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Review of Speculative "Disaster Scenarios" at RHIC

W. Busza[a], R.L. Jaffe[a], J. Sandweiss[b] and F. Wilczek[c]

a) Laboratory for Nuclear Science and Department of Physics,
Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

b) Yale University, New Haven, Connecticut 06520

c) School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA

REPORT

Fears have been expressed that heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC), which Brookhaven National Laboratory (BNL) is now commissioning, might initiate a catastrophic process with profound implications for health and safety. Dr. John Marburger, Director of BNL asked our committee to review the issues and "to reduce to a single comprehensive report the arguments that address the safety of each of the speculative 'disaster scenarios'."

Concerns have been raised in three general categories:

A. Formation of a black hole or gravitational singularity that accretes ordinary matter.

B. Initiation of a transition to a lower vacuum state.

C. Formation of a stable "strangelet" that accretes ordinary matter.

We have reviewed earlier scientific literature as well as recent correspondence about these questions, discussed the scientific issues among ourselves and with knowledgable colleagues, undertaken additional calculations where necessary, and evaluated the risk posed by these processes. Our conclusion is that the candidate mechanisms for catastrophe scenarios at RHIC are firmly excluded by existing empirical evidence, compelling theoretical arguments, or both. Accordingly, we see no reason to delay the commissioning of RHIC on their account.

Issues A. and B. are generic concerns that have been raised, and ought to be considered, each time a new facility opens up a new high energy frontier. The fact that RHIC accelerates heavy ions rather than individual hadrons or leptons makes for somewhat different circumstances. Nevertheless there are simple, convincing arguments that neither poses any significant threat, and accordingly we can summarize our review of these issues quite briefly.

First let us clear up a possible misunderstanding, which seems to underlie some of the expressed anxiety. It has to do with the difference between total energy and energy density. The total center of mass energy ($E_{\rm CM}$) of gold-gold collisions at RHIC will exceed that of any existing accelerator. But $E_{\rm CM}$ is surely not the right measure of the capacity of a collision to trigger exotic new phenomena. If it were, a batter striking a major league fastball would be performing a far more dangerous experiment than any contemplated at a high energy accelerator. To be effective in triggering exotic new phenomena, energy must be concentrated in a very small volume.

A better measure of effectiveness is the center of mass energy of the elementary constituents within the colliding objects. In the case of nuclei, the elementary constituents are mainly quarks and gluons, with small admixtures of virtual photons, electrons, and other elementary particles. Using the Fermilab Tevatron and the LEP collider at the European

Center for Nuclear Research (CERN), collisions of these elementary particles with energies exceeding what will occur at RHIC have already been extensively studied.

Black Holes and Gravitational Singularities

Exotic gravitational effects may occur at immense densities. Conservative dimensionless measures of the strength of gravity give 10^{-22} for classical effects and 10^{-34} for quantum effects in the RHIC environment, in units where 1 represents gravitational effects as strong as the nuclear force. The arguments leading to these estimates are presented in Appendix A.

We also note that collisions at RHIC are expected to be *less* effective at raising the density of nuclear matter than at lower energies where the "stopping power" is greater, while as we noted before, existing accelerators have already probed larger effective energies. In no case has any phenomenon suggestive of gravitational clumping, let alone gravitational collapse or the production of a singularity, been observed.

Vacuum Instability

Physicists have grown quite accustomed to the idea that empty space — what we ordinarily call 'vacuum' — is in reality a highly structured medium, that can exist in various states or phases, roughly analogous to the liquid or solid phases of water. This idea plays an important role in the Standard Model. Although certainly nothing in our existing knowledge of the laws of Nature demands it, several physicists have speculated on the possibility that our contemporary 'vacuum' is only metastable, and that a sufficiently violent disturbance might trigger its decay into something quite different. A transition of this kind would propagate outward from its source throughout the universe at the speed of light, and would be catastrophic.

We know that our world is already in the correct (stable) vacuum for QCD. Our knowledge of fundamental interactions at higher energies, and in particular of the interactions responsible for electroweak symmetry breaking, is much less complete. While theory strongly suggests that any possibility for triggering vacuum instability requires substantially larger energy densities than RHIC will provide, it is difficult to give a compelling, unequivocal bound based on theoretical considerations alone.

Fortunately we do not have to rely solely on theory. Cosmic rays have been colliding throughout the history of the universe, and if such a transition were possible it would have been triggered long ago. In 1983 Hut and Rees [1] calculated the total number of collisions of various types that have occurred in our past light-cone — whose effects we would have experienced. They used data on cosmic ray fluxes which have subsequently been confirmed and updated. We have re-examined their estimates and believe they remain substantially correct. A summary and analysis of cosmic ray data is presented in Appendix B.

Not knowing which would be more effective at triggering a transition, Hut and Rees looked both at proton-proton collisions and collisions of heavy nuclei. Cosmic ray data on proton fluxes go up to energies of order 10^{20} eV [3]. They conclude that proton-proton collisions with a center of mass energy exceeding 10^{8} TeV have occurred so frequently in our past light cone that even such astonishingly high energy collisions can be considered safe. For heavy ions, Hut and Rees derived an estimate of the number of cosmic ray collisions in our past light cone,

$$N \sim 10^{47} \left(\frac{f(\mathrm{A})}{f(\mathrm{Fe})}\right)^{2} \left(\frac{56}{A}\right)^{2.7} \left(\frac{100\ \mathrm{GeV}}{E}\right)^{3.4}, \tag{1}$$

where $f(A)$ is the fractional abundance of a nucleus with atomic mass A in very high energy cosmic rays, and E is the energy per nucleon in the center of mass. We have presented Hut's result so that the coefficient 10^{47} equals the number of iron-iron collisions at a center of mass energy exceeding 100 GeV/nucleon. The abundance of iron in cosmic rays has now been measured up to energies of order 2 TeV/nucleon [6], so this estimate is more reliable than it was at the time of Hut's work. While we do not have direct measurements of the fractional abundance of elements heavier than iron in cosmic rays of energy of order 100 GeV/nucleon, we do have good measurements at lower energies, where they track quite well with the abundances measured on earth and in the solar system. For gold at lower energies $f(\mathrm{Au})/f(\mathrm{Fe}) \approx 5 \times 10^{-6}$. Even if this estimate were off by many orders of magnitude, the number of 100 GeV/nucleon gold-gold collisions in our past light cone is far greater than the total number anticipated at RHIC. We can rest assured that RHIC will not drive a transition from our vacuum to another.

Since the situation has not changed significantly since the work of Hut and Rees, we do not treat this scenario in more detail here. The interested reader should consult Hut's 1984 paper for further details [1].

Strange Matter

Theorists have speculated that a form of quark matter, known as "strange matter" because it contains many strange quarks, might be more stable than ordinary nuclei. Hypothetical small lumps of strange matter, having atomic masses comparable to ordinary nuclei have been dubbed "strangelets". Strange matter may exist in the cores of neutron stars, where it is stabilized by intense pressure. A primer on the properties of strange matter and the background for the statements made here and below is provided in Appendix C.

