Strangelets, Nuclearites, Q-balls—A Brief Overview

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Abstract

Astrophysical bounds on the properties and abundances of primordial quark nuggets and cosmic ray strangelets are reviewed. New experiments to search for cosmic ray strangelets in lunar soil and from the International Space Station are described. Analogies with baryonic and supersymmetric Q-balls are briefly mentioned, as are prospects for strangelets as ultra-high energy cosmic rays.

1. Introduction

Quark nuggets, nuclearites and strangelets are different names for lumps of a hypothetical phase of absolutely stable quark matter, so-called strange quark matter because of the admixture of slightly less than one-third strange quarks with the up and down quarks. Whether strange quark matter is absolutely stable is a question yet to be decided by experiment or astrophysical observation (see [1,2] for reviews), but if it is the case, then strange quark matter objects may exist with baryon numbers ranging from ordinary nuclei to a maximum of order $2 \times 10^{57}$ corresponding to gravitational instability of strange stars.

Truly macroscopic quark matter lumps surviving from the cosmological quark-hadron phase transition are often referred to as quark nuggets, and if they hit the Earth they are sometimes dubbed nuclearites. Strangelets are smaller lumps (baryon number $A < 10^7$) where the electron cloud neutralizing the slightly positive quark charge mainly resides outside the quark core. Strangelets are unlikely to survive from the early Universe, but may form as a result of strange star binary collisions and/or acceleration from the surface of pulsars. The nomenclature is not strictly defined, and in the following the word strangelet will be used as a general name except when discussing leftovers from the early Universe.

Q-balls are non-topological solitons suggested from various origins in the early Universe and as such have nothing to do with strange quark matter (their origin and general properties were described by Kusenko at this workshop). However for some classes of Q-balls (baryonic and supersymmetric Q-balls), the astrophysical bounds that can be derived on strangelets are easily generalized to these creatures as well and are therefore of interest in the context of this Workshop on Extreme Physics with Neutrino Telescopes.

In the following I shall discuss the (unlikely) survival of cosmological quark nuggets, the more optimistic prospects for cosmic rays strangelets from strange stars, and two new experimental efforts to search for them. Due to space limitations I will not go into details with the Q-ball analogies but refer the reader to Kusenko’s contribution and to [3].
2. Sources, sizes, and fluxes

2.1. Primordial quark nuggets

In a first order cosmological quark-hadron phase transition at \( T \approx 100 \, \text{MeV} \), supercooling may lead to concentration of baryon number inside shrinking bubbles of quark phase, that may reach nuclear matter density and form quark nuggets. The baryon number inside the horizon during the cosmic quark-hadron phase transition (an upper limit for causal formation of quark nuggets) is \( A_{\text{hor}} \approx 10^{49} \). Witten \[4\] predicted that typical nuggets would be somewhat smaller than this and argued that quark nuggets might explain the cosmological dark matter problem. Quark nuggets would decouple from the radiation bath very early in the history of the Universe and behave as cold dark matter in the context of galaxy formation. Today the nuggets would move with typical galactic halo velocities of a few hundred kilometers per second through the Milky Way.

Later studies showed that the hot environment made cosmological nuggets unstable against surface evaporation \[5\] and boiling \[6\], effectively destroying nuggets with \( A \) below \( 10^{39-46} \) depending on assumptions. Small traces of primordial nuggets with lower baryon numbers could also be left over from the destruction processes in the early Universe. Even such traces may in fact be “observed” using the astrophysical detectors discussed below. Let \( v \equiv 250 \, \text{km} \, s^{-1} \, v_{250} \) and \( \rho \equiv 10^{-24} \, \text{g} \, \text{cm}^{-3} \, \rho_{24} \) be the typical speed and mass density of nuggets in the galactic halo. The speed is given by the depth of the gravitational potential of our galaxy, whereas \( \rho_{24} \approx 1 \) corresponds to the density of dark matter. Then the number of nuggets hitting the Earth is

\[
\mathcal{F} \approx 6.0 \times 10^5 A^{-1} \rho_{24} v_{250} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}.
\]

