

CHARGES ON STRANGE QUARK NUGGETS IN SPACE

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Basic Idea/History

- Witten (1984): 3 quark flavors implies same P.E., but less K.E. by Pauli Principle
- Farhi and Jaffe find SQN B.E./q rises to asymptotic value as $N=A/3$ rises
- A. De Rujula and S. Glashow Identify bunch of methods of detecting SQNs
- M. Alford, K.Rajagopal, and F.Wilczek find Cooper pairing of SQN q's

Production

- Primordial: depends on cooling by evaporation being less than cooling by neutrino emission and any other mechanisms
- $\text{Evap} \sim M^{2/3}$; neutrinos $\sim M$. $M > 10^{20}$ works
- Collisions of SQS's from NS binaries

Selected Searches

TABLE I: Some Strange Quark Nugget Searches.

Experiment/Observation	Mass Range (g)	Result
AMS ^a	$10^{-24} - 10^{-22}$	not done
RHIC ^a	$< 3 \times 10^{-21}$	not found
Mica Tracks ^b	$10^{-20} - 10^{-14}$	$\ll \rho_{DM}$
ICE CUBE ^c	$10^{-3} - 10^{-2}$	not done
Seismometers:		
Future Lunar ^d	$10^3 - 10^6$	not done
Apollo ^e	$10^4 - 10^6$	$< \rho_{DM}/10$
USGS Reports ^e	$10^6 - 10^8$	$< \rho_{DM}$

Settings

TABLE II: Settings.

Location	Radiation Source		
	<i>Extragalactic</i>	<i>Galactic</i>	<i>Solar</i>
Extragalactic	$(1+z)T_0$; CBR	DBR	
Galactic	$z_{rec} > z \geq 0$; DBR	$r_{sc} > r > r_{bh}$	
Solar	$r > r_S$; DBR	$r > r_S$	$r > r_S$

SQN Structure

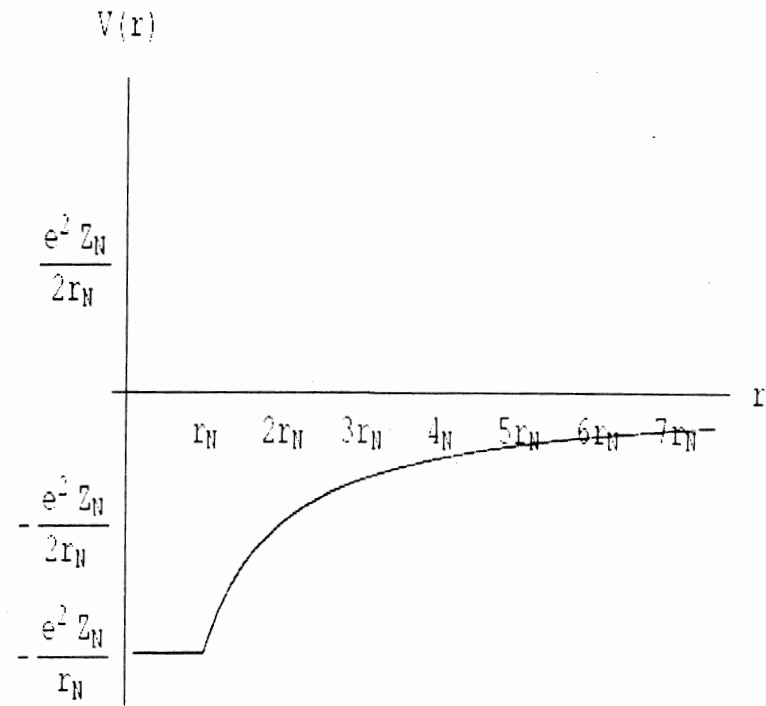
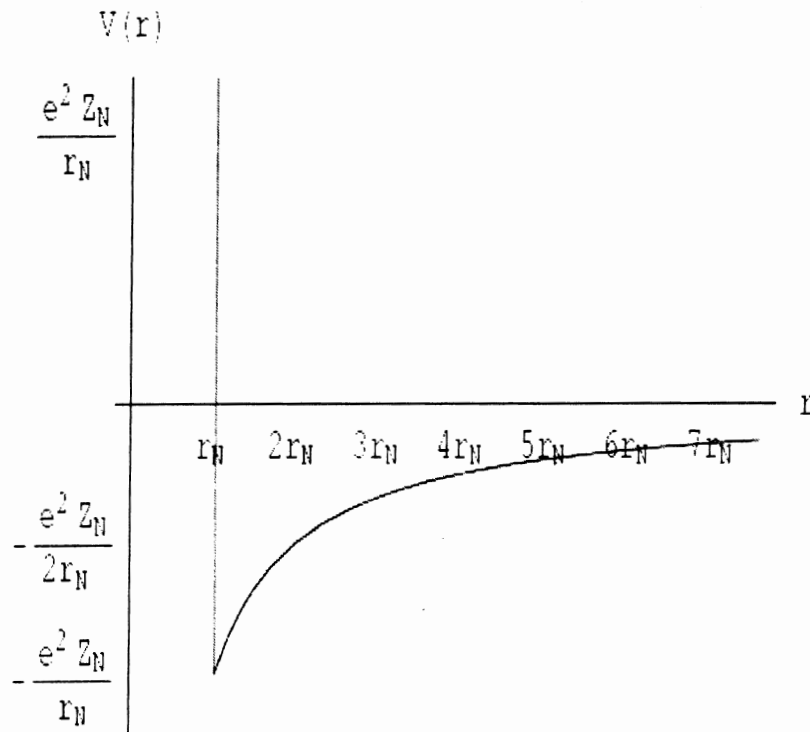


