Strangelets in cosmic rays

M.Rybczyński\(^a\), Z.Wlodarczyk\(^a\) and G.Wilk\(^b\)

\(^a\)Institute of Physics, Świętokrzyska Academy, Kielce, Poland

\(^b\)The Andrzej Soltan Institute for Nuclear Studies, Nuclear Theory Department, Warsaw, Poland

Recently new data from the Cosmo-LEP project appeared, this time from DELPHI detector. They essentially confirm the findings reported some time ago by ALEPH, namely the appearance of bundles of muons with unexpectedly high multiplicities, which so far cannot be accounted for by present day models. We argue, using arguments presented by us some time ago, that this phenomenon could be regarded as one more candidate for the presence in the flux of cosmic rays entering the Earth’s atmosphere from outer space nuggets of Strange Quark Matter (SQM) in form of so called strangelets.

1. INTRODUCTION

Recently new data from Cosmo-LEP program, this time from DELPHI detector, has been reported \(^1\). Among other things they have confirmed the findings reported before by ALEPH \(^2\), namely that one observes bunches of cosmic muons (i.e., produced at the top of the Earth’s atmosphere) of unexpected large multiplicities (up to \(N_\mu = 150\)). Their origin is so far unexplained and no model used in Monte Carlo (MC) programs simulating cascades of cosmic rays (CR) in the atmosphere is able to account for this phenomenon. In \(^1\) the expectation was made that source of this discrepancy can eventually come directly from the elementary interaction model used in MC. However, in our opinion, which we would like elaborate here in more detail, it could rather come (at least to a large extent) from the projectile initiating the cascade. Namely, as we have already done in many places on other occasions \(^3\), \(^4\), we shall argue that the above-mentioned results of both experiments can be regarded as yet another signal of the presence in the flux of CR entering the Earth’s atmosphere of nuggets of Strange Quark Matter (SQM) called strangelets. In this way results of \(^1\) and \(^2\) would just continue a long list of other phenomena explainable in this way like anomalous cosmic ray burst from Cygnus X-3, extraordinary high luminosity gamma-ray bursts from the supernova remnant N49 in the Large Magellanic Cloud or Centauro (to mention only the most interesting and intriguing examples, for more details see \(^5\) and references therein). In \(^6\) we have already provided successful explanation of ALEPH observations by using notion of strangelets and assuming their flux being the same as obtained from analysis of all previous signals of strangelets present in the literature. (Actually, at that time ALEPH results were circulated only as conference papers, however, the final results presented in \(^2\) turned out to be identical to those addressed in \(^6\)).

It is worth to remind here that CosmoLEP data are very important because: \((a)\) the high multiplicity cosmic muon events (muon bundles) are potentially very important source of information about the composition of primary CR because muons transport in essentially undisturbed way information on the first interaction of the cosmic ray particle with atmosphere; \((b)\) such events have never been studied with such precise detectors as provided by LEP program at CERN, nor have they been studies at such depth as at CERN \(^7\) (ranging between 30 and 140 meters what corresponds to muon momentum cut-off between 15 and 70 GeV).
2. SOME FEATURES OF STRANGELETS

For completeness let us remind here the most important for us features of strangelets (see [3,4] for details). They are hadron-like being a bag of up, down and strange quarks (essentially in equal proportion) becoming absolutely stable at high mass number \( A \) (more stable than the most tightly bound nucleus as iron). However, they become unstable below some critical mass number, \( A_{\text{crit}} = 300 - 400 \). Despite the fact that their geometrical radii are comparable to those of ordinary nuclei of the corresponding mass number \( A \), \( R = r_0 A^{1/3} \), they can still propagate very deep into atmosphere. This is because after each collision with the atmosphere nucleus strangelet of mass number \( A_0 \) becomes just a new strangelet with mass number approximately equal \( A_0 - A_{\text{air}} \) and this procedure continues unless either strangelet reaches Earth or (most probably) disintegrates at some depth \( h \) of atmosphere reaching \( A(h) = A_{\text{crit}} \). Actually, in a first approximation (in which \( A_{\text{air}} << A_{\text{crit}} < A_0 \), in the total penetration depth of the order of

\[
A \simeq \frac{4}{3} \lambda_{N-\text{air}} \left( \frac{A_0}{A_{\text{air}}} \right)^{1/3}
\]  

where \( \lambda_{N-\text{air}} \) is the usual mean free path of the nucleon in the atmosphere.

