature. Galactic radiation and today's diffuse background radiation (DBR) are both given roughly by electron capture ionization (DBR) are both given roughly by

For the first setting, we need an estimate for the speed and density of free electrons (or even hydrogen atoms in cases where $Z_N$ is large enough to rip off an atomic electron).

### B. SQN Structure Models

We will discuss two generic models for SQN structure. The first can be called the “no-admittance model.” An example is color-flavor locked (CFL) pairing [6], in which the $u$, $d$, and $s$ quarks pair symmetrically. Then, everywhere in the bulk there is the same number of quarks of each kind and hence charge neutrality of the bulk of the quark lattice. In this case the charge on the lattice will come at the surface where the longer Compton wavelength of the (low mass) $u$ and $d$ quarks requires that the edge quarks be $u$ and $d$ unbalanced by any of the much more massive $s$. This gives a net total charge on the order of $Z_T \sim (M/m_p)^{2/3}$, where $m_p$ is the mass of the proton. The full system would have, in vacuo, in addition, enough electrons so that the total charge is zero.

In the second, “admittance model,” there is no pairing at all or no (or weaker) pairing of s-quarks with $u$ and $d$ quarks, and the number of $s$ quarks is smaller. Then there will be a net positive charge on the quark lattice, throughout the bulk. This yields a $Z_T$ that is some percentage of the number of quarks, not a fraction of the number of quarks to the $2/3$ power, a larger value of $Z_T$. In this model, we can approximate the potential as in Fig. 1. For a large degree of ionization $Z_N$, we approximate the eigenenergy of the least bound electron in the ground state system as $E_B \sim Z_N e^2/r_N$. The kinetic energy will be negligible compared to the potential energy.

In the no-admittance model, the repulsive Coulomb force among the electrons prevents them from moving into the bulk, and we can approximate the potential as in Fig. 2. There, the cramped quarters might appear, by the uncertainty principle, to make the kinetic energy appreciable and therefore yield less binding than the potential of Fig. 1, and hence higher $Z_N$ values and easier detectability. However, the quarters are not really so cramped: the distance from $r = r_N$ to $r$ such that $V(r) = V(r_N)/2$ is $r_N$. This means that, for a given $Z_N$, the kinetic energy must fall with increasing SQN mass as $M^{-2/3}$ while the potential energy falls only as $M^{-1/3}$. That occurs for $r_N > a_B/Z_N$, with $a_B$ the Bohr radius (for hydrogen). In that case, we show below (See Eq. (10) that $Z_N \approx b \sim M^{1/3}$. The opposite inequality is addressed below. Given the $M$ dependence of the kinetic and potential energies, for the potentials of both Fig. 1 and Fig. 2, we make the approximation, for the least tightly bound electron in the $r_N > A_B/Z_N$ case, that it is S-wave and moves in a potential of positive charge $Z_T$, negative charge ($Z_T - Z_N$), and total charge $+Z_N$, with negligible kinetic energy and total energy $E_B \sim -Z_N e^2/r_N$. We emphasize that this is a conservative approximation in the sense that taking into account the effects of the Pauli principle, orbital angular momentum, and electron Coulomb repulsion for the potentials would tend to decrease the (absolute value of the) binding energy of the least bound electron, in its ground state, making ionization easier. We thus are estimating minimum values of the charge on SQNs.

For small SQN mass, $M$ and $r_N \ll a_B/Z_N$ ($a_B$ is the Bohr radius, half an angstrom), we approximate the system as an S-wave Bohr atom, and call $b$ the larger

### Table II: Settings

<table>
<thead>
<tr>
<th>Location</th>
<th>Radiation Source</th>
<th>Galactic</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extragalactic</td>
<td>$(1+z)T_0; CBR$</td>
<td>DBR</td>
<td>—</td>
</tr>
<tr>
<td>Galactic</td>
<td>$z_{esc} &gt; z \geq 0$; DBR</td>
<td>$r &gt; r_N$</td>
<td>$r &gt; r_N$</td>
</tr>
<tr>
<td>Solar</td>
<td>$r &gt; r_S$; DBR</td>
<td>$r &gt; r_S$</td>
<td>$r &gt; r_S$</td>
</tr>
</tbody>
</table>
of \( r_N \) and \( a_B/Z_N \). As noted in the previous section, we will treat the transition between the small and large \( M \) regions in a separate publication exploring the passage between the two approximations for a broad class of potentials including those of Figs. 1 and 2. In summary, for small \( r_N \), we approximate the system as having its most loosely bound electron in an S-wave state of a hydrogen-like atom, while for large \( r_N \) we take the kinetic energy as negligible.

