Interaction of strangelets with ordinary nuclei

L Paulucci$^{1,2}$ and J E Horvath$^2$

$^1$ Instituto de Física - Universidade de São Paulo
Rua do Matão, Travessa R, 187, 05508-090, Cidade Universitária
São Paulo SP, Brazil

$^2$ Instituto de Astronomia, Geofísica e Ciências Atmosféricas - Universidade de São Paulo
Rua do Matão, 1226, 05508-900, Cidade Universitária
São Paulo SP, Brazil

E-mail: paulucci@fma.if.usp.br

Abstract. Strangelets (hypothetical stable lumps of strange quark matter) of astrophysical origin may be ultimately detected in specific cosmic ray experiments. The initial mass distribution resulting from the possible astrophysical production sites would be subject to reprocessing in the interstellar medium and in the earth atmosphere. In order to get a better understanding of the claims for the detection of this still hypothetic state of hadronic matter, we present a study of strangelet-nucleus interactions including several physical processes of interest (abration, fusion, fission, excitation and de-excitation of the strangelets), to address the fate of the baryon number along the strangelet path. It is shown that, although fusion may be important for low energy strangelets in the interstellar medium (thus increasing the initial baryon number $A$), in the earth atmosphere the loss of baryon number should be the dominant process. The consequences of these findings are briefly addressed.

PACS numbers: 21.65.Qr, 96.50.sb, 96.50.sf

Submitted to: J. Phys. G: Nucl. Phys.
1. Introduction

The hypothesis of stability for strange quark matter (SQM)\textsuperscript{[1, 2, 3, 4]}, a cold form of QCD plasma composed of u, d, and s quarks, naturally leads to the consideration of its existence in the interior of neutron stars\textsuperscript{[5, 6, 7, 8, 9]}. It has been conjectured that if this is indeed the case, then some astrophysical events could eject finite pieces of SQM, called strangelets, in the Galaxy. Thus, the latter would “contaminate” the cosmic ray flux in the interstellar medium (ISM), forming an exotic component among ordinary nuclei (however, see\textsuperscript{[10, 11]} for definite counterexamples from strange stars merging simulations).

Although the density of matter in the ISM is very low (on average about 1 particle/cm\textsuperscript{3}), the confinement times of charged particles in the galactic magnetic fields are rather large, so that collisions between cosmic rays and particles composing the medium may become a relevant factor. Particularly, the passage of strangelets through regions in which the density of the ISM is substantially higher, for example, HII regions and supernovae remnants, could exert a measurable influence on the ultimate detection of the flux at a fixed mass value.

On the other hand, the density in the terrestrial atmosphere is at least fifteen orders of magnitude higher than the average one found in the ISM. Cosmic rays, thus, must travel a thick air layer before hitting the earth surface. If the reprocessing of the mass distribution in the ISM seems likely, it is unavoidable in the atmosphere, at least for strangelets penetrating deeply in the atmosphere.

There have been attempts of explaining some rare events in terms of the presence of strangelets in the cosmic ray flux\textsuperscript{[12, 13, 14, 15, 16, 17, 18]}. Those events presented one or more exotic features such as low charge-to-mass ratio, high penetration of the primary in the atmosphere, absence of neutral pion production, transverse moment of secondaries much higher than the typical values of ordinary nuclear fragmentation, and exotic secondary production.

Broadly speaking, there are two proposed explanations for the processing of strangelets (assumed to be primaries, see\textsuperscript{[19]}) that travel deep in the atmosphere, particularly those arriving with ultrarelativistic energies.

It has been suggested that strangelets of high baryon number lose mass in successive interactions with ordinary nuclei from the top of the atmosphere during their propagation towards the earth’s surface. When their baryon number reaches a value for which their mass is lower than the minimum one associated with stability, $A_{\text{crit}}$, they decay into ordinary hadrons. In this way, it would be possible to conciliate the small mean free path (of same order of ordinary nuclei) and the high penetration in the atmosphere\textsuperscript{[20]}.

On the other hand, in contrast to ordinary nuclei which tend to fragment in collisions, it has been suggested that strangelets could become more bound through the absorption of matter. Also, the electric charge of strangelets allows their trajectories to be affected by the geomagnetic field, causing an increase in the true length of the
path taken to reach a given altitude. If this is the case, then the number of interactions strangelets would suffer with atmospheric nuclei when reaching a given altitude would increase, probably resulting in its complete evaporation before reaching the desired altitude. Therefore, it has been proposed that strangelets with baryon number slightly above \( A_{\text{crit}} \) when reaching the top of the atmosphere would increase its mass instead of decreasing it, due to successive fusion reactions with atoms in the atmosphere \([21]\). The possibility of competing fission was not considered in these models.