There are number of candidates for strangelets known in the literature, the common feature is their small ratio of charge \( Z \) and mass \( A \) numbers, \( Z/A \). The so called Saito events have \( Z \simeq 14 \) and \( A \simeq 350 \) and \( A \simeq 450 \). The most spectacular is Price event with \( Z \simeq 46 \) but \( A > 1000 \). On the other hand the Exotic Track event (ET) has been produced after the respective projectile has traversed \( \sim 200 \text{ g/cm}^2 \) of atmosphere. Finally, the so called Centauro events has been produced at depth \( \sim 600 \text{ g/cm}^2 \) and contains probably \( \sim 200 \) baryons. In Fig. 1 we show the resulting flux of strangelets obtained by considering the above signals [4]. One can add to them the recently registered with AMS detector event with small ratio \( Z/A \) and also very small \( A \), estimated to be \( A \simeq 17.5 \), it could be a metastable strangelet.

3. RESULTS

This is the picture we shall use to estimate the production of muon bundles produced as result of interaction of strangelets with atmospheric nuclei. We use for this purpose the SHOWERSIM modular software system specifically modified for our present purpose. Monte Carlo program describes the interaction of the primary particles at the top of atmosphere and follows the resulting electromagnetic and hadronic cascades through the atmosphere down to the observation level. Registered are muons with momenta exceeding 70 GeV for ALEPH and 50 GeV for DELPHI. Primaries initiated showers were sampled from the usual power spectrum \( P(E) \propto E^{-\gamma} \) with the slope index equal to \( \gamma = 2.7 \) and with energies above \( 10 \cdot A \text{ TeV} \).

Registered are muons with momenta exceeding 70 GeV for ALEPH and 50 GeV for DELPHI. Primaries initiated showers were sampled from the usual power spectrum \( P(E) \propto E^{-\gamma} \) with the slope index equal to \( \gamma = 2.7 \) and with energies above \( 10 \cdot A \text{ TeV} \).

The integral multiplicity distribution of muons from ALEPH data are compared with our simulations in Fig. 2. For completeness DELPHI data are present also. At first we have used here the so called "normal" chemical composition of pri-
maries with 40% of protons, 20% of helium, 20% of C-N-O mixture, 10% of Ne-S mixture and 10% of Fe. As one can see in Fig. 2 it can describe only the low multiplicity ($N_\mu \leq 20$) region of ALEPH data. The small admixture of strangelets with the mass number $A = 400$ being just above the estimated critical one estimated $A_{\text{crit}} \sim 320$ in the primary flux of CR (corresponding to relative flux of strangelets $F_S/F_{\text{total}} \simeq 2.4 \cdot 10^{-5}$) can, however, fully accommodate ALEPH data. As can be noticed DELPHI data differ rather substantially in shape from ALEPH data. They could be described equally well for $N_\mu > 40$ but only with 5-fold smaller flux of strangelets. However, in this case events with small $N_\mu$ would fall completely outside the fit.

One should notice that results of both experiments differ already at small values of muon multiplicity. It looks like DELPHI makes preference for heavy composition of primary CR right from the beginning whereas ALEPH prefers somehow lighter (protonic) composition of CR. In any case, the excess of muons is clearly visible therefore we regard this as a possible additional signal of strangelets.

4. CONCLUSIONS

To conclude: we propose to regard the Cosmo-LEP data on CR muons obtained so far as an additional possible signal of the possible SQM admixture present in the primary CR flux. We would like to add here that such admixture would also contribute to CR flux at energies greater than GZK cut-off $E^{-2.4}$, explaining therefore this phenomenon in a quite natural way. This makes strangelets interesting subject to investigate in the future.

We would like to close with the following remark. With the flux of strangelets as estimated by us and used here (equal to $F_S/F_{\text{total}} = 2.4 \cdot 10^{-5}$ in the energy range of tens of GeV) the energetic spectrum of strangelets should fall like $\sim E^{-2.4}$, i.e., with spectral index being much smaller than for protons. Actually, this result agrees nicely with $A$-dependence of the spectral index of CR’s obtained when fitting the world CR data.

