Using the Moon as a low-noise seismic detector for strange quark nuggets

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Strange quark matter made of up, down and strange quarks has been postulated by Witten [1]. Strange quark matter would be nearly charge neutral and would have density of nuclear matter (10^{14} gm/cm^3). Witten also suggested that nuggets of strange quark matter, or strange quark nuggets (SQNs), could have formed shortly after the Big Bang, and that they would be viable candidates for cold dark matter. As suggested by de Rujula and Glashow [2], an SQN may pass through a celestial body releasing detectable seismic energy along a straight line. The Moon, being much quieter seismically than the Earth, would be a favorable place to search for such events. We review previous searches for SQNs to illustrate the parameter space explored by using the Moon as a low-noise detector of SQNs. We also discuss possible detection schemes using a single seismometer, and using an International Lunar Seismic Network.

1. INTRODUCTION

Lunar SQN search is motivated by the valuable opportunities to conduct science on the Moon, which will be offered by an armada of US and foreign spacecraft in the near future. Of particular interest is a new type of seismic event due to the passage of SQNs. The Moon is a seismically quiet body. It is therefore a favorable place to search for such transit events. From the limited measurements done during the Apollo program, it was found that the annual seismic energy release on the Moon is approximately 10^6 times smaller than that on Earth ([3], but see [4]). The absence of tectonic activity on the Moon is the main reason for the low seismicity. The absence of loading by the atmosphere and the ocean also contributes to the low seismic background. In this paper, we show that the lower seismic noise on the Moon will enable a search for SQNs in a previously inaccessible parameter space. The development of the seismometer, with sensitivity 100 times better than current state of the art, will be discussed in a separate article in these proceedings. In the following, we give a background on SQN science and discuss possible lunar detection schemes.

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2. SQN SCIENCE BACKGROUND

Strange quark matter has been an important subject in both particle physics and astrophysics. For example, a recent review article by Weber [5] contains 331 references.

Witten [1] pointed out that matter made of up, down and strange quarks is more likely to be bound than that made of just up and down:

the third quark decreases the effect of the Pauli exclusion principle, increasing binding energy per quark by about 10 percent and reduces Coulomb repulsion since the charges of both down and strange quarks are $-1/3$ while that for the up quark is $+2/3$. The nuclear physics of such systems was addressed by Farhi and Jaffe [6]. Recently the argument for the existence of strange quark matter at zero pressure has been strenthened by the observation of Wilczek *et al.* [7] that color-flavor locking in strange quark matter should produce Cooper pairs, thereby increasing binding energy over previous estimates.

SQNs are expected to have much higher ratios of mass to charge than ordinary nuclei. For a model of (non-color-flavor-locked) SQNs, $Z \approx A^{1/3}$, where Z and A are charge and mass in electron charge and atomic mass units [5]. The positive charge would be neutralized by electrons which form a cloud extending beyond the boundary of the strange quark matter by angstrom distances. Due to the charge at the boundary, SQNs interact with ordinary matter through electromagnetic interaction. SQNs would go through a body in a way similar to a bullet penetrating matter. The material within the cross section area σ of the SQN is accelerated to approximately the speed of the SQN u. A fraction β of the deposited energy is converted into seismic waves, resulting in a rate of seismic energy deposition of

$$dE/dt = \beta \rho u^3 \sigma / 2, \qquad (1)$$

where ρ is the density of the material, and β was estimated to be 5% based on observations in chemical and nuclear explosions.

Two sources of SQNs are discussed: neutron stars as strange quark stars, as worked out by Alcock, Farhi, and Olinto [8] and primordial production, as suggested by Witten [1] as a dark matter explanation. Both are controversial; neutron stars as strange quark stars because of the difficulty in explaining pulsar glitches [9], but see [10,11]; and primordial production because many believe that SQNs, even if they were formed, would turn back into ordinary matter from cooling by emitting high energy quarks (i.e., evaporation) [12] rather than by emitting weakly interacting neutrinos, but see [13]. If primordial SQNs exist, their characteristic size may be constrained by the following consideration. Gross, Politzer and Wilczek (1973) [14,15] showed that elementary particle couplings vary with energy when higher order diagrams are taken into account. In particular, the electroweak interactions grow weaker with decreasing energy while the strong interaction couplings grow stronger logarithmically. (Parenthetically, it is conjectured that the two meet at about 10^{15} GeV above which there is unification of interactions). The fact that the strong interactions grow stronger with decreasing energy means that formation of strange quark nuggets in the early universe will only take place when the temperature has become low enough. The characteristic energy would be 200 MeV; but because the fall off is logarithmic it could well be a GeV or even higher. When the SQN's are made, they would be expected to contain all the quarks within the horizon (ct, where c is the speed of light and t is the age of the universe) at that temperature. If the temperature were 200 MeV, the mass of the nugget would be about an Earth mass. For higher temperatures it would be lower. Note that the lower the temperature, the lower the ratio of surface area to volume and hence the more likely that neutrino cooling (a volume effect) would be more important than evaporation (a surface effect) and hence that the nugget would survive the cooling process.