For strange matter to pose a hazard at a heavy ion collider, four conditions would have to be met:

1. Strange matter would have to be absolutely stable in bulk at zero external pressure. If strange matter is not stable, it will not form spontaneously.

2. Strangelets would have to be at least metastable for very small atomic mass. For only very small strangelets can conceivably be created in heavy ion collisions.

3. It must be possible to produce such a small, metastable strangelet in a heavy ion collision.

4. The stable composition of a strangelet must be *negatively* charged. Positively charged strangelets pose no threat whatsoever.

Each of these conditions is considered unlikely by experts in the field, for the following reasons:

1. At present, despite vigorous searches, there is no evidence whatsoever for stable strange matter anywhere in the Universe.

2. On rather general grounds, theory suggests that strange matter becomes unstable in small lumps due to surface effects. Strangelets small enough to be produced in heavy ion collisions are not expected to be stable enough to be dangerous.

3. Theory suggests that heavy ion collisions (and hadron-hadron collisions in general) are not a good place to produce strangelets. Furthermore, it suggests that the production probability is lower at RHIC than at lower energy heavy ion facilities like the AGS and CERN. Models and data from lower energy heavy ion colliders indicate that the probability of producing a strangelet decreases very rapidly with the strangelet's atomic mass.

4. It is overwhelmingly likely that the most stable configuration of strange matter has positive electric charge.

To our knowledge, possible catastrophic consequences of strangelet formation have not been studied in detail before. Although the underlying theory (quantum chromodynamics, or QCD) is fully established, our ability to use it to predict complex phenomena is imperfect. A reasonable, conservative attitude is that theoretical arguments based on QCD can be trusted when they suggest a safety margin of many orders of magnitude. The hypothetical chain of events that might lead to a catastrophe at RHIC requires several independent, robust theoretical arguments to be wrong simultaneously. Thus, theoretical considerations alone would allow us to exclude any safety problem at RHIC confidently.

However, one need not assess the risk based on theoretical considerations alone. We have considered the implications of natural “experiments” elsewhere in the Universe, where cosmic ray induced heavy ion collisions have been occurring for a long time. Recent satellite based experiments have given us very good information about the abundance of heavy elements in cosmic rays, making it possible to obtain a reliable estimate of the rate of such collisions.

The analysis of cosmic ray collisions depends on the assumed rapidity distribution of strangelet production. If strangelets are produced in the fragmentation region, then cosmic ray collisions with stationary nuclei on the surface of the Moon provide very strong limits on dangerous strangelet production in heavy ion collisions. Elementary theoretical considerations suggest that the most dangerous type of collision is that at considerably lower energy than RHIC. They also suggest that heavy nuclei like iron are reasonable stand-ins for ultraheavy nuclei like gold. We know with certainty that there are approximately 2×10^{13} collisions/second of iron nuclei with energy in excess of 10 GeV/nucleon with iron on the surface of the Moon. Over the 5 billion year life of the Moon approximately 10^{28} such collisions have occurred. The *total* number of gold-gold collisions which will occur in 10 years of full luminosity running at RHIC is approximately 2×10^{11}, almost eighteen orders of magnitude fewer than the total number which have occurred on the Moon alone, and far fewer than occur in a single day on the surface of the Moon. Production of one dangerous strangelet at RHIC would lead us to expect production of order 10^{17} on the Moon over its lifetime.

It requires a malevolently *ad hoc* model to wipe out the safety factor of 10^{17}. The authors of Ref. [2] construct just such a model in pursuit of a “worst case” limit. They assume that strangelets are produced only in gold-gold collisions, only at or above RHIC energies, and only at rest in the center of mass. Under these assumptions lunar persistence provides no useful limit. Instead it is necessary to consider ion-ion collisions in interstellar space, where strangelets produced at rest with respect to the galaxy would be swept up into stars [2]. Dangerous strangelets would trigger the conversion of their host stars into strange matter, an event that would resemble a supernova. The present rate of supernovae — a few per millennium per galaxy — rules out even this worst case scenario.

We have included a set of appendices where we discuss some of the technical issues raised in our work. In Appendix A we discuss the parameters that govern possible gravitational effects in collisions. In Appendix B we review and summarize the most recent data on nuclei in cosmic rays. We also summarize the calculations that lead to quoted event rates on the surface of the moon and in interstellar space. In Appendix C we discuss the strangelet scenario. First we give a brief introduction to the physics of strangelets and strange matter.

Then we present what we believe to be the only plausible hazard scenario, and assess the likelihood of each ingredient in the sequence. Finally we demonstrate that cosmic ray collisions provide ample reassurance that we are safe from a strangelet initiated catastrophe at RHIC.

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APPENDIX A: STRENGTH OF GRAVITATIONAL EFFECTS

Two possible sources of novel gravitational effects might in principle be activated in collisions at RHIC. The first type is connected with classical gravity, the second type with quantum gravity.

To estimate the quantitative significance of classical gravity, an appropriate parameter is

$$k_{\rm cl} \ \equiv \ \frac{2GM}{Rc^2} \tag{2}$$

for a spherical concentration of mass M inside a region of linear dimension R, where G is Newton's constant and c is the speed of light. It is when $k_{\rm cl} \to 1$ that the escape velocity from the surface at R, calculated in Newtonian gravity, becomes equal to the speed of light. The same parameter, $2GM/c^2$, appears in the general relativistic line element

$$ds^2 \ = \ c^2dt^2(1-\frac{2GM}{rc^2}) - \frac{dr^2}{1-\frac{2GM}{rc^2}} - r^2d^2\Omega \tag{3}$$

outside a spherical concentration of mass M. In this language, it is when $k_{\rm cl} = 1$ that a horizon appears at R, and the body is described as a black hole.

Now for RHIC we obtain a very conservative upper bound on $k_{\rm cl}$ by supposing that all the initial energy of the collision becomes concentrated in a region characterized by the Lorentz-contracted nuclei. We are being extremely conservative by choosing the largest possible mass and the smallest possible distance scale defined by the collision, and also by ignoring the effect of the electric charge and the momentum of the constituents, which will resist any tendency to gravitational collapse. Thus our result will provide a bound upon, not an estimate of, the parameters that might be required to have a realistic shot at producing black holes.

With $M = 10^4$ Gev$/c^2$ and $R = 10^{-2} \times 10^{-13}$ cm, we arrive at $k_{\rm cl} = 10^{-22}$. The outlandishly small value of this over-generous estimate makes it pointless to attempt refinements.