Since there are still controversies about these phenomena by different authors, a more complete analysis is necessary to provide a definitive answer on what process of interaction could lead to an event with characteristics similar to the Centauro and a few other abnormal events.

In this paper we will discuss by which means the initial fragmentation spectra for strangelets coming from astrophysical sources could be reprocessed through collisions with the matter that compose the ISM. We will also discuss how the same hadronic interactions to which strangelets would be subject in the ISM can be also responsible for experimental signatures, possibly detectable after their passage through the earth’s atmosphere.

2. Hadronic Interactions

For the analysis of nuclear interactions between strangelets and other nuclei, we considered the following processes possibly affecting the initial baryon number of the strangelet: fusion, abrasion and fission. We also considered the processes of energy loss (de-excitation), which relieves the excitation energy acquired in the collision. Each one is described as follows:

2.1. Abrasion

The abrasion model proposed by Wilson et al \([22]\) is a simple model built to describe spallation qualitatively. It is based on geometric arguments rather than on details of particle-particle interaction. The abrasion process consists in the sheer-off of the region of overlap in the target by the projectile, possibly leading to the removal of all matter affected by the collision.

In spite of the evident loss of details, this model is very useful when there is lack of experimental data or when other models fail to give a consistent analysis. The use of this simplified model largely based on geometric arguments in this study becomes a natural choice since strangelets have not been detected yet and, consequently, models cannot be improved by comparison with experimental data.

The quantity of matter in the projectile that is abraded is given by

\[
\Delta_{\text{abr}} = F A_p [1 - \exp(-C_T/\lambda)],
\]

where \( F \) is the fraction of the projectile in the interaction zone, \( \lambda \) is the mean free path of nucleon-nucleon interaction, \( A_p \) is the baryonic mass of the projectile and \( C_T \) is the
maximum chord in the projectile-target interface (for details, see [22] and references therein).

To study the interaction of strangelets with ordinary nuclear matter, we considered parametrically the formation of “pseudo-baryons”, or clusters of three quarks temporarily bound in the interior of a strangelet, in a similar procedure to that used in the literature for the study of the difference in the binding energy between the nuclei of $^3$He and $^3$H (see, for instance [23]). It is assumed that quarks in the strangelet will maintain their identities as long as the distance between them is higher than a certain length scale, $r_0$. Whenever there is a superposition of the quarks ($r < r_0$), they are treated as confined to the same spherical region. We did not consider the formation probability of clusters other than those made of three quarks, for we are interested in analysing the change in baryon number of strangelets. This would not happen in the case of abrasion of mesons nor with the ejection of a single quark (due the effect of the colour field). We also did not take into account the abrasion of clusters containing a higher number of quarks (for example, a pentaquark) for they would have an extremely small formation probability, thus being irrelevant for the present analysis.

We considered that at a given time, a fraction of the quarks composing the strangelet are grouped in three quarks temporarily bound. We analyse the results taking this fraction of clusters $f$ as a free parameter. The mean free path is taken according to a parametrisation used for the nucleon-nucleon cross section [24] and the abrasion model is used to estimate the change in the baryon number for each collision process.

### 2.2. Fusion

The fusion process is represented generically by $A + B \rightarrow C$, where $A$ and $C$ are strangelets and $B$, the incident nucleus.

For a fusion reaction to occur, the interacting nuclei must have enough energy to overcome the repulsive Coulombian barrier between them, or it can also penetrate the barrier through the well-known quantum tunnelling effect.

For centre of mass energies lower than the Coulombian barrier of the system, we simply used the Gamow parametrisation. For energies above the Coulombian barrier, we followed the proposal of [25] and consider that when the energy deposited by the projectile into the strangelet (in the reference frame of the latter) is of order of the binding energy of the projectile in the strange quark matter, then fusion occurs. We also consider that fusion will occur only for central collisions, according to the geometric parameters defined for the abrasion process. In this way, for the smallest chord moved along by the interacting nucleus in the strangelet in a central collision (equal to $2\sqrt{2R_{str}r_p - r_p^2}$, where $R_{str}$ and $r_p$ are the strangelet’s and nucleus’ radius,