Quark nuggets have a positive electrostatic surface potential (several MeV) of the quark phase because quarks are stronger bound than electrons, so during Big Bang nucleosynthesis (\( T \leq 1 \, \text{MeV} \)), nuggets absorb neutrons but not protons. This reduces the neutron-to-proton ratio, thereby lowering the production of \( ^4\text{He} \). The helium-production is very sensitive to the total amount of nugget-area present, and in order not to ruin the concordance with observations, one finds \[7\] that only nuggets with \( A > A_{\text{BBN}} \approx 10^{22} \Omega_{\text{nug}}^2 f_n^3 \) are allowed during nucleosynthesis. Here \( \Omega_{\text{nug}} \) is the present-day nugget contribution to the cosmic density in units of the critical density, and \( f_n \leq 1 \) is the penetrability of the nugget surface.

In spite of carrying baryon number, primordial quark nuggets do not contribute to the usual nucleosynthesis limit on \( \Omega_{\text{baryon}} \). The baryon number is “hidden” in quark nuggets long before Big Bang nucleosynthesis begins, and the nuggets only influence nucleosynthesis via the neutron absorption just described. The same is true for baryon number carrying Q-balls.

While primordial quark nuggets remain a possibility within the tight restrictions mentioned, the main problem with this scenario is the need for a first order quark-hadron phase transition which is currently not favored in lattice QCD studies at zero chemical potential.

2.2. Strangelets from compact stars

If strange quark matter is absolutely stable all compact stars are likely to be strange stars (see the following Section), and therefore the galactic coalescence
rate estimated for neutron star binaries that inspiral due to loss of orbital energy by emission of gravitational radiation, believed to be of order one collision in our Galaxy every 10,000 years [8], is really the rate of strange star collisions. Each event involves a phase of tidal disruption as the stars approach each other before the final collision. During this stage small fractions of the total mass may be released from the binary system in the form of strange quark matter. No realistic simulation of collisions involving two strange stars has been performed. Simulations of binary neutron star collisions, depending on orbital and other parameters, lead to the release of anywhere from $10^{-5} - 10^{-2} M_\odot$ ($M_\odot$ is the solar mass), corresponding to a total mass release in the Galaxy of $10^{-10} - 10^{-6} M_\odot$ per year. The equation of state for strange quark matter is stiff, so strange star collisions probably lie in the low end of the mass release range. A conservative estimate of the galactic production rate of strangelets is $10^{-10} M_\odot \text{yr}^{-1}$.

Quark matter lumps released by tidal forces are macroscopic [9], but subsequent collisions lead to fragmentation, and if the collision energy compensates for the surface energy involved in making smaller strangelets, a significant fraction of the mass released from binary strange star collisions might end up in the form of strangelets with $A \approx 10^2 - 10^4$ [9].

Incidentally, a similar range of strangelet masses is expected if the surface of strange stars consists of a layer with strangelets embedded in an electron gas rather than pure quark matter all the way to the surface [10].

Assuming that strangelets from binary collisions are accelerated and propagate like cosmic ray nuclei in our Galaxy, taking proper account of their small charge-to-mass ratio, as well as energy loss, spallation, escape from the Galaxy, etc., it was shown in [11] that the expected flux for color-flavor locked strangelets (charge $Z = 0.3A^{2/3}$ [12]) near Earth is

$$\mathcal{F} \approx 10^{-6} A^{-1.47} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}. \tag{2}$$

Most of these nuggets have rigidities (momentum divided by charge) of a few GV, but with a powerlaw tail at higher rigidity. Apart from the slightly different $A$-dependence this is some 12 orders of magnitude smaller than the flux estimate for dark matter nuggets, which is not unreasonable because the total strangelet mass originating from binary collisions over the age of the Galaxy is around $1 M_\odot$, compared to $10^{12} M_\odot$ of dark matter.

Another possible cosmic ray strangelet source is extraction from the surface of pulsars and acceleration in the strong pulsar electric fields. A measurable flux is predicted in [13] within the scenario where the strange star surface consists of strangelets embedded in an electron gas [10]. Formation and acceleration in supernova explosions has also been suggested [14].