To estimate the quantitative significance of quantum gravity, we consider the probability to emit the quantum of gravity, a graviton. It is governed by

$$k_{\rm qu} \ \equiv \ \frac{GE^2}{\hbar c^5} \ , \tag{4}$$

where $\hbar$ is Planck's constant and E is the total center-of-mass energy of collision. For collisions between elementary particles at RHIC, we should put $E \approx 200$ Gev. This yields $k_{\rm qu} \approx 10^{-34}$. Once again, the tiny value of $k_{\rm qu}$ makes it pointless to attempt refinements of this rough estimate. Of course higher-energy accelerators than RHIC achieve larger values of $k_{\rm qu}$, but for the foreseeable future values even remotely approaching unity are a pipe dream.

APPENDIX B: HEAVY NUCLEI IN COSMIC RAYS

Cosmic ray processes accurately reproduce the conditions planned for RHIC. They are known to include heavy nuclei and to reach extremely high energies. Hut and Rees [1] pioneered the use of cosmic ray data in their study of decay of a false vacuum. Dar, De Rujula and Heinz [2] have recently used similar arguments to study strangelet production in heavy ion collisions. Here we summarize data on heavy nuclei (iron and beyond) in cosmic rays and carry out some simple estimates of particular processes which will figure in our discussion of strange matter. In some instances we use observations directly; elsewhere reasonable extrapolation allows us to model behavior where no empirical data are available.

We are interested in cosmic ray collisions which simulate RHIC and lower energy heavy ion facilities like the AGS. Equivalent stationary target energies range from 10 GeV/nucleon at the AGS to 20 TeV/nucleon corresponding to the center of mass energy of 100 GeV/nucleon at RHIC. The flux of cosmic rays has been measured accurately up to total energies of order 10^{20} eV [3]. Many measurements of the abundance of ultraheavy nuclei in cosmic rays at GeV energies are summarized in Ref. [4]. Combining all nuclei with $A > 70$ into our definition of "gold", we choose an abundance of $\sim 10^{-5}$ relative to iron.[1] These measurements are dominated by energies near the lower energy cutoff of 1.5 GeV/nucleon. More extensive measurements have been made of the flux of nuclei in the iron-nickel group and lighter. Data on iron are available up to energies of order 2 TeV [6]. However, we know of no direct measurements of the flux of nuclei heavier than the iron-nickel group at energies above 10 GeV.

Data on iron are available over almost the entire energy range we need. For nuclei heavier than iron, data are available close to AGS energies, but not in the 100 GeV–20 TeV domain. For ultra heavy nuclei at very high energies, we extrapolate existing data to higher energies using standard scaling laws, which agree excellently with available data.

- At energies of interest to us, the flux of every species which has been measured shows a simple power law spectrum $dF/dE \propto E^{-\gamma}$ with $\gamma \approx 2.5 - 2.7$. Swordy et al [6] found this behavior for oxygen, magnesium, silicon as well as hydrogen, helium and iron.[2]

- At all energies where they have been measured, the relative abundance of nuclear species in cosmic rays reflects their abundance in our solar system. [See, for example,

[1]Estimates range from 10^{-5} [4] to as high as 10^{-4} [5]. To be conservative, we choose a value on the low side.

[2]At energies above 10^{15} eV the power γ changes abruptly. This occurs above the energies of interest to us.

Figure 6 in Ref. [4].] Exceptions to this rule seem to be less than an order of magnitude. If anything, heavy nuclei are expected to be relatively more abundant in high energy cosmic rays.

In light of these facts we adopt the standard idealization that the A (baryon number or atomic mass) and E (energy per nucleon) dependence of the flux of primary cosmic rays *factors* at GeV–TeV energies:

$$\frac{dF}{dE} = \Gamma(A, E_0)(E_0/E)^{\gamma}, \tag{5}$$

where E_0 is some reference energy. The units of dF/dE are $\{\text{steradians,sec,m}^2, \text{ GeV}\}^{-1}$. To be conservative we will usually take $\gamma = 2.7$. The total flux at energies above some energy E is given by

$$F(A, E) = \int_E^{\infty} dE' \frac{dF}{dE'} = \frac{E}{\gamma - 1}\frac{dF}{dE} = \frac{E}{\gamma - 1}\Gamma(A, E) \tag{6}$$

We are interested in cosmic ray initiated heavy ion collisions which have occurred where we can observe their consequences. Two particular examples will figure in our subsequent considerations: a) Cosmic ray collisions with nuclei on the surface of planetoids that lack an atmosphere, like the Moon; and b) Cosmic ray collisions in interstellar space resulting in strangelet production at rest with respect to the galaxy.

Cosmic ray impacts on the moon

First we consider cosmic rays impinging on the surface of a planetoid similar to the Moon. The number of impacts per second with energy greater than E on the surface of the planet is given by $8\pi^2 R^2 F(A, E)$, where we measure R in units of R_{moon},

$$\frac{dN(A, E)}{dt} = 2 \times 10^{14} \frac{\Gamma(A, E)}{\gamma - 1} E \left(\frac{R}{R_{\text{moon}}}\right)^2 \tag{7}$$

For convenience, we use iron with $E = 10$ GeV as our reference. According to Swordy et al. [6]

$$\frac{dF}{dE}(\text{Fe}, 10 \text{ GeV}) \equiv \Gamma(\text{Fe}, 10 \text{ GeV}) \approx 4 \times 10^{-3} \{\text{ster sec m}^2 \text{ GeV}\}^{-1}. \tag{8}$$

From eqs. (6) and (7) we find

$$\frac{dN(A, E)}{dt} \approx 5 \times 10^{12} \frac{\Gamma(A, 10 \text{ GeV})}{\Gamma(\text{Fe}, 10 \text{ GeV})} \left(\frac{10 \text{ GeV}}{E}\right)^{1.7} \left(\frac{R}{R_{\text{moon}}}\right)^2 \tag{9}$$

This large instantaneous rate makes it possible to obtain useful limits from cosmic ray collisions with nuclei on the lunar surface.

Cosmic ray collisions in space

Following Ref. [2], we consider collisions of cosmic rays in which the center of mass velocity is less than $v_{\rm cm} = 0.1$ in units of c. With this $v_{\rm cm}$ strangelets produced at rest in the center of mass will have high probability of slowing down without undergoing nuclear collisions which would destroy them. The flux given in eq. (5) is associated with a density, $\frac{dn}{dE} = \frac{4\pi}{c}\frac{dF}{dE}$. The rate per unit volume for collisions of cosmic rays with energy per nucleon greater than E in which all components of the center of mass velocity are less than $v_{\rm cm}$ is given by

$$R(E) = 2c\sigma f_\theta \int_E^\infty dE_1 \int_{(1-v_{\rm cm})E_1}^{(1+v_{\rm cm})E_1} dE_2 \frac{dn}{dE_1}\frac{dn}{dE_2}, \tag{10}$$

where $\sigma = 0.18A^{2/3}$ barns is the geometric cross section, and $f_\theta = 4v_{\rm cm}^2$ is a geometric factor measuring the fraction of collisions in which the transverse velocity is less than $v_{\rm cm}$. Substituting from eq. (5), and normalizing to iron-iron collisions at $E = 10$ GeV/nucleon, we obtain

$$R(E, A) = 10^{-45}\left(\frac{10\ \text{GeV}}{E}\right)^{3.4}\left(\frac{\Gamma(A)}{\Gamma(\text{Fe})}\right)^2\left(\frac{A}{56}\right)^{2/3} \text{cm}^{-3}\text{sec}^{-1} \tag{11}$$

Although this rate appears very small, these collisions have been occurring over very large volumes for billions of years.