$\dagger$ In the additive quark model, the cross section for a given particle is proportional to the number of valence quarks which compose it. It is known that different baryon compositions affect the value of the cross section. However, this first approximation provides the correct order of magnitude for the mean free path.
respectively) we considered the maximum amount of energy deposited to be equivalent to the binding energy of the strangelet that fuses \( E_{\text{bound}} \approx M_n - M(A + A_p)/(A + A_p) \), where \( M_n \) is the mass of the neutron and \( M(A) \), the mass of the strangelet of baryon number \( A \). A scaling is taken for higher lengths (up to the strangelet’s diameter). This construction allows to associate each chord of interaction with a step function in energy for fusion, and is also consistent with the overall geometric approach adopted from the beginning.

### 2.3. Fission

The fission of strangelets may follow after processes transferring enough excitation energy in a collision. As in previous studies \cite{26}, we considered, in analogy to ordinary nuclei, a liquid drop model to address this issue.

When the distance between fragments 1 and 2 coming from the possible fission of a strangelet is \( r = 0 \) (the initial state of the spherical drop), \( E_0 \) is the difference in the rest energy (quantity of energy available for fission) given by

\[
E_0 = M(A, Z) - M(A_1, Z_1) - M(A_2, Z_2),
\]

where \((A,Z)\) represents the strangelet which may come to fission.

The smallest energy necessary for a system to fission (activation energy) is the one leading to the fragmentation of the system in two fragments of equal mass. This is easier for strangelets than for heavy nuclei because the Coulomb energy does not play an important role. In fact, we neglected the contribution of Coulomb energy in our calculations, since it is much smaller than the masses of strangelets themselves.

### 2.4. Excitation of strangelets

Even peripheral collisions not stripping baryon number from the strangelet can be significant for the excitation of the latter. The mean energy transferred to a nucleon by unit of intersected path is of order 13 MeV/fm. As strangelets are composed by quarks, it is reasonable to assume that the interaction of these particles with ordinary nuclear matter behaves similarly to that between two nuclei. In this way, the energy deposited per unit path must be of the same order of magnitude of the one between nucleons. In this work, the excitation energy due to the transfer of kinetic energy through the surface of the interacting system was taken as the nuclear value and scaled by the longest chord in the surface of projectile (for more details, see \cite{22}).

In cases in which abrasion occurs, the excitation energy coming from the distortion of the nucleus must also be considered (the parametrisation used is detailed in \cite{22}).

The SQM hypothesis suggests that the fusion of a proton with SQM leads to the additional liberation of energy for each nucleon absorbed. In the fusion process the excitation energy can be computed using the “mass excess”, \( E_x \), written as

\[
E_x = M_N(A_N) + M_{\text{str}}(A_{\text{str}}) - M_{\text{str}}(A_{\text{str}} + A_N),
\]
Interaction of strangelets with ordinary nuclei

being \( A_{\text{str}} \) and \( A_N \) the baryon numbers of strangelet and the nucleus with which it interacts and \( M_N(A) \) and \( M_{\text{str}}(A) \), the masses of ordinary nuclear matter and strange matter for a given \( A \), respectively.

2.5. De-excitation

A strangelet may suffer de-excitation through surface evaporation of nucleons. For the emission of neutrons, we followed the procedure detailed by Berger and Jaffe [27]. The emission of neutrons through the weak force leaves a strangelet with parameters changed by \( \Delta A = -1 \) and \( \Delta Y = \Delta Z = 0 \). This happens when

\[
\frac{\partial E}{\partial A} > M_n. \tag{4}
\]

On the other hand, the energy lost by the emission of pions can be calculated based on the chromoelectric flux tube model [28] and reads

\[
d\frac{E}{dt} = -1.12 \times 10^{20} A^{2/3}T^2 \exp(-381, 1/T)\text{MeVs}^{-1}. \tag{5}
\]

It is known that SQM is a poor emitter of thermal photons at energies below 20 MeV. When considering bremsstrahlung process, the emission from the surface of SQM is of four orders of magnitude smaller then the equilibrium black body emission at a given temperature \( T \) [29]. The equation to be considered is then

\[
C_v \frac{dT}{dt} = -\zeta 4\pi R^2 \sigma T^4, \tag{6}
\]

where \( \zeta \sim 10^{-4} \), \( C_v \) is the specific heat of SQM and \( \sigma \) is the Stefan-Boltzmann constant.