Despite the uncertainty in SQN mass and the aforementioned controversies, the search for SQN is an active one. It is one of the objectives of the planned Space Station Alpha Magnetic Spectrometer (AMS), a cosmic ray experiment [11]. It will also be an objective of the IceCube Antarctic neutrino experiment [16]. Detector characteristics and the ranges of likely abundances make each such search sensitive to SQNs in some limited mass range. These and other experiments will be reviewed further.

It should be emphasized that while there is greater expectation that strange quark matter could exist under high pressure inside compact stars, its existence in the form of small nuggets at zero pressure is of a higher degree of uncertainty. Currently, quantum chromodynamics (QCD) theory is not capable of giving definitive answers to

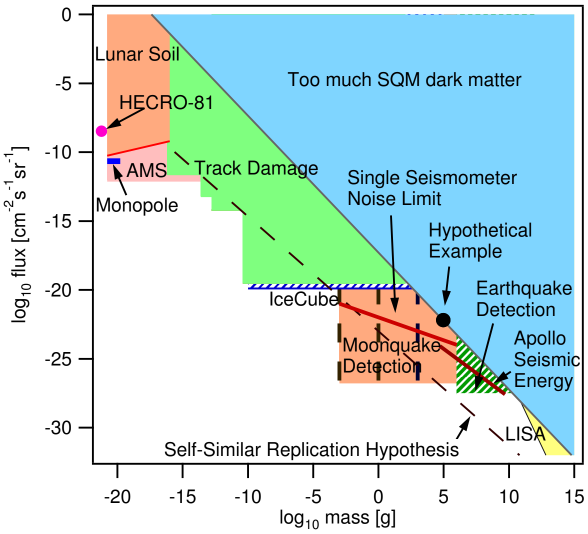

Figure 1. SQN search parameter space.

the question of SQN stability at zero pressure. However, in a recent paper, Erlich *et al.* [17] presented a string theory as an alternative to QCD. They were successful in fitting their theory to the masses, decay rates and coupling of light mesons to within 10% accuracy! This success gave credence to a paradigm-shifting way of looking at the universe, and could potentially offer a new way to address SQN stability. A search for SQNs is an experimental way to seek answers to the SQN stability question. The results could provide valuable constraints on the development of subsequent theories.

3. REVIEW OF PREVIOUS SEARCHES

Many techniques have been used to search for SQNs. However, they are only able to find nuggets of much smaller mass than those of the current proposal and the work of Refs. [18–20]. The reason is that the abundance of nuggets must fall as the mass increases; hence the area of detectors must increase with the mass of the nuggets sought. Therefore, only a detector of planetary size would have a large enough cross-section to observe rare events due to massive nuggets. Through seismology, such a detector can be realized.

Figure 1 is a plot of the flux of SQN versus its mass. The blue color region is excluded because the SQN concentrations would exceed the observed dark matter density in our galaxy. The slope of the line marked “Self-Similar Replication Hypothesis” describes a plausible power law of flux versus mass of fragments formed in collisions of two objects [21]; the vertical location of the line is not known. The results of previous SQN searches and the expected sensitivity of planned experiments are represented by the different regions on the graph. Some of the results are summarized from a review article by Klingenberg [22].