APPENDIX C: STRANGELETS AND STRANGE MATTER

The scientific issues surrounding the possible creation of a negatively charged, stable strangelet are complicated. Also, it appears that if such an object did exist and could be produced at RHIC, it would indeed be extremely dangerous. Therefore we wish to give this scenario careful consideration, even though we are certain that it will not occur.

This appendix is organized as follows. First we give a pedagogical introduction to the properties of strangelets and strange matter. Second we discuss the mechanisms that have been proposed for producing a strangelet in heavy ion collisions. We examine these mechanisms and conclude that strangelet production at RHIC is extremely unlikely. Next we discuss what would occur if a stable, negatively charged strangelet could be produced at RHIC. In light of the consequences we shall refer to such an object as a “dangerous” strangelet. We then turn to the cosmic ray data. Making physically reasonable assumptions about strangelet production mechanisms, we can decisively rule out any problems at RHIC. If we ignore our physics guidance and adopt the “worst case analysis” advocated in Ref. [2] we find that their arguments still decisively rule out dangerous strangelet production at RHIC.

A Primer on Strangelets and Strange Matter

Strange matter is the name given to quark matter at zero temperature in equilibrium with the weak interactions. At and below ordinary nuclear densities, and at low temperatures, quarks are confined to the interiors of the hadrons they compose.

It is thought that any collection of nucleons or nuclei brought to high enough temperature or pressure[3], will make a transition to a state where the quarks are no longer confined into individual hadrons. At high temperature the material is thought to become what is called a quark-gluon plasma. The defining property of this state is that it can be accurately described as a gas of nearly freely moving quarks and gluons. One main goal of RHIC is to provide experimental evidence for the existence of this state, and to study its properties. At high pressure and low temperature the material is expected to exhibit quite different physical properties. In this regime, it is called quark matter.

Quarks obey the Pauli exclusion principle — no two quarks can occupy the same state. As quark matter is compressed, the exclusion principle forces quarks into higher and higher energy states.

Given enough time (see below), the weak interactions will come into play, to reduce this energy. Ordinary matter is made of up (u) and down (d) quarks, which are the lightest species (or "flavors") of quarks. The strange quark (s) is somewhat heavier. Under ordinary conditions when an s quark is created, it decays into u and d quarks by means of the weak interactions. In quark matter the opposite can occur. u and d quarks, forced to occupy very energetic states, will convert into s quarks. Examples of weak interaction processes that can accomplish this are strangeness changing weak scattering, $u + d \to s + u$, and weak semi-leptonic decay, $u \to s + e + \bar{\nu}_e$. These reactions occur rapidly on a natural time scale $\sim 10^{-14}$ sec. When the weak interactions finish optimizing the flavor composition of quark matter, there will be a finite density of strange quarks — hence the name "strange matter".

The most likely location for the formation of strange matter is deep within neutron stars, where the mammoth pressures generated by the overlayers of neutrons may be sufficient to drive the core into a quark matter state. When first formed, the quark matter at the core of a neutron star would be non-strange, since it was formed from neutrons. Once formed, however, the quark matter core would rapidly equilibrate into strange matter, if such matter has lower free energy at high external pressure.

Initially, the non-strange quark matter core and the overlaying layer of neutrons were in equilibrium. Since the strange matter core has lower free energy than the overlaying

[3]For theoretical purposes a better variable is chemical potential, instead of pressure. But either can be used.

neutrons, its formation disrupts the equilibrium. Neutrons at the interface are absorbed into the strange matter core, which grows, eating its way outward toward the surface.

There are two possibilities. If strange matter has lower internal energy than the nuclear matter even at zero external pressure, the strange matter will eat its way out essentially to the surface of the star. On the other hand, if below some non-zero pressure, strange matter no longer has lower energy than nuclear matter, the conversion will stop. Even in the second case a significant fraction of the star could be converted to strange matter. The “burning” of a neutron star as it converts to strange matter has been studied in detail [7,8]. It is not thought to disrupt the star explosively, because the free energy difference between strange matter and nuclear matter is small compared to the gravitational binding energy.

In 1984, E. Witten suggested that perhaps strange matter has lower mass than nuclear matter even at zero external pressure [9]. Remarkably, the stability of ordinary nuclei does not rule this out. A small lump of strange matter, a “strangelet”, could conceivably have lower energy than a nucleus with the same number of quarks. Despite the possible energy gain, the nucleus could not readily decay into the strangelet, because it would require many weak interactions to occur simultaneously, in order to create all the requisite strange quarks at the same time. Indeed, we know that changing one quark (or a few) in a nucleus into an s quark(s) — making a so-called hypernucleus — will raise rather than lower the energy.

Witten’s paper sparked a great deal of interest in the physics and astrophysics of strange quark matter. Astrophysicists have examined neutron stars both theoretically and observationally, looking for signs of quark matter. Much interest centers around the fact that a strange matter star could be considerably smaller than a neutron star, since it is bound principally by the strong interactions, not gravity. A small quark star could have a shorter rotation period than a neutron star and be seen as a sub-millisecond pulsar. At this time there is no evidence for such objects and no other astrophysical evidence for stable strange matter although astrophysicists continue to search and speculate [10].

Strange matter is governed by QCD. At extremely high densities the forces between quarks become weaker (a manifestation of asymptotic freedom) and one can perform quantitatively reliable calculations with known techniques. The density of strange matter at zero external pressure is not high enough to justify the use of these techniques. Nevertheless the success of the ordinary quark model of hadrons leads us to anticipate that simple models which include both confinement and perturbative QCD provide us good qualitative guidance as to the properties of strange matter [11].

Such rough calculations cannot answer the delicate question of whether or not strange matter is bound at zero external pressure reliably. Stability seems unlikely, but not impossible.

Some important qualitative aspects of strange matter dynamics that appear extremely robust are as follows:

- Binding Systematics

  The overall energy scale of strange matter is determined by the confinement scale in QCD which can be parameterized by the "bag constant". Gluon exchange interactions between quarks provide important corrections. Calculations indicate that gluon interactions in quark matter are, on average, repulsive, and tend to destabilize it. To obtain stable strange matter it is necessary to reduce the value of the bag constant below traditionally favored values [10,11]. This is the reason we describe stability at zero external pressure as "unlikely".

- Charge and flavor composition [11]

  If strange matter contained equal numbers of u, d and s quarks it would be electrically neutral. Since s quarks are heavier than u and d quarks, pure Fermi gas kinematics (ignoring interactions) would dictate that they are suppressed, giving strange matter a positive charge per unit baryon number, $Z/A > 0$.