Finally, cooling by neutrino emission produces a luminosity \( L_\nu = dE_\nu/dt \) given by

\[
L_\nu = \frac{4}{3} \pi R^3 \epsilon_\nu, \tag{7}
\]

where \( \epsilon_\nu \) is the neutrino emissivity. The specific heat is taken from references [30, 31] for SQM without pairing and from [32] for CFL SQM.

3. Interactions in the ISM

If produced in astrophysical sites, strangelets would interact with the ISM matter causing a reprocessing of the mass distribution injected at the sources.

To analyse all the possible processes of hadronic interaction described above between ordinary nuclei and strangelets and actual de-excitation channels, we built a computer code tracking interactions on an individual basis. Starting from a given strangelet of baryon number \( A \) and kinetic energy \( E \), the following steps are taken:

(i) \textbf{Setup of the collision:}
Random sampling of the impact parameter, \( b \leq R_N + R_{\text{str}} \), where \( R_N \) and \( R_{\text{str}} \) are the nuclei and strangelet’s radius, respectively. From this parameter, the distance of closest approach is calculated;
Random sampling of the excitation energy for the strangelet resultant from the transference of energy in the collision (in half of the events, the target is considered to be in a excited state and the projectile in the other half);

(ii) **Hadronic interaction:**

If the distance of closest approach is higher than the sum of the radius of the two particles, Coulombian scattering is assumed to happen;

On the other hand, for energies below the Coulomb barrier, there is a probability of quantum tunnelling, sampled numerically. For energies above barrier, the criteria for energy deposition are checked. If conditions are met, fusion is assumed to occur and the corresponding excitation energy is obtained;

If the conditions for fusion are not fulfilled, then abrasion is considered according to equation [1] and the corresponding excitation energy is obtained. If there are no baryons extracted in the interaction, scattering is said to have taken place.

(iii) **Fission:**

Fission can only happen if the total excitation energy is above the activation energy. If this is the case, then the most likely channel for fission is considered, i. e., the strangelet will fragment in two daughters with same baryon number and the kinetic and excitation energies are equally divided between the fragments;

(iv) **De-excitation:**

The strangelet’s temperature is obtained according to the First Law of Thermodynamics so that the de-excitation processes can be evaluated (emission of photons, neutrinos and pions and neutron evaporation).

Figure [1] presents the probabilities of abrasion, fusion and scattering processes, as described in section [2] for the collision with protons in the ISM as a function of the incident energy of the strangelet.

As discussed above, the fraction of “baryons” inside a strangelet is taken as a free parameter in the calculations and is related to the probability (impossible to calculate reliably) that at a given moment there is a certain quantity of clusters of three quarks formed internally. This value is relevant for verifying the relative importance of the processes of abrasion and scattering.

For energies below the Coulomb barrier, fusion occurs due to quantum tunnelling and for energies above barrier, it is the ultimate result of energy deposition of the projectile in a central collision. As the energy increases, the probability of a central collision in which the projectile deposits all its kinetic energy (in the strangelet’s referential) progressively decreases until the kinetic energy is above the maximum associated to fusion (the one correspondent to the deposition along the strangelet’s diameter), where the probability goes to zero.

Due to the decrease of the fusion probability as the energy increases, the abrasion process becomes important. Also the mean free path decreases with the increase of

\[ \text{In this analysis we considered the dependence on the strangelet’s mass with the baryon number according to [33].} \]
energy, causing the collision between the proton and the pseudo-baryons inside the strangelet to be more probable. Nevertheless, if the fraction of clusters is too low, the abrasion process becomes dominant only at high energies, since the passage of the proton through the strangelet does not change its baryon number.

Although the dependence of the electric charge is less important for CFL strangelets (which would in turn influence the determination of the distance of closest approach), for high enough energies this effect is indeed irrelevant, and this explains why there are no significant differences between the two states (unpaired and CFL) in Fig. 1. This fact is mainly due to the assumption about the mean free path for the ordinary nucleus with the pseudo baryons formed inside the strangelet, considered to be the same for both states in this study. As the number of clusters increases, the influence of the abrasion process becomes more important with a raise in the number of baryons abraded. For energies per baryon number high enough (above \( \approx 10^5 \) MeV), the relation between abrasion and scattering processes tends to an asymptotic value.