The “HECRO-81” result was obtained in a Cherenkov counter on a balloon flight [23]. Two events consistent with charge $Z = 14$ and mass A = 110-370 amu were found. Since SQN is nearly charge neutral, its signature would be a much higher mass-to-charge ratio than ordinary nuclei where $A/Z < 3$. Another event consistent with $Z = 45$ and $A > 10^3 - 10^4$ amu was observed by Price *et al.* [24] in a stack of Lexan track detectors and nuclear emulsions. This event was initially postulated to be due to a magnetic monopole, and is labeled as “Monopole”. The AMS will continue this line of search on the ISS [11]. Its expected sensitivity is also shown.

It has been suggested that SQNs of small mass in cosmic rays may have been captured by the Earth and the Moon. Therefore, SQNs may exist at a small concentration in ordinary matter. Since an SQN is in a lower energy state than nuclei, Farhi and Jaffe [25] suggested that an ion beam may be able to overcome the Coulomb barrier, and fuse with the SQNs, releasing energy in the form of gamma rays. Such an experiment was performed by Perillo Isaac *et al.* [26] using lunar samples. The negative results have excluded the region labeled as “Lunar Soil”. Lunar samples were used because they were less disturbed by geological processes.

Experiments searching for damage tracks left by transiting SQNs in various materials [27] were performed in space on Skylab, on mountain top, at sea level, and from underground samples of mica and plastic track detectors. The region excluded by this method is labeled as “Track Damage”. Since tracks in natural samples would accumulate over geological times ($\sim 10^8$ years), the searches even in small-size samples set a very restrictive upper bound on the flux.

IceCube, primarily a neutrino detector that uses a 1-km^3 volume of Antarctic ice, will be able to detect light generated by the heated tracks of non-relativistic SQNs [16]. Its sensitivity is labeled as "IceCube".

The LISA gravitational wave antenna will also be sensitive to the gravity of a massive SQN which passes by. Assuming that there is an independent way to discriminate events due to asteroids, we estimated the sensitivity and label it as "LISA".

Additional limits on the SQN mass were set by the relative scarcity of dark massive objects detected by gravitational lensing in MACHO sky surveys [28]. MACHO eliminated objects with mass greater than $\sim 10^{27}$ g (mass of Mars) as dark matter candidates.

A seismic search for SQN passage events [18] was attempted on Earth by Anderson *et al.* Initially, one such event was found. But Selby *et al.* [29] found that the calibration of a clock in one of the seismic stations used was off. After proper corrections, the event was found to be consistent with an earthquake [19]. The region excluded by this search is labeled as "Earthquake Detection".

In Ref. [19] Herrin *et al.* used the annual seismic energy release on the Moon measured during the Apollo program to set a bound on SQN abundance. This bound is shown by the line labeled "Apollo Seismic Energy".

In a recent paper, Nakamura and Frohlich [30] reported that out of 28 shallow moonquakes observed during the Apollo program, 23 occurred when the lunar nearside was in the general direction of the Virgo constellation, leading them to postulate a possible extra-solar-system origin. If this observation is not a coincidence, then it could be a ground breaking astrophysical observation. A sensitive lunar seismometer will allow additional studies of such events.

4. POSSIBLE DETECTION SCHEMES

We discuss two possible detection schemes - one using a network of six or more seismic stations, and one using one or two seismic stations.

4.1. DETECTION WITH AN INTERNATIONAL LUNAR SEISMIC NETWORK

We have considered the advantages of the Moon over the Earth as a seismic detector for SQN [31,32]. The detection scheme envisioned was derived from the earthquake detection scheme of Anderson *et al.* [18]. This scheme requires a network of seismic stations distributed widely around the globe to detect the time of arrival of seismic waves. Since it takes six variables to specify a linear nugget trajectory (2 entry and 2 exit points; 1 entry and 1 exit times), it will require a minimum of six seismic stations. The scope of this scheme is large, and it would be best implemented as an international collaboration. Since US, Japan, China, India, Russia and Europe have shown interest in landing on the Moon, only one or two seismometers per party will be needed. Such an international lunar seismic network can also be used to study detailed interior structure of the Moon. This detection scheme is capable of identifying discrete SQN events.

The main source of the seismic signal is due to heating by the SQN passage. Therefore one would expect that only compression waves (P waves) are generated. However, asymmetry in rock or the breaking of rocks may generate shear waves (S waves). If the arrival times of both S and P waves can be identified, the difference can be used to calculate the distance of the closest approach to the path of the SQN. This would reduce the number of required seismic stations.