  If this kinematic suppression were the only consequence of the strange quark mass, strange matter and strangelets would certainly have positive electric charge. In a bulk sample of quark matter this positive quark charge would be shielded by a Fermi gas of electrons electrostatically bound to the strange matter, as we discuss further below. Energy due to the exchange of gluons complicates matters. As previously mentioned, perturbation theory suggests this energy is repulsive, and tends to unbind quark matter. However, gluon interactions weaken as quark masses are increased, so the gluonic repulsion is smaller between s-s, s-u or s-d pairs than between u and d quarks. As a result, the population of s quarks in strange matter is higher than expected on the basis of the exclusion principle alone. If, in a model calculation, the strength of gluon interactions is increased, there comes a point where strange quarks predominate. Then the electric charge on strange matter becomes negative.

  Increasing the strength of gluon interactions pushes the charge of quark matter negative. However it also unbinds it. Unreasonably low values of the bag constant are necessary to compensate for the large repulsive gluonic interaction energy[4]. For this reason we consider a negative charge on strange matter to be extremely unlikely.

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[4]Some early studies that suggested negatively charged strange matter for broad ranges of parameters were based on incorrect applications of perturbative QCD.

- Finite size effects [11–14]

  If it were stable, strange matter would provide a rich new kind of "strange" nuclear physics [11,12,15]. Unlike nuclei, strangelets would not undergo fission when their baryon number grows large. Nuclear fission is driven by the mismatch between the exclusion principle's preference for equal numbers of protons and neutrons and electrostatics' preference for zero charge. In strange matter there is little mismatch: $u \approx d \approx s$ coincides with approximately zero charge.

  On the other hand strangelets, like nuclei, become less stable at low baryon number. Iron is the most stable nucleus. Lighter nuclei are made less stable by surface effects. Surface energy is a robust characteristic of degenerate fermion systems. Estimates suggest that strange matter, too, has a significant surface energy, which would destabilize small strangelets [11–13]. The surface tension which makes light nuclei and water droplets roughly spherical is a well known manifestation of positive surface energy.

  The exact value of A below which strangelets would not be stable is impossible to pin down precisely, but small values of A (eg. less than 10–30) are not favored.

  Some very small nuclei are very stable. The classic example is ^{4}He. The reasons for helium's stability are very well understood. A similar phenomenon almost certainly *does not* occur for strangelets. The pattern of masses for strangelets made of 18 or fewer quarks can be estimated rather reliably [11]. Gluon interactions are, on average, destabilizing. They are most attractive for six quarks, where they still fail to produce a stable strange hadron. The most bound object is probably the H, composed of $uuddss$ [16]. It is unclear whether this system is stable enough to be detected. On empirical grounds, it is certainly not lighter than the non-strange nucleus made of six quarks — the deuteron. For $2 < A \leq 6$, QCD strongly suggests complete instability of any strangelets. Larger strangelets, with baryon numbers up to of order 100, have been modelled by filling modes in a bag [13,14,17]. These admittedly crude studies indicate the possible existence of metastable states, but none are sufficiently long-lived to play a role in catastrophic scenarios at a heavy ion collider. Thus, even if it were stable in bulk, strange matter would be unlikely to be stable in small aggregates.

- Searches for Strange Matter

  In addition to the astrophysical searches reviewed in Refs. [8,10] experimental physicists have searched unsuccessfully for stable or quasi-stable strangelets over the past 15 years. Searches fall in two principal categories: a) searches for stable strangelets in matter; b) attempts to produce strangelets at accelerators.

  Stable matter searches look for stable stangelets created sometime in the history of our Galaxy, either in cosmic ray collisions or as by products of neutron star interactions. Due to its low charge to mass ratio, a stable light strangelet would look like an ultraheavy isotope of an otherwise normal element. For example a strangelet with $A \approx 100$ might have $Z = 7$. Chemically, it would behave like an exotic isotope of nitrogen, ^{100}N(!) Searches for ultraheavy isotopes place extremely strong limits on such objects [18]. The failure of these searches further reduces the likelihood that strange matter is stable in bulk at zero external pressure [19].

Accelerator searches assume only that strangelets can be produced in accelerators and live long enough to reach detectors. Experiments to search for strangelets have been carried out at the Brookhaven National Laboratory Alternating Gradient Accelerator (AGS) and at the CERN Super Proton Accelerator (SPS). At the AGS the beam species and energy were gold at an energy of 11.5 GeV per nucleon [20]. At the CERN SPS the beam was lead at an energy of 158 GeV/nucleon [21]. Experiments (with less sensitivity) were also done at CERN with sulfur beams at an energy of 200 GeV per nucleon [22]. In all of these experiments the targets were made of heavy elements (lead, platinum and tungsten).

All of the experiments were sensitive to strangelets of both positive and negative electric charge. All of the experiments triggered on the low value of Z/A characteristic of strangelets. The experiments were sensitive to values of $|Z/A| \lesssim 0.3$, masses from 5 GeV/c^2 to 100 GeV/c^2, and lifetimes longer than 50 ns (5×10^{-8} seconds).

None of the experiments detected strangelet signals. Limits were therefore set on the possible production rates of strangelets with the stated properties. The limits achieved were approximately less than one strangelet in 10^9 collisions at the AGS and from one strangelet per 10^7 to 10^9 collisions at CERN energies, depending on the precise properties of the strangelet.

These experiments are relevant to the issue at hand since the strangelets which could present a hazard at RHIC would need to be stable on the time scale examined. Furthermore the mass range studied extended up to 100 GeV/c^2, which encompasses what could be made at RHIC (see the next section). The experiments also involved collisions between heavy species (Pb-Pb, Au-Pt), accentuating the resemblance to RHIC conditions.

Strangelet Production in Heavy Ion Collisions

The lack of a plausible mechanism whereby hypothetical dangerous strangelets might be produced is one of the weakest links in the catastrophe scenario at a heavy ion collider.

Before discussing production mechanisms in detail, it is worthwhile to summarize some of the very basic considerations that make dangerous strangelet production appear difficult.

- Strangelets are cold, dense systems. Like nuclei, they are bound by tens of MeV (if they are bound at all). Heavy ion collisions are hot. If thermal equilibrium is attained, temperatures are of order one hundred MeV or more. The second law of thermodynamics fights against the condensation of a system an order of magnitude colder than the surrounding medium.

- $q\bar{q}$ pairs, including $s\bar{s}$ pairs, are most prevalent in the central rapidity region in heavy ion collisions. Baryon chemical potential is highest in the nuclear fragmentation regions. To produce a strangelet one needs both high chemical potential and many s quarks made as $s\bar{s}$ pairs. But the two occur in different regions.

- Strangelets include many strange quarks. The more negative the strangelet charge, the more strange quarks. For example, a strangelet with $A = 20$ and $Z = 4$ would include 12 s quarks if the number of u and d quarks are equal (as expected). However, a strangelet with $A = 20$ and $Z = -1$ would have to contain 22 s quarks. The more strange quarks, the harder it is to produce a strangelet. Thus dangerous strangelets are much harder to make than benign ($Z > 0$) strangelets.