C. The Formulary

We equate the rate, \( Z_+ \), at which electrons are ionized by photons in the radiation bath (or unidirectional “radiation shower” in some cases) to the rate at which they are replaced by capture from the electron bath or shower, \( Z_- \). We write

\[
Z_+ = \pi b^2 \int_{Z_N e^2/r_N}^{\infty} dE N_e(E) \left[ N_e(E_B < E) \sigma (\gamma + SQN - e + SQN, 1) \right]
\]

where: \( b = \max[r_N, a_B/Z_N]; \ r_N \) is (still) the SQN radius \([3M/4\pi\rho]^{1/3} = r_N\); \( N_e(E)dE \) is the number of photons per unit area per unit time with energy between \( E \) and \( E + dE \); \( N_e \) is the number of electrons per unit area with binding energy \( E \) or less; \( \sigma \) is the particle physics cross section for ionization and can be evaluated using standard relativistic quantum mechanics. The square bracket under the integral sign is the probability of the photon, when it hits the SQN, actually liberating an electron. Because a probability is needed, when that product is greater than one, it must be replaced with one.

Similarly, we have

\[
Z_- = \pi r_N^2 \int_{Z_N e^2/r_B}^{\infty} v_e(E)n_e(E) \left[ 1 + f_e(E, Z_N) \right] h(E)g(e + SQN - SQN + X, E) dE
\]

where \( h(E) \) is the distribution of incoming electron energies and \( g(E) \) is the probability that the incoming electron will be slowed and captured. We integrate over the distribution of incoming electron energies; \( v_e \) is electron speed; \( n_e dE \) is the number of electrons per unit volume with energies between \( E \) and \( E + dE \). The function \( f_e \) is given by

\[
f_e = 4\alpha h c Z_N/(r_N E_e)
\]

\( f_e \) is the enhancement of the effective cross sectional area of the SQN from the SQN charge focusing the incoming electrons. Note that the coefficient on the right-hand side in Eq(3) is \( \pi b^2 \) while that in Eq. (4) is \( \pi r_N^2 \) (with \( b \) the larger of \( r_N \) and \( \alpha h/(a_B Z_N) \)). This takes account of the fact that a photon can eject an electron out to \( b \) while an electron must penetrate to \( r_N \) to be captured.

Scattering off the bound electrons or the much more numerous quarks and the absence of relativistic electrons at the \( Z \) values under consideration make it a reasonable approximation to assume that all electrons up to energies significantly higher than \( m_e + E_B \) are captured. In the spirit of this approximation we set the product \( gh \) equal to \( \delta(E - \bar{E}_e) \), where \( \bar{E}_e \) is the average electron energy, and replaced the whole integral by \( n_e u_e(1 + f_e) \).

We solve the equation \( Z_+ = Z_- \) for a range of SQN mass \( M \) in the various settings described, letting \( M \) range from \( 10^{-21}g \) to \( 10^{30}g \). We continue to make the conservative approximation that the kinetic energy is negligible compared to the potential energy and hence use \( E \sim -Z_N e^2/r_N \) for \( r_N > a_B/Z_N \)

For large \( Z_N \), each SQN will be surrounded by an excess of electrons and there will be screening which will affect both electron capture, Eq. (4), by limiting the distance over which there is an attractive force, and electron liberation, Eq. (3), by impeding escape to infinity. In the first approximation of this work, we do not attempt to estimate the size of these effects, but note that, because they appear to have opposite effects, there is a possibility of first order cancellation.

We have solved the equation \( Z_+ = Z_- \) for some values of the parameters, and with some (further) approximations. The most important of the approximations is replacing the product \( N_e \sigma \) in Eq. (3) with unity. This is a good approximation because, with \( Z_T \sim M^{2/3} \), we have \( N_e = Z_T/(4\pi b^2) \sim \text{few} \times 10^{35} \text{cm}^{-2} \), independent of \( M \). Since \( \sigma \sim 10^{-20} \text{cm}^2 \), the probability of a photon liberating an electron from an SQN is of the order of one if the photon’s impact parameter lies within the effective cross section from the center of the nugget, and if the photon is sufficiently energetic.