FIG. 1: Potential for least bound electron. FIG. 2: Approximation to potential for least bound electron.

Our Calculation

- Find Z_N such that rate ambient photons ionize SQN electrons = rate ambient e^- 's replace them.
- LHS falls with increasing Z_N ; RHS rises.
- SQN radius (r_N) < Bohr radius/ Z_N : Coulomb;
- $r_N > r_B/Z_N$: electrons feel 2d potential and assume $K.E. \ll P.E. = Z_N^2 \alpha^2 / r_N$ (conservative)

Rates

$$\dot{Z}_+ = \pi b^2 \int_{Z_N e^2 / r_N}^{\infty} dE N_\gamma(E) \left[N_e(E_B < E) \sigma(\gamma + SQN \rightarrow e + SQN), 1 \right]$$

$$\dot{Z}_- = \pi r_N^2 \int_{m_e - E_B}^{\infty} v_e(E) n_e(E) \left[1 + f_e(E, Z_N) \right] h(E) g(e + SQN \rightarrow SQN + X, E) dE$$

$$f_e = 4\alpha \hbar c Z_N / (r_N E_e)$$

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

Parameters

SQN Location	Radiation	n_e	$v_e/10^6$
Solar Xray Flare	$T = 10^3 \text{ eV}$	7	50
Galaxy Center	DBR $N_\gamma = 1.5 \times 10^5 F_H$.05	8
IGM Today	DBR $N_\gamma = F_H$	4×10^{-9}	1
Quiet Sun	$T = 0.5 \text{ eV}$	7	50
IGM Pre Recombo	CBR $T = 0.26 \text{ eV}$	5	30
DBR near sun	$N_\gamma = 15 F_H$	7	50
IGM Today	CBR $T = 2.75 K$	4×10^{-9}	1