- As we have previously discussed, the smaller the strangelet, the less likely it is to be stable or even metastable. The last several items make it clear that the larger the strangelet, the less likely it is to be produced in a heavy ion collision.

We find that these arguments, though qualitative, are quite convincing. Especially, they strongly suggest that strangelet production is even more unlikely at RHIC than at lower-energy facilities (e.g. AGS and CERN) where experiments have already been performed.

Unfortunately, the very unlikelihood of production makes it difficult to make a reasonable model for how it might occur, or to make a quantitative estimate.

Two mechanisms have been proposed for strangelet production in high energy heavy ion collisions: a) coalescence and b) strangeness distillation. The coalescence process is well known in heavy ion collisions and many references relate to it. A recent study which summarizes data at the AGS energies has been reported [23]. The strangeness distillation process was first proposed by Greiner et al. [24].

The coalescence process has been carefully studied at AGS energies [23]. The model is most easily summarized in terms of a penalty factor for coalescing an additional unit of baryon number and/or strangeness onto an existing clump. By fitting data, Ref. [23] finds a penalty factor of 0.02 per added baryon. The additional penalty for adding strangeness has been estimated at 0.2, however the data of Ref. [23] suggests that it might be as small as

0.03. Given that the probability of producing a deuteron in the collision is about unity, this suggests that the yield of strangelets with, for example A=20, Z=2, and S=16 is about one strangelet per 10^{43} collisions (taking the strangeness penalty factor as 0.2).

Furthermore, the coalescence factors might be expected to decrease as the collision energy increases. This is because the produced particles are more energetic, and therefore less likely to be produced within the narrow range of relative momentum required to form a coalesced state. If one compares the coalescence yields at the Bevalac, the AGS, and the CERN experiments, this expectation is dramatically confirmed. From the point of view of coalescence, the most favorable energy for strangelet production is below that of the AGS.

The strangeness distillation mechanism is considerably more speculative. It assumes that a quark gluon plasma (QGP) is produced in the collision and that the QGP is baryon rich. It further assumes that the dominant cooling mechanism for the QGP is evaporation from its surface. Since it is baryon rich, there is a greater chance for an $\bar{s}$ quark to find a u or d quark to form a kaon with positive strangeness than for an s quark to find a $\bar{u}$ or $\bar{d}$ quark to form a kaon with negative strangeness. The QGP thus cools to a system containing excess s quarks, which ultimately becomes a strangelet.

This mechanism requires a collision energy sufficient to form a QGP. RHIC should be high enough. Many heavy ion physicists believe that even the fixed target CERN experiments have reached a sufficient energy and are in fact forming a QGP. If this is the case, the failure of the CERN experiments to find strangelets argues against either the existence of this mechanism or the existence of strangelets. A substantial body of evidence supports the view that a QGP is formed at CERN energies, but a truly definitive conclusion is not possible at present. In any case, the indication at CERN, and the theoretical expectation for RHIC, are that the central rapidity region, where a QGP can be formed, is baryon poor, not baryon rich. Moreover, there is considerable evidence that the systems formed in CERN heavy ion collisions do not cool by slow evaporation from the surface but rather by rapid, approximately adiabatic expansion, as is also expected theoretically. Altogether, the strangeness distillation mechanism seems very unlikely to be effective for producing strangelets at RHIC.

One can also consider a thermal model in which it is assumed that particle production reflects an equilibrium state assumed to exist until the fireball cools and collisions cease. In this model the "free" parameters are the temperature and the baryon chemical potential at freeze-out [25]. Applying this model to the AGS experimental situation gives a reasonably good account of particle ratios, and indicates a freeze-out temperature of 140 MeV and a baryon chemical potential of 540 MeV. With these parameters the model can predict the production probability of strangelets with any given baryon number, charge, and strangeness. Braun-Munzinger and Stachel [26] have carried out detailed calculations for the AGS case and find very small production. For example, the yield of a strangelet with A=20, Z=2, and S=16 is $\sim 2 \times 10^{-27}$ per central collision. Since central collisions are about 0.2 of all collisions this translates into a yield of one strangelet (with these parameters) in 2×10^{27} collisions.

As the collision energy increases, this model predicts higher temperatures and smaller baryon chemical potentials. The result is that in this model strangelet production is predicted to decrease quickly with total center of mass energy in this model. The thermal model clearly favors an energy even lower than the AGS for the optimum for producing strangelets, should they exist.

In summary, extrapolation from particle production mechanisms that describe existing heavy ion collision data suggests that strangelets with baryon number large enough to be stable cannot be produced. With one exception, all production models we know of predict that strangelet production peaks at low energies, much lower than RHIC and perhaps even lower the AGS. The one exception is the hypothetical strangeness distillation mechanism. However, available data suggests that this mechanism does not apply to actual heavy ion collisions.

Catastrophe at RHIC?

What is the scenario in which strangelet production at RHIC leads to catastrophe? The culprit would be a stable (or long-lived, metastable) negatively charged strangelet produced at RHIC. It would have to be a light representative of a generic form of strange matter with *negative* electric charge in bulk. It would have to live long enough to slow down and come to rest in matter. Note that the term "metastable" is used rather loosely in the strangelet literature. Sometimes it is used to refer to strangelets that live a few orders of magnitude longer than strong interaction time scales. Here we require a lifetime at least greater than 10^{-8} sec — the time necessary to traverse the apparatus and reach the shielding.

Once produced, a negative metastable strangelet would be captured quickly by an ordinary nucleus in the environment. Cascading quickly down into the lowest Bohr orbit, it would react with the nucleus, and absorb several nucleons forming a larger strangelet. The reaction would be exothermic. After this reaction its electric charge would be positive. However, if the energetically preferred charge were negative, the strangelet would rapidly capture electrons until it once again had negative charge. At this point the nuclear capture and reaction would repeat. Since there is no upper limit to the baryon number of a strangelet, the process of nuclear capture and weak electron capture would continue until the strangelet grew to a radius comparable to the electron Compton wavelength $\sim 4 \times 10^{-11}$cm.

As it approached this size, the strangelet's character would begin to change. Its baryon number would be of order 10^6 and even with an extremely small (negative) charge to mass ratio, it would no longer be possible to ignore electromagnetism. For example, with $Z/A \sim -0.001$ the quarks would have charge $\sim -10^3$. This charge would be more than enough to trigger electron positron pair creation. The positrons would bind tightly to the strangelet and would (partially) screen the strangelet's negative charge. The quark matter ends abruptly (over a distance scale of fermis) at the strangelet's surface. The positrons, on the other hand, would form a Fermi gas that would extend out beyond the strangelet's surface. The exact distribution can be obtained from a Thomas-Fermi model. An atom which came into contact with such a strangelet would be stripped of its electrons by e^+e^- annihilation. The exposed nucleus would then be absorbed by the ever growing strangelet. This process would continue until all available material had been converted to strange matter. We know of no barrier to the rapid growth of a dangerous strangelet. It is indeed fortunate that they will not be produced at RHIC.