The final result of these approximations in Equations (3) and (4) is that \( Z_+ = Z_- \) reduces to

\[
\pi b^2 c F_\gamma(E > E_B) = \pi r_N^2 n_e \bar{v}_e(1 + f_e)
\]

where: \( b = \max[r_N, a_B/Z_N] = Z_N \alpha h c/E_B; \ F_\gamma(E > E_B) \) is the number of \( \gamma \)-s per unit volume with energies greater than \( E_B; \ E_B \) is the binding energy of the least bound remaining electron in the SQN; \( n_e \) is the density of ambient electrons; \( \bar{v}_e \) is their (average) speed; and \( f_e \) is the (classical) focusing factor of Eq. (5). For four settings - \( z = 1089, z = 0, \text{quiet sun, and X-ray flare} \) - we use a thermal distribution; for three - intergalactic, near the sun, and milkyway center diffuse radiation backgrounds (DRB) - we use a non-thermal, power law spectrum approximating the graph given by Henry [15]. The number of photons per unit volume with energy \( E_\gamma \) = \( E > E_B \), denoted \( F_H \) is given by

\[
F_H(E) = -c^{-1}(\beta_0 + 1)^{-1} A_b E^{(\beta_0 + 1)}
\]
for \( E > E_{ab} \), and

\[ F_H(E) = -c^{-1}((\beta_a + 1)^{-1}A_{ab}E^{(\beta_a+1)} - (\beta_a + 1)^{-1}E_{ab}^{(\beta_a+1)} + (\beta_b + 1)^{-1}A_{ab}E_{ab}^{(\beta_b+1)}) \]  

for \( E < E_{ab} \),

with \( E_{ab} = 10^{15}h = 4.8 \text{ eV} \) (\( h \) is Planck’s constant); \( \beta_a = -2.45; \beta_b = -3.05; \log(A_b) = 6.77; \log(A_b) = 7.14. \)

III. RESULTS

Figure 3 gives results for the equilibrium values of \( Z_N(M) \) for seven selected settings. The seven curves, proceeding from top to bottom, are:

- (1) the sun shining on an SQN during an X-ray flare;
- (2) the relatively intense diffuse galactic background radiation (DGBR) at the center of the galaxy (COG) shining on an SQN located near the center;
- (3) the diffuse background radiation (DBR) shining on an extragalactic SQN;
- (4) the (quiet) sun shining on an SQN at the distance of the Earths orbit;
- (5) an SQN in the primordial universe at recombination;
- (6) the DGBR shining on a solar system SQN; and
- (7) an SQN in the CBR today (ignoring all other radiation).

In the Log-Log plot of Fig. (3), the second and third curves from the top are barely distinguishable from each other, with the 4th and 5th even less so. The little, relatively flat tails on the left in Fig. 3. give a rough approximation to the behavior in the mass region in which there is a transition between the “atomic model” \( r_N < a_B/Z_N \) and the \( M^{1/3} \) behavior for \( r_N > a_B/Z_N \). In Fig. 3 we have truncated curves where the computer program gives \( Z_N(M) \leq 1 \).

Table III gives the parameters for the radiation and electron baths and showers in the same order as just described. Based on it, one can understand the order of the curves in Fig. 3. The largest SQN charge, among the settings considered, is in the X-ray shower from a solar X-ray flare. The neighborhoods of supernovae and other explosive astrophysical events, however, might well be even better, depending on the extent to which assets like the Swift satellite are able to get sufficient data, in seeing SQN effects. The CBR by itself is, today, the worst, but it is perhaps interesting that, for sufficiently massive SQNs, it would contribute. We have not, however, at this level of approximation, added multiple contributions to \( Z_+ \).

In Fig. 4, we give the times (in years) necessary to reach \( Z_N(\tau(M) = Z_N/Z_+ = Z_N/Z_-) \) for (just) the dominant contribution in each location. The results for \( Z_N \) do not vary with distance from the sun because both the radiation and electron showers fall off like \( r^{-2} \). However, the times to reach \( Z_N \) do vary with \( r \) like \( r^2 \). The times are about a day and a half for a nanogram, and fall as \( M^{-1/3} \) as shown in Fig. 4, for both the quiet sun and the X-ray flare at \( r \) equal the distance of the Earth from the sun (one AU). As shown below (see Eq. 9), the results for the times do not depend, in our approximations, on the radiation – only on the electron bath or shower. This is because both \( Z_N \) and \( Z(=Z_+ = Z_-) \) have the same \( M^{1/3} \) dependence on \( M \).