REFERENCES

1. J. Ridky and P. Travnicek (for DELPHI Collaboration), Acta Phys. Polon. 35 (2004) 1813; cf. also J. Ridky, these proceedings.
2. V. Avati et al., Astropart. Phys. 19 (2003) 513.
3. G. Wilk and Z. Włodarczyk, J. Phys. G22 (1996) L105; Heavy Ion Phys. 4 (1996) 395 and Nucl. Phys. B Proc. Suppl. 52B (1997) 215.

4In fact nothing better can be done because neither ALEPH or DELPHI can at the moment provide any explanation of this visible discrepancy of their respective results.

5There are still expected data from L3 experiment, however, so far the muonic part is not yet ready.

6If it will be finally confirmed by experiment.

Figure 2. Our results (dotted line corresponds normal composition of compared with ALEPH data [2]. Notice that there is big discrepancy between ALEPH and DELPHI data [1], shown here for comparison.
4. M. Rybczyński, Z. Włodarczyk and G. Wilk, Acta Phys. Polon. B33 (2002) 277.
5. R. Klingerberg, J. Phys. G25 (1999) R273.
6. M. Rybczyński, Z. Włodarczyk and G. Wilk, Nucl. Phys. B Proc. Suppl. 97 (2001) 85.
7. C. Timmermans (L3+C Coll.), 26th Int. Conf. Cosmic Ray Conf., Salt Lake City (1999), Contributed Papers, Vol. 2 (1999) 9. See also: C. Taylor et al., (CosmoLEP Coll.), CosmoLEP and underground cosmic ray muon experiment in the LEP ring CERN/LEP 99-5 (1999) LEPC/P9 and Cosmic multi-muon events in ALEPH as part of the CosmoLEP project, CosmoLEP Report 1 (1999); cf. also: CERN Courier, Vol. 39-8, October (1999) 29.
8. T. Saito, Y. Hatano and Y. Fukuda, Phys. Rev. Lett. 65 (1990) 2094.
9. P.B. Price, Phys. Rev. D38 (1988) 3813.
10. M. Ichimura et al., Nuovo Cim. A106 (1993) 843.
11. C.M.G. Lattes, Phys. Rep. 65 (1980) 151; J.D. Bjorken and L.D. McLerran, Phys. Rev. D20 (1979) 2353.
12. G. Wilk and Z. Włodarczyk, Nucl. Phys. B Proc. Suppl. 52 (2001) 215.
13. V. Choutko (AMS Coll.), 28 ICRC (2003) OG1, 1765.
14. A. Wrotniak, Report No. 85-195, Univ. of Maryland (1985).
15. See talk by P. Le Coultre, these proceedings.
16. J. Madesn and J.M. Larsen, Phys. Rev. Lett. 90 (2003) 121102.
17. See talks by: K. Shinozaki (AGASA), S. Westerhoff (HIRES) and K.H. Kampert (AUGER), these proceedings.
18. B. Wiebel-Sooth, Astronomy and Astrophysics 330 (1998) 389; see also A. Dar, astro-ph/0409464.
Strangelets in cosmic rays

M. Rybczyński *, Z. Wlodarczyk *† snd G. Wilk b ‡

* Institute of Physics, Świętokrzyska Academy, Kielce, Poland
† The Andrzej Soltan Institute for Nuclear Studies, Nuclear Theory Department, Warsaw, Poland
‡ e-mail: wilk@fuw.edu.pl

Recently new data from the Cosmo-LEP project appeared, this time from DELPHI detector. They essentially confirm the findings reported some time ago by ALEPH, namely the appearance of bundles of muons with unexpectedly high multiplicities, which so far cannot be accounted for by present day models. We argue, using arguments presented by us some time ago, that this phenomenon could be regarded as one more candidate for the presence in the flux of cosmic rays entering the Earth’s atmosphere from outer space nuggets of Strange Quark Matter (SQM) in form of so called strangelets.

