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Will relativistic heavy-ion colliders destroy our planet?

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Abstract

Experiments at the Brookhaven National Laboratory will study collisions between gold nuclei at unprecedented energies. The concern has been voiced that "strangelets"– hypothetical products of these collisions– may trigger the destruction of our planet. We show how naturally occurring heavy-ion collisions can be used to derive a safe and stringent upper bound on the risk incurred in running these experiments.

1   Introduction

Experiments scheduled to start at the Brookhaven National Laboratory (BNL) in the fall of 1999 will study heavy-ion collisions at record energies [1]. There has been a recent surge of concern regarding the possibility that "strangelets" –hypothetical products of these collisions– may initiate the destruction of our planet. The trigger of this characteristically millenarian concern may have been a comment by Frank Wilczek in the July 1999 issue of Scientific American [2], comparing strangelets to "ice-9", a science-fiction substance that would, on contact, freeze an ocean. We derive a bound on the probability that the BNL experiments may produce dangerous strangelets, not basing our considerations on our theoretical understanding of heavy-ion collisions, but only on existing empirical knowledge. Though our line of argument is based on a succession of worst-case choices, our results are appeasing.

Strangelets are hypothetical forms of nuclear matter: single particles made of many u, d and s quarks. In putting together an ensemble of fermions in their ground state, it is advantageous to have as many different particle types as possible, to circumvent the exclusion principle. The substitution of a u or a d quark by an s quark may be energetically favourable, in spite of the penalty implied by the greater mass of the s. On this basis Bodmer [3] and Witten [4] suggested that strangelets, like ordinary nuclear matter, may be stable. There are tight upper limits on the natural abundance of strangelets [5, 6, 7, 8], and reasons why they may not have been produced in the early Universe [9].

Our understanding of the interactions between quarks is insufficient to decide with confidence whether or not strangelets are stable forms of matter. Estimates based on the MIT bag model [10, 11] leave the question open for any mass (or baryon) number, A, between a single-digit quantity and the value for neutron stars, $A \sim 1.7 \times 10^{57}$. Stable nuclei have a charge-to-baryon-number ratio $Z/A \sim 1/2$. Except for very small s-quark masses and for values of the chromodynamic forces between quarks so large that the theory is no longer trustable, the estimated Z/A for strangelets is positive [10], but much smaller than for nuclei. This is a direct reflection of the borderline interplay between the exclusion principle, which would favour identical numbers of u, d and s constituents ($Z = 0$), and the mass excess of the s quarks, which disfavours their constituency andresults in a positive Z. A positive strangelet is not a threatening object. Exactly as an atomic nucleus, it would gather an electron cloud and sit snugly in whatever solid material it happens to find itself.

The recently headlined "doomsday scenario" –whereby a strangelet would gather atomic nuclei, become increasingly massive, fall to the Earth's centre and accrete the whole planet– requires the theoretically unexpected existence of stable strangelets of negative charge. Imagine that, for some unforeseen reason, there is a "valley of stability" for negative strangelets. Suppose that, somehow, such an object is produced in a laboratory high-energy reaction and that it survives the collisions that eventually bring

it to rest in matter. The negative strangelet would attract a positive nucleus and may eat it. The resulting object may loose positive charge and adjust its strangeness by electron capture or positron β-decays. The new strangelet may be negative again, and maintain an appetite for nuclei. If its mass grows to some 0.3 ng ($A \sim 2 \times 10^{14}$) it falls to the centre of the Earth [5], for its weight overcomes the structural energy density of matter (10^9 erg cm^{-3} or ~ 0.1 eV per molecular bond). At a mass above 1.5 ng, for a typical nuclear density, the object becomes larger than an atom and the positron cloud that it has been developing sits mainly inside the strangelet itself (for stable strangelets that have grown this large, the sign of Z is immaterial). Even without the help of the Coulomb attraction, gravity and thermal motion may then sustain the accreting chain reaction until, perhaps, the whole planet is digested, leaving behind a strangelet with roughly the mass of the Earth and ~ 100 m radius. The release of energy per nucleon should be of the order of several MeV and, if the process is a run-away one, the planet would end in a supernova-like catastrophe.

Experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL should study Au–Au collisions at a centre-of-mass (cms) energy $\sqrt{s} \sim 200\,A$ GeV ~ 40 TeV ($A \simeq 197$ for gold). At the design luminosity of 2×10^{26} cm^{-2} s^{-1} and for the anticipated six months per year of running, RHIC would make some 2×10^{10} Au–Au collisions per year. It would take RHIC 100 years to accumulate the statistics gathered by NA50 at CERN for Pb–Pb collisions [12], but this fixed-target experiment was conducted at a smaller cms energy: $\sqrt{s} \sim 17\,A$ GeV ~ 3.5 TeV ($A \simeq 207$ for lead). Since the Earth survived NA50 and all other Pb-Pb and Au-Au collision experiments at CERN and BNL, the "BNL doomsday scenario" must suppose that the formation of "killer" strangelets occurs only at an energy above that of the previous experiments, or that the difference between a collider experiment (RHIC) and a fixed-target one (NA50) is not irrelevant.

In a proton–proton collision the probability of producing heavy nuclei or antinuclei is utterly negligible, as the energy required to make these relatively delicate ensembles is far above their binding energy. Strangelets would be, like atomic nuclei, fragile objects that should be easy to disassemble. In collisions between nuclei, in which the initial baryon densities are high, the production of strangelets may be favoured [13, 14, 15]. At the very high energies of RHIC at BNL, however, it is very difficult to imagine how a strangelet could be made and could survive [16]. But this question cannot be settled theoretically with the tools at our disposal. Moreover, it may not even be the right question.

We pose the question of whether one can, on the basis of established facts, exclude beyond the shadow of a doubt the "BNL doomsday scenario". This sort of question has arisen once and again as new particle accelerators were built and operated. The standard answer relies on a comparison of the laboratory collisions with those that have occurred in nature since the beginning of time. If the latter have taken place in numbers enormously larger than those envisaged in the lab, the

probability of a catastrophic outcome is correspondingly negligible. We shall see that the most conventional reasoning –involving cosmic rays impinging on stars and planets– may contain a potential loophole. But nature provides us with an alternative line of argument, which we use to derive a fool-proof and stringent limit on the potential danger of the BNL experiments.

2   Traditional cosmic-ray limits

Consider a strangelet made by a cosmic ray (CR) in matter. Collisions of the RHIC-type certainly occur in nature. Lead and gold nuclei are similar. Lead is relatively abundant in CRs, in interstellar gas, or on the outskirts of celestial bodies without a protective light-gas atmosphere, such as the Moon or an asteroid. In a collision between a Pb CR and a Pb nucleus at rest, the CR energy equivalent to the RHIC cms energy is $E \sim 4 \times 10^3$ TeV. This is a modest energy by CR standards: it is around the "knee" in the CR spectrum [17]. The CR composition is measured directly up to ~ 100 TeV and shows a relative abundance of heavy elements which increases with energy. Extensive air-shower data indicate that the trend continues at energies beyond the knee. The CR flux is known, from meteorite records, to have been steady for billions of years. Reasoning along these lines it is possible to deduce that, since the Moon has not been destroyed by strangelet run-away reactions, the probability of RHIC destroying the Earth in five years of running is "only" of the order of one in a thousand. The CR-induced conversion of an asteroid into a large strangelet –a "killer asteroid" that would in turn destroy the Sun as it falls onto it– leads to a stronger limit. So does the production of a strangelet in the collision of a Pb CR on an interstellar Pb atom, with the strangelet continuing its voyage into the Sun, and destroying it.

The argument regarding the Sun's survival can be extended to the $\sim 10^{21}$ stars of the visible Universe, which are not being destroyed at a rate larger than that of supernova explosions. The margin of safety is now astronomical. But, alas, there is a potential flaw in the argument.

In RHIC, heavy-ion beams of equal energy and opposite momenta will be made to collide (the centre-of-mass system coincides in this case with the laboratory system). The hypothetical strangelets may be produced with cms velocities v that are *not* close to the speed of light ($c = 1$ in our units). This small-velocity or "central" production is completely contrary to the conventional expectation [12, 13, 14, 15] that strangelets ought to be mainly made in the "baryon-rich" environment of the fast forward- and backward-moving fragments of the colliding nuclei. In the case of central production, RHIC would be the first machine with the potential to make strangelets nearly at rest in the laboratory. In terms of the risk that we are discussing, central production is the worst-case scenario, as we proceed to explain.