In the calculations we have taken the DBR and the diffuse galactic background radiation (DGBR) from Stecker and Salamon [16] combined with the graph of Henry [15], with the assumptions that the DGBR near the sun is about 15 times that in extragalactic space and the DGBR near the center of the galaxy is about \( 10^4 \) times greater than it is in the local neighborhood (that is, most of the X-ray and higher energy radiation is coming from the accretion disk around the supermassive

**TABLE III:** Parameters for the seven curves of Fig. 3. \( n_e \) has units of \( \text{cm}^{-3} \); \( v_e \) has units of \( \text{cm/sec} \). \( N_r \) is the number of photons with energy greater than \( E \) where \( E \) is in eV and \( F_H \) is the function defined by Eq. (7) and Eq. (8).

<table>
<thead>
<tr>
<th>SQN Location</th>
<th>Radiation</th>
<th>( n_e )</th>
<th>( v_e / 10^6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Xray Flare</td>
<td>( T = 10^5 \text{eV} )</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>Galaxy Center</td>
<td>( \text{DBR } N_r = 1.5 \times 10^5 F_H )</td>
<td>0.05</td>
<td>8</td>
</tr>
<tr>
<td>IGM Today</td>
<td>( \text{DBR } N_r = F_H )</td>
<td>( 4 \times 10^{-10} )</td>
<td>1</td>
</tr>
<tr>
<td>Quiet Sun</td>
<td>( T = 0.5 \text{eV} )</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>IGM Pre Recombo</td>
<td>( \text{CBR } T = 0.26 \text{ eV} )</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>DBR near sun</td>
<td>( N_r = 15 F_H )</td>
<td>7</td>
<td>50</td>
</tr>
<tr>
<td>IGM Today</td>
<td>( \text{CBR } T = 2.75K )</td>
<td>( 4 \times 10^{-7} )</td>
<td>1</td>
</tr>
</tbody>
</table>
In Fig. 4, and again in the second column of Table IV, we give results for the time $\tau_{\text{eq}}(M)$ (in years) for $Z_N$ to reach equilibrium (as in Fig. 4) as well as the binding energy of the least tightly bound electron, $E_B(M)$ for $M > 10^{-10} \text{g}$ and for $M = 10^{-21} \text{g}$ for the seven settings. Recall from subsection B above that $E_B = -Z_N e^2 / b; b = \text{Max}[\tau_N, a_B / Z_N]; 10^{-10} \text{g}$ is the boundary, roughly, between the two regions. $\tau_{\text{eq}}(M)$ varies as $M^{-1/3}$ for all settings. Other variation with $\tau_N \sim M^{+1/3}$ cancels out in the ratio $Z_N / Z$: e.g. Fig. 4 does not have the kinks that are present in Fig. 3. The lack of any variation in $E_B(M)$ for $M > 10^{-10}$ should aid in devising SQN detection schemes with the whole range of masses giving the same signal. In those cases in which the charge focusing parameter $f_e$ of Eq. (5) satisfies $f_e >> 1$, we can write a simple closed form for $\tau_{\text{eq}}$. Letting $b = \text{Max}[\tau_N, a_B / Z_N]$, writing $\zeta = 1(2)$ according to $b \neq a_B / Z_N$ ($b = a_B / Z_N$), and recalling $E_B = -Z_N e^2 / (\zeta b)$, we have $f_e = -4\zeta b E_B / (\tau_N e^2)$.

Consequently, it follows from Eq. (5) and the assumption that the integral in the capture rate, Eq. (4), is $n_e v_e f_e$ that we have

$$\tau^{-1} = Z_N / Z = 4\pi n_e^2 n_e \tau_N (h \epsilon / e^2)$$  \hspace{1cm} (9)

Eq. (9) shows that the time to reach equilibrium depends only on the electron bath (or shower), not the radiation and that this is confirmed in the numerical results of Table IV.