Figure 2 shows the mean baryon number abraded when abrasion becomes relevant. There are no important differences in this parameter for non-CFL and CFL strangelets. As the strangelet energy increases, the quantity of abraded matter increases until it approaches an asymptotic value for very high energies. Obviously, this value is also affected by the fraction \( f \) of clusters temporarily bound in the strangelet. The higher this fraction, the higher the loss of strangelet mass per collision.

In a collision of a strangelet with ordinary nuclei the excitation energy must be higher than the activation energy in order to fission to happen. As mentioned above, the most likely channel for the fission of strangelets (apart of possible shell effects, not taken into account here) is the one with two fragments of same baryon number (note the difference with ordinary nuclei influenced by the Coulomb terms). For strangelets interacting with protons in the ISM the highest energies acquired in the interaction in this analysis were not enough (by a factor of at least 10) to cause fission of strangelets of relatively low mass. Moreover, for high-mass strangelets, fission is again disfavoured because, although there is a small difference in binding energy between the strangelet and its fragments, the high baryon number pumps the activation energies to even higher values than the ones for low-mass strangelets, as expected.

We can estimate which processes dominate the de-excitation of strangelets from their mean temperatures in the collisions (shown in Figure 3). From the latter, we conclude that the process of neutron evaporation due to the raise in the temperature is not likely to be relevant unless the temperatures do rise above tens of MeV. The emission of neutrons might still be possible during the pre-equilibrium configuration, while the energy released during fusion is not still uniformly distributed inside the strangelet. Nevertheless, and even if this is the case, this process would probably contribute with the emission of very few baryons since thermal equilibrium must be reached very quickly.

In addition, cooling by neutrino emission is hardly the main mechanism for energy

\[ \text{At relativistic energies, it mimics full stopping of the projectile in the target.} \]
loss since the temperatures associated with the collisions of protons and strangelets are always below a few MeV, i.e., before neutrino emission dominates the photon emission. Those temperatures are obviously not enough for pion emission either. Therefore, we conclude that the dominant de-excitation mode must be photon emission.

4. Interactions in the earth atmosphere

The interactions of strangelets with the main atmospheric component, the nitrogen molecule, have been analysed afterwards. We have not considered the possibility of partial fusion.

The same procedure of section 3 was performed to evaluate the relative importance of the abrasion, fusion, fission and scattering processes of strangelets travelling in the earth’s atmosphere.
The analysis shows that the fusion process only happens for strangelet energies lower than those in the ISM, due to the substantial difference in the rest masses of the proton and nitrogen (see figure 5). The fusion probability increases with $A$ because the increase of the strangelet radius leads to a longer path in central collisions for the deposition of kinetic energy of the nucleus with which the strangelet interacts (in the reference frame of the latter).

The probability for abrasion remains low for low energies, due to the competition with the fusion process, and increases with the raise in energy because, with the reduced influence of the Coulombian sheer off, scattering becomes less likely to happen. These
Figure 4. Probability of occurrence of hadronic processes for strangelets with (below) and without (above) pairing of $A = 100$ and fraction of clusters of baryons of 0.1 (to the left) and 1 (to the right) with atmospheric nitrogen. The full, dashed and dotted lines are for the processes of scattering, fusion and abrasion, respectively.

observations are weakly dependent on $A$.

The abrasion process probability increases with energy and the quotient abrasion/scattering tends asymptotically to a constant value (close to 1) for relativistic strangelets due to the dependence of the mean free path of nucleon-nucleon interaction with energy. This observation is independent of both $A$ and the different fractions of clusters temporarily formed inside the strangelet.

The mean excitation energy for each process after collisions is up to $\sim 800$ MeV for abrasion (depending weakly on $A$ and independent of the state of SQM within the considerations adopted in this work) and up to $\sim 1.3$ GeV and $\sim 3$ GeV for strangelets without pairing and CFL, respectively, after fusion of the strangelet with nitrogen. These values justify the observation of induced fission for CFL strangelets of low mass (see figure [6]). For low energies, fission occurs due to the liberation of energy from fusion (both probability curves can be superimposed, see figures [5] and [6]).
Interaction of strangelets with ordinary nuclei

For higher energies, fission of strangelets with and without pairing happens due to the excitation energy available from the deformation of the strangelet as the result of abrasion of a quite high baryon number $A^*$. Although the mean excitation energy in the abrasion process is smaller than the activation energy, a fraction of those events can reach energies for which fission is allowed. In these cases, the probability is smaller for lower fractions of pseudo-baryons since it would result in a small quantity of abraded matter (i.e., less distortion of the strangelet). Nevertheless, this result must be taken with caution because the abrasion model, established for the description of ordinary
nuclear matter, certainly did not predict the abrasion of such high amounts of baryons \( A^* \). For high-mass strangelets, the total decrease in baryon number can reach values of order \( 10^2 \), which in turn might lead to overestimated excitation energies.