Let $E_B \sim 7$ MeV be the typical nuclear binding energy per nucleon. A nucleus with kinetic energy per nucleon smaller than some 5 MeV ($v < v_{\rm crit} \sim 0.1$) has a fair chance of surviving a collision with another nucleus. A strangelet is also a form of nuclear matter, and its binding energy per baryon (or per quark triplet) cannot be much bigger than that of a nucleus: the survival probability in nuclear collisions cannot be very differentfor strangelets and for nuclei. This means that a slow strangelet ($v < v_{\rm crit}$) exiting a RHIC detector –and colliding with iron nuclei in a magnet or with concrete in the building– should have a fair probability of surviving without being ruptured into potentially harmless fragments. A slow and heavily ionizing strangelet would come to rest after traversing a column density of about $1 \ {\rm g \, cm}^{-2}$, at which point it might hypothetically start eating nuclei. This is the gate onto the "doomsday scenario".

If only centrally produced in the cms ($v < v_{\rm crit}$), "natural" strangelets made by cosmic rays colliding with stationary matter will be flying off with the cms Lorentz factor $\gamma = E/M$, which is of the order of 100 for Pb–Pb collisions at the RHIC-equivalent energy. At this very high energy ($v \simeq 1$), the strangelet has a very small probability of surviving a single nuclear collision. Elastic (non-destructive) collisions have small momentum and energy transfers. Very many successive ones would be necessary to bring the strangelet, unscathed, to rest: the overall survival probability "exponentiates" to a truly tiny number. This may compensate for the great number of strangelet-producing collisions of cosmic rays with fixed targets that have taken place in nature since the dawn of time. It may also "explain" why NA50, in spite of its large statistics, did not trigger a cataclysm. To avoid this conceivable loophole we look for a natural imitation of an ion-collider facility.

3   Heavy-ion collisions in space

In-flight collisions between cosmic rays are a rare but non-negligible occurrence. In a fraction of these encounters the centre-of-mass system moves sufficiently slowly for the process to be similar to the ones studied at RHIC: the flaw discussed in the previous section is avoided. The risk incurred in running RHIC experiments can be estimated by studying the putative effects of *slow* strangelets made in CR–CR collisions. Rather than making a risk estimate, we shall systematically impose exaggeratedly weak observational constraints, thereby overestimating the danger.

Let p be the probability to make a slow strangelet in a single RHIC Au–Au collision. For the planned running conditions, the number of these particles made per year is

$$N = 2 \times 10^{10} \ p \ {\rm year}^{-1} \, , \tag{1}$$

which will play the role of normalization.

For collisions whose cms velocity u or rapidity $y = \ln[(1+u)/(1-u)]/2$ are sufficiently small, therapidity distribution of the produced strangelets will be similar to the $u = 0$

rapidity distribution of an ion collider. We are interested in collisions for which $u < v_{\rm crit}$, and we take as a reference value $v_{\rm crit} \sim 0.1$, the velocity below which we estimated a strangelet to be immune to nuclear collisions. To satisfy this condition in the very high-energy collisions of interest, the momenta p_i of the cosmic rays must be nearly equal and nearly oppositely directed. Let $\theta \sim 2 p_T/E$ be the (isotropically distributed) angle between $\vec{p}_1$ and $\vec{p}_2$, with p_T the total transverse momentum and $E \sim E_1 \sim E_2$. The fraction f_θ of collisions with cms transverse velocity $v_T \sim p_T/(2E)$ smaller than $v_{\rm crit}$ is $f_\theta \sim 4 v_{\rm crit}^2$. The condition for the cms longitudinal velocity to be smaller than $v_{\rm crit}$ is that the ratio E_1/E_2 be in the range $1 \pm v_{\rm crit}$. In the worst-case scenario in which strangelets are only centrally produced, we are exclusively interested in these nearly head-on collisions between CRs of nearly the same energy.