Results $Z_N(M)$

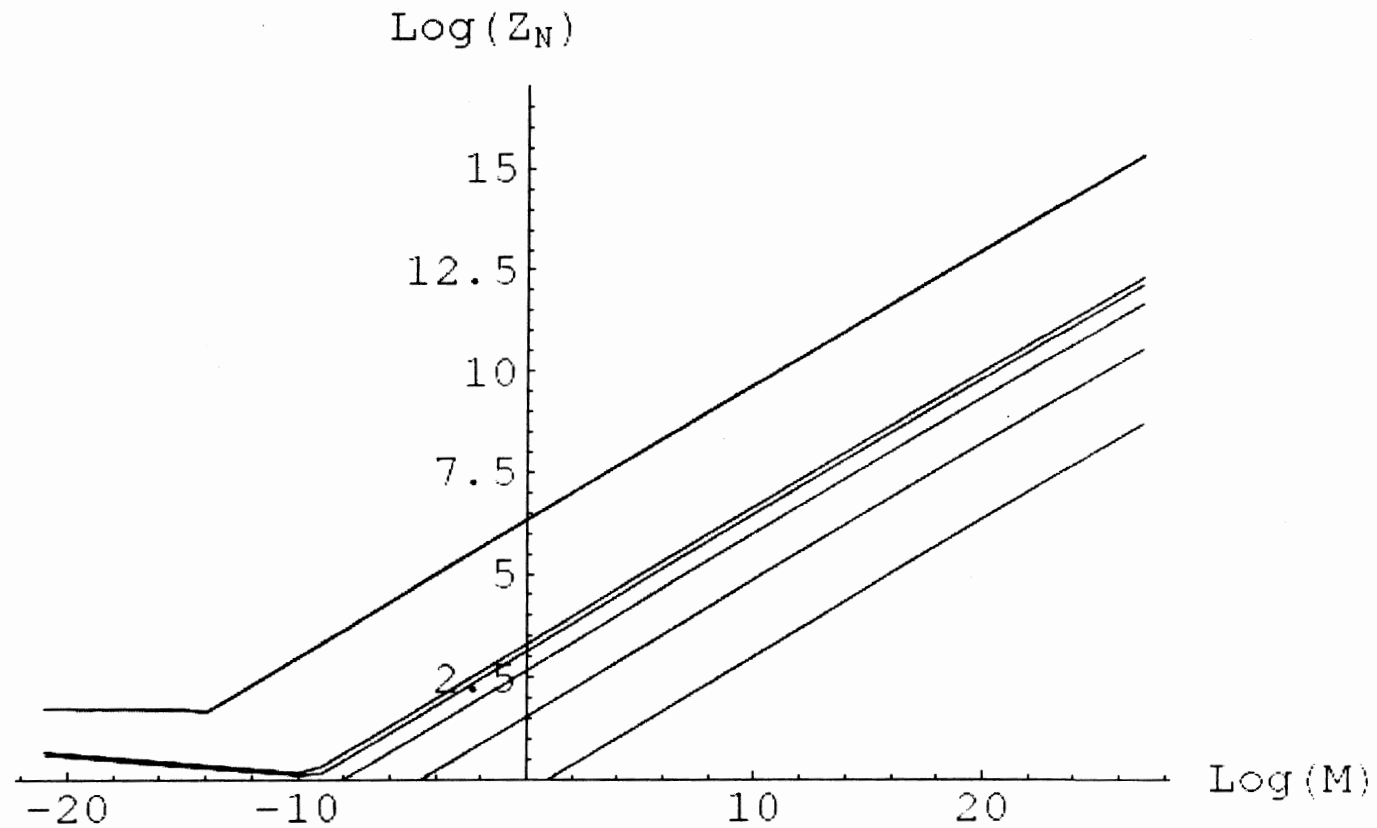
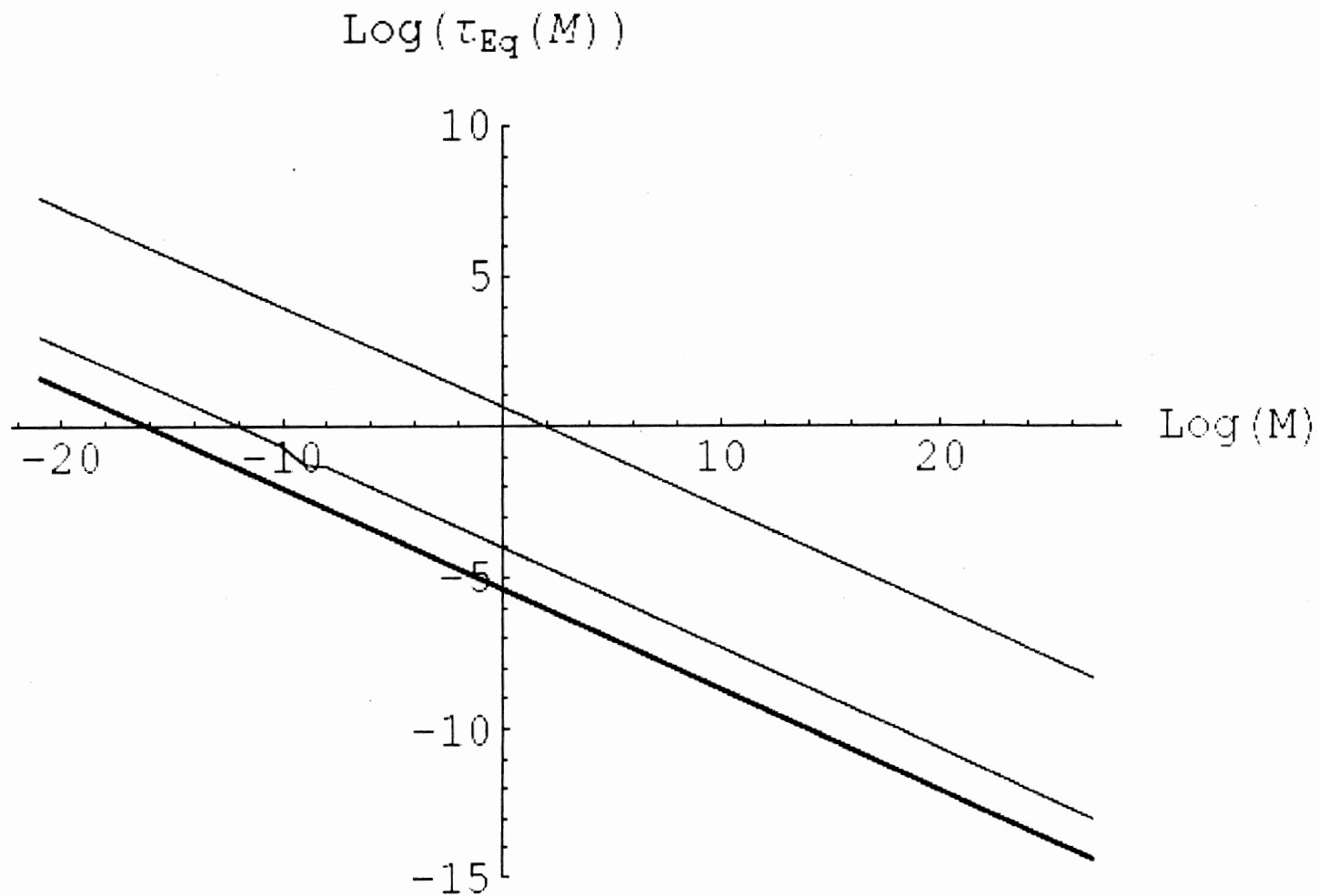