1. INTRODUCTION

Recently new data from Cosmo-LEP program, this time from DELPHI detector, has been reported [1]. Among other things they have confirmed the findings reported before by ALEPH [2], namely that one observes bunches of cosmic muons (i.e., produced at the top of the Earth’s atmosphere) of unexpectedly large multiplicities (up to $N_\mu = 150$). Their origin is so far unexplained and no model used in Monte Carlo (MC) programs simulating cascades of cosmic rays (CR) in the atmosphere is able to account for this phenomenon. In [1] the expectation was made that source of this discrepancy can eventually come directly from the elementary interaction model used in MC. However, in our opinion, which we would like elaborate here in more detail, it could rather come (at least to a large extent) from the projectile initiating the cascade. Namely, as we have already done in many places on other occasions [3,4], we shall argue that the above mentioned results of both experiments can be regarded as yet another signal of the presence in the flux of CR entering the Earth’s atmosphere of nuggets of Strange Quark Matter (SQM) called strangelets. In this way results of [1] and [2] would continue a long list of other phenomena explainable in this way like anomalous cosmic ray burst from Cygnus X-3, extraordinary high luminosity gamma-ray bursts from the supernova remnant N49 in the Large Magellanic Cloud or Centauro (to mention only the most interesting and intriguing examples, for more details see [4,5] and references therein). In [6] we have already provided successful explanation of ALEPH observations by using notion of strangelets and assuming their flux being the same as obtained from analysis of all previous signals of strangelets present in the literature. (Actually, at that time ALEPH results were circulated only as conference papers, however, the final results presented in [2] turned out to be identical to those addressed in [6]).

It is worth to remind here that CosmoLEP data are very important because: (a) the high multiplicity cosmic muon events (muon bundles) are potentially very important source of information about the composition of primary CR because muons transport in essentially undisturbed way information on the first interaction of the cosmic ray particle with atmosphere; (b) such events have never been studied with such precise detectors as provided by LEP program at CERN, nor have they been studied at such depth as at CERN [7] (ranging between 30 and 140 meters what corresponds to muon momentum cut-off between 15 and 70 GeV).
2. SOME FEATURES OF STRANGELETS

For completeness let us remind here the most important for us features of strangelets (see [3,4] for details). They are hadron-like being a bag of up, down and strange quarks (essentially in equal proportion) becoming absolutely stable at high mass number $A$ (more stable than the most tightly bound nucleus as iron). However, they become unstable below some critical mass number, $A_{\text{crit}} = 300 - 400$. Despite the fact that their geometrical radii are comparable to those of ordinary nuclei of the corresponding mass number $A$, $R = r_0 A^{1/3}$, they can still propagate very deep into atmosphere. This is because [3] after each collision with the atmosphere nucleus strangelet of mass number $A_0$ becomes just a new

\[ \Lambda \approx \frac{4}{3} \lambda_{N-\text{air}} \left( \frac{A_0}{A_{\text{air}}} \right)^{1/3} \]

where $\lambda_{N-\text{air}}$ is the usual mean free path of the nucleon in the atmosphere.

There are number of candidates for strangelets known in the literature, the common feature is their small ratio of charge $Z$ and mass $A$ numbers, $Z/A$. The so called Saito events have $Z \approx 14$ and $A \approx 350$ and $A \approx 450$ [8]. The most spectacular is Price event [9] with $Z \approx 46$ but $A > 1000$. On the other hand the Exotic Track event (ET) [10] has been produced after the respective projectile has traversed $\sim 200$ g/cm$^2$ of atmosphere. Finally, the so called Centauro events [11] has been produced at depth $\sim 600$ g/cm$^2$ and contains probably $\sim 200$ baryons [12]. In Fig. 1 we show the resulting flux of strangelets obtained by considering the above signals [4]. One can add to them the recently registered with AMS detector [13] event with small ratio $Z/A$ and also very small $A$, estimated to be $A \approx 17.5$, it could be a metastable strangelet.