The possibility of fission for high-mass strangelets is not reached for the excitation energies in the collision of these particles with nitrogen are never sufficient to overcome their activation energies.

The mean abraded matter is higher in the atmosphere than in the ISM since the interaction overlap between the target and projectile is substantially higher (see figure 7). It also increases with the fraction of clusters of baryons \( f \), but shows significant differences only for \( f = 0.1 \) for high energies due to the difference in the mean free path. For low energies, the difference in the amount of abraded material with the change in \( f \) is more pronounced. These conclusions hold for different baryon numbers of strangelets and is weakly dependent on the pairing state of SQM (unpaired or CFL).

The temperatures associated with the fusion process in the atmosphere are higher than those for fusion in the ISM because, with complete fusion, a large amount of energy is liberated per nucleon of the nitrogen. This allows fission of CFL strangelets of low baryon number. The temperatures obtained after fusion are lower than \( \sim 6 \) MeV for unpaired strangelets and when fusion is followed by fission, up to \( \sim 18 \) MeV for CFL strangelets. For strangelets without pairing and CFL with \( A > 1000 \), temperatures from the fusion process (not followed by fission), which are strongly dependent on the baryonic content, are always lower than \( \sim 3 \) MeV and \( \sim 14 \) MeV, respectively.

The temperatures obtained in the present analysis indicate that the most likely channel for de-excitation for strangelets interacting in the atmosphere is photon emission. For the highest possible temperatures, emission of pions is also possible, but with a less effective contribution than photon de-excitation. Even at the highest

---

**Figure 7.** Mean abraded matter as a function of energy for CFL strangelets in the atmosphere. On the left, for \( A = 1000 \) and fraction of baryon clusters \( f \) as indicated. On the right, amount of abraded matter for \( f = 0.3 \) with the full, dashed and dotted curves standing for \( A = 100 \), \( A = 1000 \) and \( A = 3000 \), respectively.
temperatures, neutron emission is not important after thermal equilibration.

4.1. Atmospheric showers initiated by strangelets

Strangelets penetrating deeply in the atmosphere may lead to the generation of showers. Note that we have not considered the formation of “SQM” (possibly metastable due to the high temperatures) in collisions of ordinary cosmic rays with components of the atmosphere [19].

To evaluate the possible development of the interaction of strangelets penetrating the atmosphere from the results shown in the previous section, it is also necessary to address the geomagnetic field influence on those particles.

Strangelets with kinetic energies per baryon number lower than hundreds of MeV to some GeV will have their flux at the surface of the earth lowered due to the local geomagnetic cutoff. Also, if the rigidity is above the local cutoff but $E/A$ is of order of tens to few hundreds of MeV, depending on the strangelet mass, it is more likely that they will become trapped in the geomagnetic field lines, if their pitch angles are adequate [34]. Therefore, the possibility of showers generated by low energy strangelets is substantially reduced. Also, the possibility that the fusion process is the one allowing penetration of strangelets to low altitudes seems very unlikely because the results of the previous section indicate that fusion should be important precisely for these low energy strangelets affected by the magnetic field.

If we assume that the column density travelled between collisions of strangelets with nuclei in the atmosphere is of order 30 g/cm$^2$, a value appropriate when $R_{strang} \sim R_{ar}$ 14, and imposing that in a typical collision the energy loss is $\Delta E/E \sim 3\%$ [14], we obtained a crude evaluation of the evolution in baryon number for strangelets as a function of the column density traversed, shown in Figure 8.

As expected, the steepness of the mass loss increases for higher baryon number and/or higher energies at fixed $A$.

It is worth to remark that fission is important for low mass strangelets. Although less likely than abrasion, this process contributes to prevent these particles from penetrating deeply the atmosphere before reaching the minimum $A$ for which SQM should be stable.