FIG. 3: SQN charge $Z_N(M)$.

Results: Time to Reach Equilibrium



Results: Binding Energies

Setting	$M^{1/3}\tau_{Eq}(\text{y})$	$E_B(\text{eV})$ $M > 10^{-10}g$	$E_B(\text{eV})$ $10^{-21}g$
Galactic Center	10^{-4}	39	330
IGM Today: DBR	4.4	26	240
Solar system:			
during X-ray flare	4.5×10^{-6}	3.8×10^4	4.2×10^4
from DBR	0.66		240
Quiet Sun	4.5×10^{-6}	14	18
Recombo with CBR	3.8×10^{-6}	9.5	12
Today from CBR	4.4	8.7×10^{-3}	0.012

Features of Results

- Shape of $ZN(M)$ expected.
- IGM e-numbers chosen as geometric mean between complete and residual H-ionization.
- Largest ZN is case of solar X-ray flare.
- Closed form

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

- Vacuum breakdown for $B.E. > 2m(el)$

Particle Detectors

$$dN_{ev}/dt = n_{SQN} v_{SQN} A$$

- Let $N(SQN) = \rho(DM)/M$; get $A t/M \sim 10^{17}$
- Note expect primordial $M \sim 10^{24} \text{g}$
- If “lucky,” could have shower of SQNs from SQS-SQS collision

Absorption and Emission Lines and Edges

- Explosive events could give trifecta: gamma absorption for $E > 2m(e)$; emission at $2m(e)$; and emission at $m(e^-)$ from e^+ production.
- There are questions of e^+ production in COG, and of pair instability SNe. SQM roles possible
- Possible detection of SQN emission line from e^- capture during X-ray flare needs estimate.

Early Universe Effects

- CMB effects such as possible oscillations of Debye cloud around primordial SQNs??
- Entropy prod'n: $\gamma + \text{SQN} \rightarrow 2\gamma + \text{SQN}$?
- SQN catalysis of molecular hydrogen formation before pop 3 stars?

Summary and Future Work

- Have calculated ZN , $t(eq)$ and B.E. for 7 settings in limits of SQN radius greater or less than Bohr radius divided by ZN .
- Need look at transition region.
- Need see if any of effects cited are detectable.

BACKUP: SQM problems

- SQS as NS: pulsar glitches; superburst QPOs.
- Negative results of terrestrial (and “lunar”) searches.
- Primordial production possibly precluded by neutrino diffusion nixing inhomogeneities