To obtain a lower limit on strangelet production in CR–CR collisions we assume, conservatively, that strangelets are made only in collisions between heavy nuclei (Pb–Pb or Au–Au) and only above the RHIC energy $E_{\rm beam} \simeq 20$ TeV. The Pb abundance in CRs of that energy is not directly measured, but the abundance and energy spectrum of nuclei of the Fe group are [17]. At smaller energies, the ratio of Pb-like nuclei to Fe nuclei is measured [18] to be $\sim 3 \times 10^{-5}$; it is safe to adopt this value at higher energies, as the relative abundance of the heavier elements increases with energy: they are more efficiently accelerated and confined. We deduce that the flux F and number density n of Pb in CRs are not less than:

$$\frac{dF}{dE} = \frac{c}{4\,\pi}\,\frac{dn}{dE} \simeq 5.3 \times 10^{-11} \left[\frac{E}{1\ {\rm TeV}}\right]^{-2.6} ({\rm cm}^2\ {\rm s\ sr\ TeV})^{-1}\ . \tag{2}$$

We assume this locally measured flux to be representative of the CR flux in the disk of galaxies such as ours.

The flux of Eq. (2) decreases very fast with E and we are restricting ourselves to CR collisions with $E_1 \simeq E_2 > E_{\rm beam}$. It is therefore adequate to adopt an energy-independent strangelet production cross section $p\,\sigma$, with p the RHIC probability defined in Eq. (1) and $\sigma \sim 6.5 \times 10^{-24}$ cm^2 the Pb–Pb nuclear cross section. The rate per unit volume of strangelet production in the relevant Pb–Pb CR collisions (whose cms is travelling with longitudinal and transverse velocities smaller than $v_{\rm crit}$) is:

$$R = 2\,c\,p\,\sigma\,f_\theta \int_{E_{\rm beam}} dE_1 \int_{(1-v_{\rm crit})E_1}^{(1+v_{\rm crit})E_1} dE_2\ \frac{dn}{dE_1}\,\frac{dn}{dE_2}\ . \tag{3}$$

The integral over E_1 converges so rapidly that it can be extended to $E_1 = \infty$.

Once produced, a charged strangelet with velocity $v < v_{\rm crit}$ will be confined by a typical galactic magnetic field $B \sim 3\,\mu$G to a region of size $3 \times 10^{-11}\,A/|Z|$ kpc. For $v = 0.1$ and $|Z| = 1$, interactions with ambient hydrogen with an intestellar density of 1 atom per cm^3 bring the particle to rest in a mere 5×10^6 years. By galactic standards, the strangelets stay put where they are born. CR fluxes have been steady for billions of years and were presumably larger some $T_0 = 10^{10}$ years ago, when galaxies were young

and the star formation rate (to which the CR production rate should be proportional) was higher [19]. We underestimate the accumulated number density of strangelets in interstellar space as $n = R\,T_0$. Carrying out the integrals in Eq. (3), we obtain:

$$n = R\,T_0 \simeq 10^{-41}\, p \left[\frac{v_{\rm crit}}{0.1}\right]^3 \left[\frac{20\,{\rm TeV}}{E_{\rm beam}}\right]^{3.2} {\rm cm}^{-3}\ , \qquad (4)$$

where we have specified the energy dependence to facilitate comparison with colliders other than RHIC.

A sufficiently large strangelet-production probability p entails visible astrophysical consequences. How large can p be?

4   The fate of stars and planets

Slow strangelets produced in CR–CR collisions come to rest and accumulate in the material that is to become a star. We are interested in stars being born and dying at the current cosmological epoch. At a typical interstellar density of 1 atom per cm^3, the material to become a solar-mass star fills a volume $V \sim 10^{57}$ cm^3 (the average star is somewhat less massive than the Sun; we allow ourselves a small degree of imprecision in various relevant parameters, since the observational constraints we shall impose could be made very much tighter). The protostellar gas is concentrated, presumably by supernova shocks, into a "molecular cloud", of density $\sim 10^3$ atoms per cm^3, that collapses gravitationally. In all this process the strangelet constituency, either at rest or magnetically confined, would follow along with the ordinary matter and end up in the protostar. The product $V\,n$, with n as in Eq. (4):

$$P_\star \equiv V\,R\,T_0 \sim 10^{16}\, p \left[\frac{v_{\rm crit}}{0.1}\right]^3 \left[\frac{20\,{\rm TeV}}{E_{\rm beam}}\right]^{3.2}\ , \qquad (5)$$

is the probability for a solar-mass star to contain a strangelet (or, if $P_\star > 1$, the average number of strangelets it would contain).