3. Detection of cosmic ray strangelets (or why either all or no compact stars are strange)

De Rújula and Glashow [15] argued that quark nuggets hitting the Earth would show up as unusual meteor-events, earth-quakes, etched tracks in old mica, in meteorites and in cosmic-ray detectors. A negative search for tracks in ancient mica corresponded to a lower nugget flux limit of $8 \times 10^{-19} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}$ for nuggets with $A > 1.4 \times 10^{14}$ (smaller nuggets being trapped in layers above the mica samples studied).
Later investigations have improved these flux limits by a few orders of magnitude and extended them to lower $A$, though with higher flux limits (see other contributions to these proceedings for examples). This has excluded quark nuggets with $3 \times 10^5 < A < 5 \times 10^{25}$ as dark matter, but a low flux from the Big Bang or from collision of strange stars cannot be ruled out.

Neutron stars and their stellar progenitors may be thought of as alternative large surface area, long integration time detectors leading to much tighter flux limits [16], see also [17]. The presence of a single quark nugget in the interior of a neutron star is sufficient to initiate a transformation of the star into a strange star [4,18]. The time-scale for the transformation is short, between seconds and minutes, so observed pulsars would have been converted long ago if their stellar progenitors ever captured a quark nugget, or if neutron stars absorbed one after formation.

To convert a neutron star into strange matter a quark nugget should not only hit a supernova progenitor but also be caught in the core [16]. A main sequence star is capable of capturing non-relativistic quark nuggets with baryon numbers below $A_{\text{STOP}} \approx 10^{31}$, which are braked by inertia, i.e. they are slowed down by electrostatic scatterings after plowing through a column of mass similar to their own, and settle in the stellar core. Relativistic nuggets may be destroyed after collisions with nuclei in the star, but even a tiny fraction of a nugget surviving such an event and settling in the star is sufficient to convert the neutron star to a strange star, so the non-relativistic flux limits may still apply.

For nuggets with $A < A_{\text{STOP}}$ the sensitivity of main sequence stars as detectors is given by the limit of one nugget hitting the surface of the supernova progenitor in its main sequence lifetime. Converted into a flux, $F$, of nuggets hitting the Earth it corresponds to

$$F \approx 4 \times 10^{-42} \upsilon_{250}^2 \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.$$  \hspace{1cm} (3)

This is a factor of $10^{20} - 10^{40}$ more sensitive than direct detection experiments!

If it is possible to prove that some neutron stars are indeed neutron stars rather than strange stars, the sensitivity of the astrophysical detectors rules out quark nuggets as dark matter for $A < 10^{34-38}$. And it questions the whole idea of stable strange quark matter, since it is impossible to avoid polluting the interstellar medium with nuggets from strange star collisions or supernova explosions at fluxes many orders of magnitude above the limit measurable in this way.

If on the other hand strange quark matter is stable, then all neutron stars are likely to be strange stars, again because some pollution can not be avoided.

4. Experiments underway

Several experiments have searched for strangelets in cosmic rays. While some interesting events have been found that are consistent with the predictions for strangelets, none of these have been claimed as real discoveries. Interpreted as flux limits rather than detections these results are consistent with the flux estimates given above. For discussions see [19,20].

If the interesting events were actual measurements, two experiments that are currently underway will reach sensitivities that would provide real statistics.

**AMS-02:** The Alpha Magnetic Spectrometer (AMS) is a space-based particle physics experiment involving several hundred physicists from more than 50 institutions in 16 countries, led by Nobel laureate Samuel Ting of MIT. A prototype (AMS-01) flew in June 1998 aboard the Space Shuttle Discovery [21], and AMS-
AMS-02 is currently scheduled to fly to the International Space Station (ISS) in 2009. Once on the ISS AMS-02 will remain active for at least three years. AMS-02 will provide data with unprecedented accuracy on cosmic ray electrons, positrons, protons, nuclei, anti-nuclei and gammas in the GV-TV range and probe issues such as antimatter, dark matter, cosmic ray formation and propagation. In addition it will be uniquely suited to discover strangelets characterized by extreme rigidities for a given velocity compared to nuclei \[19,20\]. AMS-02 will have excellent charge resolution up to \(Z \approx 30\), and should be able to probe a large mass range for strangelets. A reanalysis of data from the AMS-01 mission has given hints of some interesting events, such as one with \(Z = 2, A = 16\) \[22\] and another with \(Z = 8\), but with the larger AMS-02 detector running for 3 years or more, real statistics is achievable.