We should emphasize that production of a strangelet with positive charge would pose no hazard whatsoever. It would immediately capture electrons forming an exotic "strangelet-atom" whose chemical properties would be determined by the number of electrons. The strange "nucleus" at its core would be shielded from further nuclear interactions in exactly the same way that ordinary nuclei are shielded from exothermic nuclear fusion. We see no reason to expect enhanced fusion processes involving atoms with strangelets at their core. It has been suggested that an atom with a strangelet at its core would undergo fusion reactions with light elements in the environment and, like a negatively charged strangelet, grow without limit [27]. This will not occur. First, the strength and range of the strong interactions between a strangelet-atom and an ordinary atom are determined by well-known, long-range properties of the nuclear force which are exactly the same for strangelets as for nuclei. Second, fusion is suppressed by a barrier penetration factor proportional to the product of the charge on the strangelet times the charge on the nucleus, $f \propto e^{-Z_1 Z_2 K}$. The most favorable case would be a strangelet of charge one fusing with hydrogen. Hydrogen-hydrogen fusion at room temperature is so rare that it is a subject of intense debate whether it has ever been observed. Even if strangelet-atom-hydrogen fusion were enhanced by some unknown and unexpected mechanism, the suppression factor that appears in the exponent would be doubled as soon as the strangelet had acquired a second unit of charge. As the strangelet's charge grows each successive fusion would be breathtakingly more suppressed.

To provide a concrete example, we have calculated the rate of fusion of a thermalized (room temperature) strangelet with baryon number 396 (the baryon number present in the entire Au-Au collision) and $Z = 6$, with hydrogen. Using standard and well tested nuclear reaction theory, we find a fusion rate of $\sim 10^{-2\times 10^5}$ sec^{-1}.

On theoretical grounds alone, as discussed above, we believe creation of a dangerous strangelet at RHIC can be firmly excluded. However, as we have emphasized throughout this report, whenever possible we strive not to rely on theory alone. We now turn to the important evidence from cosmic rays.

Cosmic Ray Data Relevant to the Strangelet Scenario

It is clear that cosmic rays have been carrying out RHIC-like "experiments" throughout the Universe since time out of mind. Here we choose some specific conditions and summarize briefly the arguments that place restrictions on dangerous strangelet production at RHIC. We have been aided in these estimates by the recent paper by Dar, De Rujula and Heinz [2].

In order to extract bounds from cosmic ray data, it is necessary to model the rapidity distribution of strangelets. It will turn out that the most important distinguishing features of a production mechanism are how it behaves at central and extreme values of the rapidity. Inclusive hadronic processes generally fall like a power of the rapidity near the limits of phase space. In light of this, we see no reason for strangelet production to be exponentially suppressed at $Y_{\rm min}$ and $Y_{\rm max}$. On the other hand, long-standing theoretical ideas and phenomenology suggest the emergence of a "central plateau" away from the kinematic limits of rapidity, along which physics is independent of the rapidity. Insofar as these ideas are correct, a singularity at central rapidity would violate the principle of relativity.

So for our first model we assume a power law dependence at the kinematic limits of rapidity, and an exponential fall off away from the target fragmentation region, where the baryon chemical potential decreases. By convention we take $y = 0$ to be the kinematic limit and we model the strangelet production near $y = 0$ by,

$$\left.\frac{d\Pi}{dy}\right|_{\rm BG} = Npy^a e^{-by}, \tag{12}$$

where a and b are parameters, N is a normalization constant chosen so that p is half the total strangelet production probability per collision (the other half comes near the other rapidity limit). The subscript "BG" stands for "best guess".

The authors of Ref. [2] have pointed out that an extreme model of strangelet production, where production is completely confined to central rapidity, evades a class of cosmic ray limits. Their model can be approximated by a δ function at central rapidity,

$$\left.\frac{d\Pi}{dy}\right|_{\rm DDH} = p\delta(y - Y/2), \tag{13}$$

where Y is the total rapidity interval. Although we find such a model hard to justify on any theoretical grounds, we will use this rapidity distribution when we review the work of Ref. [2].

The limits from cosmic ray considerations depend on the assumed rapidity distribution of strangelet production, in the following respect. If strangelets are produced in the nuclear fragmentation regions, then cosmic ray collisions with stationary nuclei on the surface of the moon provide more than adequate limits on dangerous strangelet production at RHIC. On the other hand, if strangelets were produced only at zero rapidity in the center of mass, then strangelets produced on the Moon would not survive the stopping process. Under this hypothetical — and we believe, quite unrealistic — assumption the persistence of the Moon provides no useful limit on strangelet production. Following Ref. [2], we can, even in this case, derive very strong limits on dangerous strangelet production at RHIC, by considering cosmic ray collisions in the interstellar medium.

Dar, De Rujula, and Heinz introduce the parameter, p, as a simple way to compare limits obtained in different processes [2]. p measures the probability to make a strangelet in a single collision with speed low enough to survive the stopping process at RHIC. For simplicity we will assume that p is independent of the atomic mass of the colliding ions, at least for iron and gold. We also assume p is the same for RHIC and AGS energies. A single choice of p simplifies our presentation. We will discuss the qualitative differences between AGS and RHIC energies and between collisions of different nuclear species where they arise.

At design luminosity, running for a scheduled six months per year for ten years, RHIC will produce approximately 2×10^{11} gold–gold collisions. $p \sim 5 \times 10^{-12}$ would correspond to the production of one dangerous strangelet at RHIC. In discussing cosmic ray processes our object will be to see if it is possible to bound p well below this value.

We begin with our neighbor, the Moon, because we know the environment well and know the Moon is not made of strange matter. [5] The Moon has a rocky surface rich in iron. Using the data from Appendix A it is easy to calculate the rate of collisions between specific heavy ions on the lunar surface.

Consider a cosmic ray nucleus A colliding with a nucleus A' with fractional abundance $f_{A'}$ in the lunar soil. The total number of collisions at energies greater than E over the 5 billion year lifetime of the moon (from eq. (9)) is[6]

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[5]Collisions of cosmic rays with the outer envelopes of stars, gaseous planets, or even terrestrial planets with atmospheres like the earth and venus, lead overwhelmingly to collisions with light nuclei like hydrogen, helium, etc. This is not a likely way to make strange matter.