We can go on to find a simple closed form equation for $E_B$, if $b = \tau_N$, in the approximations of either $f_e >> 1$ or $f_e \ll 1$. Using $Z_+ = Z_-$ with Eqs. (5) and (6) gives, for the first of these two cases

$$F'(E_B) = 4\pi \zeta e n_e \tau_N / (b E_e)$$ \hspace{1cm} (10)

where $F'(E_B)$ is a function of a form that depends on the nature of the radiation distribution $N_e$ (here, thermal or power law). It is, for the case of $f_e >> 1$, the integral of the photon distribution function from $E_B$ to infinity divided by $E_B$. Variation in $E_B$ as a function of SQN mass $M$ is small for small $M$, as well as absent for large, in the case of thermal radiation. This might be expected since the thermal spectral energy density cutoff is exponential (with $E_B$ in the exponent), but is significant for the diffuse radiation backgrounds where it is only a low power. A similar separation of $Z_+ = Z_-$ into an equation with one side depending only on the radiation and the other depending only on the electrons can be made if $f_e \ll 1$. We do not provide estimates of $E_B(M)$ for $M$ in the transition region between small and large mass, since these should be most sensitive to more accurate wave functions of $[3]$. Some features of the results include the following:

- In Fig. 3 we have used the parameterization of Eq's. (7) and (8), with two line segments, for the diffuse background radiation, derived from that plotted in Ref [15] (intergalactic, in the area of the solar system, and at the center of the galaxy). These are the only three non-thermal baths considered. An alternative to our two segment parameterization would be simply to connect reasonable initial and final points with a single straight line. The result of this alternative, on the Log-Log plot of $F(E)$ is a single line with slope $\beta = -2.65$ (compared with $-2.45$ and $-3.05$ for the two segment fit used in calculations for Fig 3). For the coefficient $A$ of $E^\beta$, it is $\log A = 6.1$. This alternative gives, for the intergalactic medium (IGM) $Z_N = 1007 M^{1/3}$ compared with $1395 M^{1/3}$ for the two segment fit to the DRB intensity. The difference would be difficult to see on a Log-Log plot. The X-ray GLAST mission should significantly improve data in the $2m_e c^2$ region over that available to [15].
• The fact that \( Z_N(M) \) behaves as \( M^{1/3} \) for the region in which \( b = r_N \), i.e. where \( M \) is large enough that the Bohr radius is inside the SQN, can be seen from Eq. 6. If \( b = r_N \) holds, all explicit dependence on \( M \) disappears from that equation and one just solves once for \( E_B = a \hbar Z_N/b \), the binding energy of the most loosely bound electron. That the dependence of \( Z_N \) on \( M \) is the same as that of \( b \) implies \( Z_N \sim M^{1/3} \).

• Physically, one expects that the value of \( Z_N \) should rise with \( M \) so as to make the binding energy of the most loosely bound electron independent of the radius of the SQN in the \( M \) region for which \( \pi b^2 = \pi r_N^2 \). The more interesting question is that of the negative slope of the little tails on the left in Fig. 3. (The answer is that, in that \( M \) region, \( Z_N \) grows as \( M^{2/3} \) from the increase in \( r_N \), while \( Z_+ \), with \( b \) fixed at the appropriate Bohr radius, lacks that increase. This drives the solution to Eq. (6) to lower \( Z_N \) to compensate.)

• One sees from Table III that, in the numerical calculations, we have chosen the density of electrons in the IGM today, \( n_e \), to be a mean between that corresponding to complete ionization of all IGM atoms and that corresponding to ionization at the \( 10^{-5} \) level. “Complete ionization,” as used here, includes the case in which the SQN electric field is strong enough to polarize atoms and remove their electrons. As noted, it follows from Eq. (6) that, for \( b = r_N \) (large \( M \)), the results for \( Z_N \) vary like \( n_e^{1/3} \). Numerical calculations show a much smaller, more complicated variation for \( b > r_N \). One also sees that the same situations obtains for varying \( v_e \).

• The largest \( Z_N \) values occur for solar system X-ray flares. Since these only last for minutes, one will need to consider carefully whether there is sufficient time to realize the large values and, even more importantly, sufficient time to exploit them for SQN detection.

• The results for SQNs at recombination are about the same as the results for the (quiet) sun because, while the temperature in the sun is higher than that in the CBR just after recombination, the electron density then is lower than that in today’s solar wind near the Earth.