**LSSS:** The Lunar Soil Strangelet Search (LSSS) is a search for \(Z = 8\) strangelets using the tandem accelerator at the Wright Nuclear Structure Laboratory at Yale \[20,23\]. The experiment involves a dozen people from Yale, MIT, and Århus, led by Jack Sandweiss of Yale. The experiment which is about to begin its real data taking phase, studies a sample of 15 grams of lunar soil from Apollo 11. It will reach a sensitivity of \(10^{-17}\) over a wide mass range, sufficient to provide detection according to Eq. (2) if strangelets have been trapped in the lunar surface layer, which has an effective cosmic ray exposure time of around 500 million years and an effective mixing depth due to micrometeorite impacts of only around one meter, in contrast to the deep geological and oceanic mixing on Earth. Combined with the fact that the Moon has no shielding magnetic field, this results in an expected strangelet concentration in lunar soil which is at least four orders of magnitude larger than the corresponding concentration on Earth.

### 5. Strangelets as ultra-high energy cosmic rays

The existence of cosmic rays with energies well beyond \(10^{19}\text{eV}\), with measured energies as high as \(3 \times 10^{20}\text{eV}\), is one of the most interesting puzzles in cosmic ray physics \[24\]. It is almost impossible to find a mechanism to accelerate cosmic rays to these energies. Furthermore ultra-high energy cosmic rays lose energy in interactions with cosmic microwave background photons, and only cosmic rays from nearby (unidentified) sources would be able to reach us with the energies measured. Strangelets circumvent both problems \[25\], and therefore provide a possible mechanism for cosmic rays beyond the socalled GZK-cutoff.

**Acceleration:** All astrophysical “accelerators” involve electromagnetic fields, and the maximal energy of a charged particle is proportional to its charge. The charge of massive strangelets has no upper bound in contrast to nuclei, so highly charged strangelets are capable of reaching energies much higher than those of cosmic ray protons or nuclei using the same “accelerator” \[25\].

**The GZK-cutoff** is a consequence of ultrarelativistic cosmic rays hitting a 2.7K background photon with a Lorentz-factor \(\gamma\) large enough to boost the \(7 \times 10^{-4}\text{eV}\) photon to energies beyond the threshold of energy loss processes, such as photon production or photo-disintegration. The threshold for such a process has a fixed energy, \(E_{\text{Thr}}\), in the frame of the cosmic ray, e.g., \(E_{\text{Thr}} \approx 10\text{MeV}\) for photo-disintegration of a nucleus or a strangelet, corresponding to \(\gamma_{\text{Thr}} = E_{\text{Thr}}/E_{2.7K} \approx 10^{10}\), or a cosmic ray total energy

\[
E_{\text{Total}} = \gamma_{\text{Thr}} Am_0c^2 \approx 10^{19} A\text{ eV}.
\]
Since strangelets can have much higher $A$-values than nuclei, this pushes the GZK-cutoff energy well beyond the current observational limits for ultra-high energy cosmic rays [25,26].

6. Conclusion

Lumps of strange quark matter (quark nuggets, nuclearites, strangelets) may form in a first-order cosmological quark-hadron phase transition (unlikely), or in processes related to compact stars (more likely). Flux estimates for lumps reaching our neighborhood of the Galaxy as cosmic rays are in a range that makes it realistic to either detect them in upcoming experiments like AMS-02 or LSSS, or place severe limits on the existence of stable strange quark matter. A similar line of reasoning applies to Q-balls.

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