[6]Eq. (14) was obtained by multiplying eq. (9) by $\sim 15 \times 10^{16}$, the number of seconds in five billion years, and by the fractional abundance, $f_{A'}$. In addition, the collision cross section varies with A and A' like $(A^{1/3} + A'^{1/3})^2$. Since the dominant constituents of the moon are lighter than iron, the probability of a cosmic ray interacting with iron (or gold) is higher than measured by its fractional

$$N(A,E)|_{\rm moon} \approx 8\times 10^{29} f_{A'} \frac{\Gamma(A, 10\ {\rm GeV})}{\Gamma({\rm Fe}, 10\ {\rm GeV})}\left(\frac{10\ {\rm GeV}}{E}\right)^{1.7} \tag{14}$$

Using iron, $f_{\rm Fe} = 0.012$ [28], cosmic ray data from Appendix B, and the value of $p = 5\times10^{-12}$, we calculate the number of dangerous strangelets which would have been created on the surface of the moon in several cases of interest,

I. Dangerous strangelet production in lunar iron-iron collisions at AGS energies.

   Taking $E = 10$ GeV and $f_{\rm Fe} = 0.012$ we obtain $N_{\rm moon}$(Fe-Fe, AGS) $\approx 5\times10^{16}$.

II. Dangerous strangelet production in lunar iron-iron collisions at RHIC energies.

   Scaling E to 20 TeV, we find $N_{\rm moon}$(Fe-Fe, RHIC) $\approx 10^{11}$

III. Dangerous strangelet production in lunar "gold"-iron collisions at AGS energies.

   The penalty of demanding "gold" is a factor of 10^{-5} in cosmic ray flux, so $N_{\rm moon}$(Au-Fe, AGS) $\approx 5\times10^{11}$.

IV. Dangerous strangelet production in lunar "gold"-iron collisions at RHIC energies.

   Scaling E to 20 TeV, we find $N_{\rm moon}$(Au-Fe, RHIC) $\approx 10^{6}$.

The Moon will turn out not to provide useful limits for targets less abundant than iron.

The total number of collisions on the surface of the Moon is huge compared to the number anticipated at RHIC. However, strangelets produced with even relatively low rapidity in the lunar rest frame do not survive subsequent collisions with nuclei in the lunar soil. Consider a strangelet with atomic mass A, charge Z and rapidity y in the lunar rest frame. Its survival probability is

$$\begin{aligned} P(y,A,Z) &= \exp[-n\sigma(A)\lambda(y,Z,A)] \\ &= \exp[-4.85(1+\frac{1}{3}A^{1/3})^2(\cosh y - 1)A/Z^2] \end{aligned} \tag{15}$$

Here n is the density of lunar soil (assuming silicon, $n = 0.5\times10^{23}{\rm cm}^{-3}$), $\sigma(A)$ is the geometric cross section for the strangelet to collide with a silicon nucleus, $\sigma(A) = 0.4(1+\frac{1}{3}A^{1/3})^2$ barns, and $\lambda(y,Z,A)$ is the stopping distance calculated assuming that the strangelet loses energy only by ionization, $\lambda(y,Z,A) = 242(\cosh y - 1)A/Z^2$cm.

For a representative dangerous strangelet, e.g. $A = 20$, $Z = -1$, the suppression factor in eq. (15) is very large, $P(y,20,-1) = \exp[-350(\cosh y - 1)]$, so only strangelets with $y \approx 0$

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abundance alone. We ignore the A dependence of the cross section because it is small, it increases the strength of our bounds, and it complicates our equations.

survive. For the rapidity distribution, eq. (13), chosen by DDH, all dangerous strangelets produced at RHIC would survive stopping, but no strangelet would survive stopping on the moon. The more realistic production mechanism of eq. (12) suppresses dangerous strangelet production at RHIC by several orders of magnitude,[7] while yielding lunar suppression factors ranging from 10^{-3} to 10^{-7} as the parameter a (which controls the small y behavior of dN/dy) ranges from 1 to 4.[8] For a suppression factor of 10^{-7} we obtain survival of $\sim 5 \times 10^9$, $\sim 10^4$, $\sim 5 \times 10^4$, and $\sim 10^{-1}$ dangerous strangelets for the conditions I–IV during the lifetime of the moon.

Since we believe strangelet production to be more likely at AGS energies than at RHIC, and believe iron to be a reasonable "heavy nucleus", we take the limit from Case I very seriously. Scaling to RHIC energies (Case II) or replacing iron by gold at AGS energies (Case III) still leaves a comfortable margin of error. If however, one insists on recreating exactly the circumstances at RHIC and insists on the worst case rapidity distribution, then lunar limits are not applicable. To eliminate this case we turn to the approach of Dar, De Rujula and Heinz [2].

DDH explore the consequences of dangerous strangelet production in nucleus-nucleus collisions in interstellar space. They adopt "worst case" assumptions at every opportunity. In particular, they demand RHIC energies and ultra heavy nuclei (gold rather than iron), and they assume that a dangerous strangelet is produced only at zero rapidity in the center of mass. Given these restrictive conditions they compute the rate at which strangelets are produced at rest relative to the galaxy. Taking an energy of 100 GeV and an abundance relative to iron of 10^{-5} in eq. (11),[9] we reproduce their result, $R(100\text{GeV}, \text{Au}) \approx 10^{-58}$. Multiplying by the age of the galaxy (T_0 = 10 billion years) and by the probability, p, of dangerous strangelet production, we find the number of dangerous strangelets produced per cm^3 in the galaxy,

$$N(100 \text{ GeV}, \text{Au}) = T_0 p R(100 \text{ GeV}, \text{Au}) = 10^{-41} p \text{ cm}^{-3}. \tag{16}$$

DDH estimate that the material contained in a volume of 10^{57}cm^3 is swept up in the formation of a "typical star", so that the probability of a dangerous strangelet ending up in a star is

[7] We ignore this in our discussion of limits, making our estimates very conservative.

[8] These estimates apply to $A = 20$, $Z = -1$. Larger A are more suppressed, but we do not consider production of a negatively charged strangelet with A much larger than 20 to be credible. Larger Z reduces the suppression.

[9] DDH assume an $E^{-2.6}$ decay of the cosmic ray spectrum and take $\Gamma(\text{Au})/\Gamma(\text{Fe}) \approx 3 \times 10^{-5}$, slightly different from our choices.

approximately $P_\star \approx 10^{16}p$. They then go on to argue that the subsequent destruction of the star would be detectable as a supernova-like event. Based on $P_\star$ and the observed rate of supernovas, DDH limit p to be less than 10^{-19}, a factor of 10^8 below the value required for the safety of RHIC. Actually, we believe that DDH have been too conservative. Good physics arguments indicate that lower energy collisions are more likely to create strangelets, and iron is nearly as good a "heavy" ion as gold. If we scale down E from RHIC energies (100 GeV) to AGS energies (4.5 GeV) we gain a factor of 4×10^4 from the $E^{-3.4}$ dependence in eq. (11). If we replace gold by iron we gain a factor of 10^{10}. So the safety factor is more nearly 10^{22}.

In conclusion, we find that any significant strangelet production in the target fragmentation region is effectively ruled out by the persistence of the Moon. The "worst case" scenario of production only at central rapidity forces us to abandon lunar limits, but other simple astrophysical limits still apply. In either case we can derive very large safety factors.

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