In the consumption of a star by a strangelet the energy release is of the order of the gravitational binding energy $\sim G M^2/r$ of the strange remnant. For a solar mass star and typical nuclear density, $r \sim 10$ km and the energy release is $\Delta E \sim 10^{53}$ erg, two orders of magnitude bigger than the time-integrated kinetic and visual energy of a supernova. A star of less than a few solar masses would not become a black hole that could potentially engulf all released energy. The late stages in the conversion of a lighter star into strange matter are presumably akin to a supernova explosion. We discuss in turn a supernova-like signature and a putative slower star consumption.

A typical galaxy contains $N_\star \sim 2.5 \times 10^{10}$ stars, currently dying as supernovae at a slower rate than $R_{\rm SN} \sim 5$ per millenium [20]. The corresponding rate at which $N_\star$

6

stars are being destroyed by strangelets is $R_{\text{destr}} \sim N_\star P_\star / T_0 = V R$, with $P_\star$ as in Eq. (5). It would not be possible to have a 50% addition of a completely new type of (strangelet) supernova without unacceptably upsetting our understanding of this field. The condition $R_{\text{destr}} < R_{\text{SN}}/2$ yields

$$p < 10^{-19} \left[\frac{0.1}{v_{\text{crit}}} \right]^3 \left[\frac{E_{\text{beam}}}{20 \, \text{TeV}} \right]^{3.2} . \tag{6}$$

Compare this result with the RHIC rate of Eq. (1). For the RHIC beam energy and the reference v_{crit}, our extremely conservative conclusion is that it is safe to run RHIC for 500 million years. This is reassuring, but what if the conversion of a star into strange matter occurs over a longer period than the visual display of a supernova?

We should only be concerned about the destruction of the Earth in less than $T_0 \sim 10^{10}$ years, since by the time the age of galaxies doubles, the Sun will have become a red giant and engulfed our planet. We do not attempt to estimate the time it takes a strangelet to become large enough to sink to the centre of a planet or a star, but the rate per unit mass at which a strangelet would ingurgitate the Earth is certainly inferior to the corresponding rate for a star, for all the conceivably relevant parameters (temperature, pressure, speed of sound, gravitational free-fall time,...) favour a faster star rate. We conclude that the time for a strangelet-contaminated star to develop an Earth-mass strange core is smaller than the time it would take a strangelet-contaminated Earth to be destroyed. How much longer would it take for the rest of the star to be processed?

Even if strangelets are lighter (at fixed baryon number) than nuclei, we do not expect ^{56}Fe, say, to decay into a strangelet containing ~ 56 s-quarks. The reason for this is thatthe states of intermediate strangeness may not be less massive than Fe, and the overall decay process is a ~ 56th-order weak interaction. The ominous scenario that we are discussing tacitly presumes that for sufficiently large strangelets such a decay barrier does not exist, and the weak first-order transitions which process ordinary into strange matter ($u\, d \to s\, u$, $u\, e^- \to s\, \nu$, and $u \to s\, e^+ \nu$) can occur unimpeded. The u-excess constituency provided by ordinary matter accreting into a strangelet would then exponentially decay away with a time constant comparable to, or faster than, that of neutron decay (ten minutes). The rate of consumption of a star would be governed by the much slower rate at which matter can accrete onto the core strangelet. Let m_p, n_p and v_p be the proton mass, number density and thermal velocity in the neighbourhood of the strangelet's surface. We estimate the mass-accretion rate as:

$$\frac{dM}{dt} \sim m_p\, n_p\, v_p\, S = m_p\, n_p\, v_p\, 4\pi \left(\frac{3\, M}{4\pi\, \rho_s} \right)^{2/3} , \tag{7}$$

where ρ_s is the strangelet's mass density and S is its surface. For the sake of guidance, adopt the conditions prevailing in the center of the Sun: $m_p n_p \sim 1 \, \text{kg/cm}^3$, $v_p \sim 10^{-3}\, c$, $\rho_s \sim 10^{39}\, m_p/\text{cm}^3$. The result for a solar-mass star is then $t \sim 130$ years, negligible

with respect to T_0. In worrying about the Earth's survival until the Sun engulfs it, we are therefore concerned with stars becoming strange in the same span of time: $\tau < T_0$.