The analysis presented in [26] models the possibility for fission following the process of fusion with air nuclei of strangelets in the atmosphere taking into account the contribution of rotational energy. Particles with high values of deformation by rotation have higher probability of fission in a collision than spherical particles (without any deformation). Nevertheless, their spallation estimate is not modelled in detail, rather considering that the strangelet will lose the same mass number as the air nucleus in each

\footnote{For strangelets with high baryon number, the values obtained for the final mass after a given column density traversed must be overestimated then, since their radius are big when compared to the nitrogen radius. In this sense, the mean distance between collisions in the atmosphere should be lower than the one equivalent to 30 g/cm$^2$ of column density.}
collision. Besides that, our results are not too different in absolute values (although the curves of mass evolution for strangelets do have opposite curvatures), which leads us to believe that the curves shown in Figure 8 should be actually considered as upper limits.

When considering the celebrated Centauro events, our results indicate that the events might be explained by a high-mass and high-energy strangelet penetrating the upper atmosphere and suffering successive baryon number losses until it reaches ground experiments. Nevertheless, further analysis related to the kinematics and multiplicities of the secondary production are necessary for a firmer conclusion.

5. Conclusions

The most important feature of this work is to propose a consistent approach which accounts simultaneously for different processes of interaction between strangelets and ordinary nuclei. The use of the abrasion method allows the evaluation of the abraded matter for strangelets, rather than assuming a fixed baryon number extracted by the interacting nuclei or any other oversimplified assumption (as in, for example, \cite{20, 21, 26, 35}).

We have shown that the reprocessing in mass number of strangelets in the ISM is a process that must be effectively operating for long periods due to the high mean free path for interactions caused by the low-density of nuclei in the Galaxy.

For the analysis of spallation we used the abrasion model, strongly rooted on geometrical arguments. In spite of the generality of the assumptions, this has the advantage of making the results quite independent of experimental data, which are non-

**Figure 8.** Baryon number evolution for a strangelet as a function of the column density traversed in the earth atmosphere. These values are not significantly changed with the pairing state of strangelets in this work. On the right, the strangelet’s baryon number is fixed to \( A = 1000 \) and the full, dashed and dotted curves are for \( E/A = 100, 10^4, 10^6 \) MeV, respectively. On the left, the strangelet’s energy per baryon number is fixed in \( E/A = 1 \times 10^6 \) MeV and the full, dashed and dotted lines stand for \( A = 100, 1000, 3000 \), respectively.
existent in this present case. This adaptation of the existing models obviously does not describe the details found in experiments of nuclear matter collision, but is qualitatively acceptable, and thus we expect the results presented here to point towards a general trend for strangelet-nucleus interactions.

We have shown that important differences in the results arise with the assumptions of the fraction of clustering of quarks between \( f = 0.1 \) and 1. Obviously, \( f = 1 \) is not realistic at all, since in this case one could consider the strangelet as a kind of gas of \( \Lambda \) particles, something which is inconsistent with the strange quark matter stability hypothesis from the very beginning \[36\]. However, and in spite of this uncertainty, the analysis suggests that adopting spallation with nuclear parameters as the mechanism for reprocessing of strangelets in the ISM should overestimate the change in baryon number of the primaries. In addition, the treatment of spallation presented here can overcome the problems of considering that this specific process of interaction simply destroys the strangelet (as assumed, for example, by Madsen \[35\]). Also, we contend that fusion should be considered as an important process for interaction with protons at low energies. The estimates of the reprocessing of the initial mass distribution of strangelets in the ISM should be reanalysed for the better prediction of the most likely channels for their ultimate detection and evaluation of existing upper limits to their flux. The consistent framework of relevant interactions facing the unknown physics of strangelets presented here can provide elements for such reanalysis.

On the other hand, we believe that in the terrestrial atmosphere, the dominant mechanism to which strangelets are subject is the loss of baryon number, mostly due abrasion, but also featuring a contribution from the fission process.

If strangelets are part of the cosmic ray flux, it would be possible to detect them, especially in experiments located at the top of mountains \[37\] since the mass loss due to interaction with atmospheric particles tend to be catastrophic for high column densities crossed. It is not ruled out that Centauro events may have their origin in strangelets, although these suggestive results are still to be analysed in further details.

Acknowledgments

We acknowledge the financial support received from the Fundação de Amparo à Pesquisa do Estado de São Paulo. J.E.H. wishes to acknowledge the CNPq Agency (Brazil) for partial financial support.