• Extragalactic SQNs have high \( Z_N \) values and ones near the solar system much lower ones because of the great difference in electron densities.

• A check on the results is the fact that higher \( Z_N \) values for a setting correlate directly with a lower mass for the transition from \( Z_N(M) \sim \text{constant} \) with \( M \) to \( Z_N \sim M^{1/3} \). See Fig. 3

• The results above for the potential of Fig. 1 apply about equally to the potential of Fig. 2, for large \( r_N, \tau_N > a_B/Z_N \). They also apply for small \( r_N \) (atom-like structure). However the results in the transition region will be different. For that region, there will be less binding energy, with the potential of Figure 2, for a given \( Z_N \), again meaning, as noted, that our use of the approximation of the Fig. 1 potential is conservative in that it tends to underestimate the SQN charge.

• Note that \( Z_N \) is limited by vacuum breakdown to less than \( E_\gamma(Z_N) = 2m_e \). For \( M > 10^{-15}g \) this occurs at \( Z > 137 \). For \( M < 10^{-20}g \), there are not enough electrons in the no-admittance model for it to occur at all.

IV. DISCUSSION

There are a variety of techniques to consider once the order of magnitude of the charges on SQNs, and the binding energies of their most loosely bound electrons, are known. One could look for emission lines from electrons being captured by the SQN. One could look for absorption lines and/or absorption edges in radiation coming toward us from behind an SQN population. One could try to detect the static charge along with the very small charge-to-mass ratio. Finally there is the possibility of indirect detection by means of some astrophysical effect of a population of charged SQNs. Below we give a few examples of such lines of inquiry. The main problem in looking for a signal will be the low SQN abundance given the number density limit \( \rho_{DM}/M > n_{SQN}(M) \).

Particle Detection Techniques. One could consider space-based particle detection techniques, including ones that might be based on the Moon. The major capability needed is wide area coverage. Consider the event rate

\[
dN_{\text{ev}}/dt = n_{\text{SQN}}v_{\text{SQN}}A
\]

where \( n \) and \( v \) are the number density and speed of the SQNs and \( A \) is the effective detector area. Again, suppose all SQNs are of mass \( M \) and that \( n_{\text{SQN}} \sim \rho_{DM}/M \). If we want to detect one SQN in the time \( \tau \), we need (recall \( \rho_{DM} \sim 5 \times 10^{-25} \text{ g/cm}^3 \)) \( \rho_{DM}/M > 10^{17} \) assuming that \( v_{\text{SQN}} \sim 250 \text{ km/s} \), the galactic virial velocity. If a square kilometer could be instrumented, nanogram SQNs might be detected at rates up to 100/s and gram SQNs once a year.

Absorption and Emission Lines and Edges. A second approach is to search settings in which there is identifiable absorption or emission. One example would be to look for settings in which there is sufficient high energy radiation to bring SQNs to a high enough degree of ionization that pair creation ensues if another electron is ejected. We expect that to happen when \( E_B \), the binding energy of the least bound electron, is \( 2m_e c^2 \). At such a point, there should be an emission line at \( E = 2m_e c^2 \) from electron capture. This would result from a strong
enough photon distribution to preclude lower $E_B$ and vacuum pair creation preventing a larger one. The result would be that any electron capture would produce a $2m_e$ photon, a very distinctive signal. We emphasize that careful calculations are needed to determine whether that signal would rise above the strong backgrounds in an explosive event. Once $E_B$ is at $2m_e c^2$, any further electron ejection results in creation of an $e^+e^-$ pair so that there would also be emission of gammas with $E_y = m_e c^2$ from $e^+ - e^-$ annihilation. This signal should occur as the SQN, in the radiation and electron baths, oscillates about the equilibrium value $Z_N$. It requires an SQN mass above about $10^{-20}g$ so that the total number of electrons is sufficient to reach that point.

In addition to gammas from the positrons annihilating with ambient electrons and the $2m_e c^2$ emission there might be an accompanying absorption edge at $2m_e c^2$ since photons of energy over that value could liberate electrons from the SQN, but less energetic ones could not. Our preliminary calculations summarized above indicate the diffuse radiation background is not able to ionize SQNs to that degree. Other places to look would be toward explosive events, including supernovae (of various types), gamma ray bursts, and neutron star bursts and superbursts. It is far from clear that the populations of SQNs would be sufficient to produce a detectable signal or that any signal would be separable from expected backgrounds.