For an SQN transit, Eq. 1 states that the deposited seismic energy $E \propto \sigma \propto m^{2/3}$, where σ and m are the cross sectional area and mass of the SQN. Since $E \propto A_o^2$, where A_o is amplitude of the seismic signal, we obtain the result $m \propto A_o^3$. A 10-fold improvement in the resolution of A_o would result in a 1000-fold improvement in the resolution of m. The smallest detectable A_o may be limited by the background seismic noise on the Moon or the noise of the seismometer. The vertical dashed lines in Fig. 1 show that if the minimum detectable A_o decreases by 10, 100 and 1000 over Earth's value, then m as small as 1 kg, 1 g and 1 mg could be detected, respectively. The left-hand limit of this region, which is labeled as "Moonquake Detection", is not well established at this point. We will need to understand better the lunar background noise before we can predict this lower mass limit. But we expect the seismometer we are building to be able to reach this 1-mg limit if the the Moon is quiet enough.

4.2. DETECTION WITH ONE OR TWO SEISMIC STATIONS

We discuss another possible detection scheme with fewer seismic stations, which may be used to search for primordial SQNs.

Primordial SQNs are thought to have a narrow mass distribution since they were formed under similar conditions. They would be traveling with a similar speed (of galactic virial speed). It is fortuitous that the Moon has a seismic ringdown time (of the order of 10's of minutes) that is long compared to the SQN transit time (∼15 s), but about the same as the time it takes seismic waves to transit the globe. As a result, the Moon can be approximated to some extent as an energy integrator. This approximation is worse for point sources like meteoroid impacts, where the detected energy is also a function of the distance to the impact site. But for an SQN transit, the source is distributed over a global scale; the effect of distance is less significant. With this approximation one should observe many seismic events of a certain size.

We assume that the energy distribution of moonquakes is similar to that of earthquakes, i.e., $N \sim 1/E$, where N is the cumulative seismic event rate with energy larger than E. Statistics for meteoroid impacts follows a similar power law [21]. Since from Eq. 1, $E \propto \sigma \propto m^{2/3}$, the statistical uncertainty in N is $\Delta N \propto m^{-1/3}$. Assuming that stable SQNs much less massive than Earth mass could have formed shortly after the Big Bang, A hypothetical example shown by the solid circle in Fig. 1 corresponds to a SQN passage rate of $N_o = 3800$ per year. This value is much larger than $\Delta N = N^{1/2} \cong 39$ per year from Apollo measurements. Therefore, SQN could possibly be detectable as a step increase in a plot of $\log(N)$ versus $\log(E)$, as E is reduced below E_o, the seismic energy released when the SQN passes through the center of the Moon. Notice that the cumulative event rate $N(r) \propto \pi r^2$, where r is distance of closest approach from the center of the Moon to the passage path, while the total seismic energy release E is proportional to the length of the passage path in the Moon $2\sqrt{R^2 - r^2}$, where R is the radius of the Moon. One can show that as E is reduced from E_o to $E_o/2$, N would increase by $(3/4)N_o$, where N_o is total passage rate of SQNs. This scheme will require further study to incorporate the effects of damping. The line labeled "Single Seismometer Noise Limit" indicates the parameter space to be explored by this technique.

It should be noted that a majority of lunar seismic events are due to thermal moonquakes from local sources. signals from these quakes have high frequency contents (> 1 Hz). They tend to occur when the rate of temperature change is at maximum. These quakes must be filtered out before one can study global events like SQN passages. With two widely separated seismic stations, one can filter them out by removing non-coincident events. With a single seismometer, the effectiveness of various filtering schemes will have to be further studied.

SQNs from collisions of compact stars would have a wide mass distribution, and passage events from them would not be distinguishable from other seismic activities with this technique.

Since the speed of SQNs is much larger than the speed of seismic waves, one might expect the "N" shaped waveform of a sonic boom, which could be identified. But the Moon has a fractured crust of $\sim$ 40-km thickness, which scatters seismic waves and randomizes any identifiable waveforms.

5. SUMMARY

In summary, the Moon can be used as a large cross-section and low-noise detector for SQNs. If SQNs were found, the discovery would have important implications in the understanding of the universe. If not found, it would set upper limits on the mass and flux of SQNs. In either case, the result will provide valuable constraints on the development of QCD theory, string theory and cosmology.

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