[1] E. Witten. *Phys. Rev. D*, 30:272, 1984.
[2] A. Bodmer. *Phys. Rev. D*, 4:1601, 1971.
[3] S. A. Chin and A. Kerman. *Phys. Rev. Lett.*, 43:1292, 1979.
[4] H. Terazawa. *Tokyo U. Report.*, pages INS–336, 1979.
[5] C. Alcock, E. Farhi, and A. Olinto. *Phys. Rev. Lett.*, 57:2088, 1986.
[6] P. Haensel, J. Zdunik, and R. Schaeffer. *Astron. Astrophys.*, 160:121, 1986.
[7] O. G. Benvenuto, J. E. Horvath, and H. Vucetich. *Int. J. Mod. Phys. A*, 6:4769, 1991.
[8] M. A. Alpar. *Phys. Rev. Lett.*, 58:2152, 1987.
[9] N. K. Glendenning and F. Weber. *Astrophys. J.*, 400:647, 1992.
[10] W. Kluzniak and W. H. Lee. *Mon. Not. R. Astron. Soc.*, 335:L29, 2002.
Interaction of strangelets with ordinary nuclei

[11] A. Bauswein, H.-T. Janka, R. Oechslin, G. Pagliara, I. Sagert, J. Schaffner-Bielich, M. M. Hohle, and R. Neuhuser. Mass ejection by strange star mergers and observational implications. arXiv:0812.4248, 2008.

[12] M. Ichimura et al. Nuovo Cim. A, 106:843, 1993.

[13] P. B. Price, E. K. Shirk, W. Z. Osborne, and L. S. Pinsky. Phys. Rev. D, 18:1382, 1978.

[14] J. D. Bjorken and L. McLerran. Phys. Rev. D, 20:2353, 1979.

[15] M. Rybczynski, Z. Wlodarczyk, and G. Wilk. Acta Phys. Polon., B33:277, 2002.

[16] T. Saito et al. Phys. Rev. Lett., 65:2094, 1990.

[17] V. Choutko. In Proc. 28th Internat. Cosmic Ray Conf., Tsukuba, Japan, page 1765. Universal Academic Press, Tokyo, 2003.

[18] S. Banerjee, S. K. Ghosh, S. Raha, and D. Syam. Phys. Rev. Lett., 85:1384, 2000.

[19] A. L. S. Angelis, E. Gladysz-Dziadus, Yu. V. Kharlov, V. L. Korotkikh, G. Mavromanolakis, A. D. Panagiotou, and S. A. Sadovsky. Phys. Atom. Nucl., 67:396, 2004.

[20] G. Wilk and Z. Wlodarczyk. J. Phys. G: Nucl. Part. Phys., 22:L105, 1996.

[21] S. Barnerjee et al. J. Phys. G: Nucl. Part. Phys., 25:L15, 1999. See also S. Barnerjee et al., Phys. Rev. Lett. 85, 1384 (2000).

[22] J. W. Wilson, L. W. Townsend, and F. F. Badavi. Nucl. Instr. Meth. Phys. Res. B, 18:225, 1987.

[23] V. Koch and G. A. Miller. Phys. Rev. C, 31:602, 1985.

[24] R. Dymarz and T. Kohmura. Phys. Lett., 124B:446, 1983.

[25] H. Vucetich and J. E. Horvath. Phys. Rev. D, 57:5959, 1998.

[26] F. Wu, R. Xu, and B. Ma. J. Phys. G, 33:597, 2007.

[27] M. S. Berger and R. L. Jaffe. Phys. Rev. C, 35:213, 1987. 44, 566(E) (1991).

[28] B. Banerjee, N. K. Glendenning, and T. Matsui. Phys. Lett. B, 127:453, 1983.

[29] V. V. Usov. Astrophys. J., 550:L179, 2001.

[30] N. Iwamoto. Ann. Phys., 141:1, 1982.

[31] J. E. Horvath, O. G. Benvenuto, and H. Vucetich. Phys. Rev. D, 44:3797, 1991.

[32] D. Blaschke, T. Klahn, and D. N. Voskresensky. Astrophys. Journal, 533:406, 2000.

[33] L. Paulucci and J. E. Horvath. Phys. Rev. C, 78:064907, 2008.

[34] L. Paulucci, J. E. Horvath, and G. A. Medina-Tanco. Phys. Rev. D, 77:043003, 2008.

[35] J. Madsen. Phys. Rev. D, 71:014026, 2005.

[36] H. A. Bethe, G. E. Brown, and J. Cooperstein. Nucl. Phys. A, 462:791, 1987.

[37] Z. Sahnoun. Search for strange quark matter and q-balls with the slim experiment. arXiv:0812.3248, 2008.