For τ shorter than ~ 300 years, a single strange star would have a luminosity $\Delta E/\tau$ superior to the bolometric luminosity $L \sim 10^{43}$ erg/s of a galaxy containing $N_\star$ stars; this case is covered by our previous considerations on supernovae. For longer τ, very conservatively, we demand that the ensemble of strange stars in a galaxy be insufficientto overshine the normal stars: $P_\star N_\star \Delta E/\tau < L$. The weakest condition is obtained for $\tau = T_0$, and it gives the same numerical result as Eq. (6).

It could be agnostically argued that, since the process of accretion onto a strangelet is surely difficult to model with confidence, our use of Eq. (7)is suspicious, and we should only abstract from it the fact that the accretion times of different objects may be in proportion to the cubic root of their masses, which is the result for fixed $n_p v_p$. For a solar-mass star the time would be ~ 100 times longer than for our planet. The last paragraph's argument, for $\tau = 10^2 T_0$, gives a condition two orders of magnitude weaker than Eq. (6). Comparing with the RHIC rate of Eq. (1) we would then deduce, in this most unnaturally pessimistic case, that running the RHIC experiments for five million years is still safe.

5   ALICE at the LHC

At the Large Hadron Collider (LHC) currently being built at CERN, the experiment ALICE [21] will study Pb-Pb collisions at $E_{\rm beam} \sim 600$ TeV, roughly 30 times higher than at RHIC. At the LHC, the planned number of heavy-ion collisions per year is similar to the corresponding figure at RHIC. To analyze the LHC case in the same spirit with which we have studied RHIC, we have to raise the threshold energy for strangelet production to the LHC energy, even though this assumption was already ultra-conservative for RHIC. Raising the threshold energy, and reusing Eq. (5), we conclude that the safety margin for ALICE is a factor $30^{3.2} \sim 5.3 \times 10^4$ lower than it is for RHIC. This means that, in discussing ALICE, it would presumably be advisable to improve our very safe limits based on the fate of stars and/or to develop considerations that rely more heavily than ours on our understanding of heavy ion collisions. For example, if one were to argue that, at a fixed energy per nucleon, Fe-Fe collisions are as good or better than Pb-Pb collisions at making strangelets, the probability $P_\star$ in Eq. (5) would increase by about 11 orders of magnitude, due to the smaller equivalent CR energy per nucleus, and the much larger CR abundance of Fe. The safety margins we have derived would improve by the same factor.

6 Discussion and conclusions

We have argued that the experiments at RHIC do not represent a threat to our planet. But, is this "beyond the shadow of a doubt"? Considerations analogous to ours have been made for other questionably dangerous physical possibilities, such as the production of black holes or the trigger of a reaction whereby the vacuum in which we are would be catastrophically converted into a "true" vacuum of lower energy density [22]. In these cases one is dealing with relatively simple theoretical constructs and one can draw conclusions that are correspondingly uncontroversial. In thecase of strangelets, we are dealing with the properties of an incompletely understood hypothetical form of nuclear matter. It is always possible to come up with an "ad hoc" hypothesis and invalidate any arguments. In the case at hand, it would suffice to assume that strangelets are stable only for masses smaller than the mass of the Earth, so that the conversion process to strange quark matter is eventually stopped. Even if all stars contained a stable Earth-mass strange core, it would not be easy to tell. To have the upper limit of strangelet stability at a mass comparable to that of the Earth, it is necessary to tune the parameters of the underlying theory to a relative precision $\epsilon$of the order of the ratio of a typical nuclear binding energy to the rest energy of the Earth, $\epsilon \sim 10^{-49}$. The a priori probability for the parameters to be so fine-tuned is of order ϵ. This gives an idea of how exceedingly ad hoc any hypothesis of this kind would have to be.

We conclude that, beyond reasonable doubt, heavy-ion experiments at RHIC will not endanger our planet.

Note added. After the completion of our manuscript we received an article by W. Busza *et al.*, hep-ph/9910333, in which limits stronger than ours are derived, with use of arguments based on heavy ion collision theory.

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