It is possible that GLAST data, when available, could contain some evidence of this triad of signals: an emission line at $E = m_e c^2$, an emission line at $E = 2m_e c^2$, and an absorption edge starting from $E = 2m_e c^2$. The emission line at a single photon energy of $2m_e c^2$ (resulting from $\gamma$'s keeping $E_B \geq 2m_e c^2$ and vacuum pair creation keeping $E_B \leq 2m_e c^2$) would be a dramatic SQN signal. It may well be that the background would swamp any signal, but this three-pronged test would be such a crucial indicator that it is important to assess its feasibility. An important place to look for an analogous signal would be in the solar system during a solar X-ray flare. Then we would expect an X-ray signal of about 50 KeV and some absorption of X-rays over that (see Table IV and Fig. 4). Additionally, we note that a strong X-ray signal from electron-positron annihilation strongly concentrated at the center of our galaxy has been observed most recently with the INTEGRAL satellite. See, for example, Yuksel [17] for a brief review. We have, however, not seen any reports of 1.02 MeV photons, so it would be premature for SQNs to clamor for entry into Yuksel’s list of about two dozen “exotic” models that might account for the positrons.

Finally, we can derive, from Eq. (6) a condition for $E_B$ to reach $2m_e c^2$. Consider a thermal photon distribution at temperature $T$. We have, after evaluating the integral for such a distribution over all $E > E_B$, (with $x = E_B/T$)

$$\frac{(2 + (2 + x)x)e^{-x}}{x} = 4(\hbar c)^3/(E_c T^2)n_e(\nu_\gamma/c) \quad (12)$$

This equation could prove useful in evaluating the likelihood of finding the $2m_e c^2$ line in various settings, including explosive ones.

**Early Universe Effects.** Two indirect searches for SQNs or limits on their abundance, based on the results of the charge calculations, would be to consider their effects on the cosmic microwave background (CMB) and on the production of the first (population III) stars.

With regard to the CMB, consider the early universe picture, just before recombination, of free protons, free electrons and mass $M$, charge $Z_N$ SQNs. Oversimplified, there will be, around each SQN, an electron-rich cloud nearby and an outer proton rich region. The size of these regions will depend on the SQN masses. While not bound, the ensemble is likely to have some coherence, and hence some $M$-dependent electromagnetic effects, such as resonant frequencies, that could lead to observable features in CMB observations. If so, there could be discovery or new limits on abundance of primordial SQNs. There will also be continued production of photons of (decreasing) energies less than about 10 eV as the universe expands and $e^-$ capture continues. Depending on SQM masses and abundances, such CMB perturbations might be observable.

Another early universe effect that might lead to SQN indications or bounds could be entropy production by the chain of reactions $\gamma + N_2 \rightarrow e^- + N_{2+1} \rightarrow e^+ + 2e^- + N_{2+1} \rightarrow N_{2+2} \gamma$ discussed above. Its effect is to turn one photon with $E > 2m_e c^2$ into two photons of lower energy. Conceivably this chain could occur sufficiently rapidly to have a noticeable effect on the baryon to photon ratio and hence the abundance of helium or other light elements produced in primordial nucleosynthesis.

With regard to Population III stars, one might ask the extent to which SQNs would catalyze hydrogen molecule formation as a function of red shift $z$. Hydrogen molecules are necessary to radiate (from collisionally excited vibration states) energy from the collapsing protostar gas cloud when the cloud temperature has fallen below the energy differences among hydrogen atom states. The picture would be one of an SQN population of mass $M$ with charge $Z_N$ on each SQN. Each SQN would tend to polarize hydrogen atoms which would then adhere to the SQN. With multiple adhering atoms, atoms could meet and combine to form a hydrogen molecule which could be ejected in collisions, as is the case with dust catalysis of hydrogen molecule formation in today’s galaxies.

We do not know which, if any, of these effects of non-zero, and sometimes large, $Z_N$ will be amenable to observation if SQNs exist. Additionally, we note that recent results on neutron star superbursts (see Watts in [18]) cast some doubt on whether Neutron stars are, in fact, strange quark stars. However, the implications of SQM existence are sufficiently extensive that it is important to make certain whether or not the universe has a population of SQNs.
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