3. RESULTS

This is the picture we shall use to estimate the production of muon bundles produced as result of interaction of strangelets with atmospheric nuclei. We use for this purpose the SHOWERSIM [14] modular software system specifically modified for our present purpose. Monte Carlo program describes the interaction of the primary particles at the top of atmosphere and follows the resulting electromagnetic and hadronic cascades through the atmosphere down to the observation level. Registered are muons with momenta exceeding 70 GeV for ALEPH and 50 GeV for DELPHI. Primaries initiated showers were sampled from the usual power spectrum $P(E) \propto E^{-\gamma}$ with the slope index equal to $\gamma = 2.7$ and with energies above $10 \cdot A$ TeV.

The integral multiplicity distribution of muons from ALEPH data are compared with our simulations in Fig. 2. For completeness DELPHI data are present also. At first we have used here the so called “normal” chemical composition of pri-
aries with 40% of protons, 20% of helium, 20% of C-N-O mixture, 10% of Ne-S mixture and 10% of Fe. As one can see in Fig. 2 it can describe only the low multiplicity ($N_\mu \leq 20$) region of ALEPH data. The small admixture of strangelets with the mass number $A = 400$ being just above the estimated critical one estimated $A_{crit} \sim 320$ in the primary flux of CR (corresponding to relative flux of strangelets $F_S/F_{total} \approx 2.4 \cdot 10^{-5}$) can, however, fully accommodate ALEPH data. As can be noticed DELPHI data [1] differ rather substantially in shape from ALEPH data. They could be described equally well for $N_\mu > 40$ but only with 5-fold smaller flux of strangelets. However, in this case events with small $N_\mu$ would fall completely outside the fit$^4$.

One should notice that results of both experiments differ already at small values of muon multiplicity. It looks like DELPHI makes preference for heavy composition of primary CR right from the beginning whereas ALEPH prefers somehow lighter (protonic) composition of CR. In any case, the excess of muons is clearly visible therefore we regard this as a possible additional signal of strangelets$^5$.

4. CONCLUSIONS

To conclude: we propose to regard the Cosmo-LEP data on CR muons obtained so far as an additional possible signal of the possible SQM admixture present in the primary CR flux. We would like to add here that such admixture would also contribute to CR flux at energies greater than GZK cut-off [4,16] explaining therefore this phenomenon in a quite natural way$^6$. This makes strangelets interesting subject to investigate in the future.

We would like to close with the following remark. With the flux of strangelets as estimated by us and used here (equal to $F_S/F_{total} = 2.4 \cdot 10^{-5}$ in the energy range of tens of GeV) the energetic spectrum of strangelets should fall like $\sim E^{-2.4}$, i.e., with spectral index being much smaller than for protons. Actually, this result agrees nicely with $A$-dependence of the spectral index of CR’s obtaine when fitting the world CR data [18].

REFERENCES

1. J. Ridky and P. Travnicek (for DELPHI Collab.), Acta Phys. Polon. 35 (2004) 1813; cf. also J. Ridky, these proceedings.
2. V. Avati et al., Astropart. Phys. 19 (2003) 513.
3. G. Wilk and Z. Wlodarczyk, J. Phys. G22 (1996) L105; Heavy Ion Phys. 4 (1996) 395 and Nucl. Phys. B Proc. Suppl. 52B (1997) 215.

$^4$In fact nothing better can be done because neither ALEPH or DELPHI can, at the moment provide any explanation of this visible discrepancy of their respective results.

$^5$There are still expected data from L3 experiment, however, so far the muonic part is not yet ready [15].

$^6$If it will be finally confirmed by experiment [17].
4. M. Rybczyński, Z. Włodarczyk and G. Wilk, Acta Phys. Polon. B33 (2002) 277.
5. R. Klingerberg, J. Phys. G25 (1999) R273.
6. M. Rybczyński, Z. Włodarczyk and G. Wilk, Nucl. Phys. B Proc. Suppl. 97 (2001) 85.
7. C. Timmermans (L3+C Coll.), 26th Int. Conf. Cosmic Ray Conf., Salt Lake City (1999), Contributed Papers, Vol. 2 (1999) 9. See also: C. Taylor et al., (CosmoLEP Coll.), Cosmic and underground cosmic ray muon experiment in the LEP ring CERN/LEP 99-5 (1999) LEPC/P9 and Cosmic multi-muon events in ALEPH as part of the CosmoLEP project, CosmoLEP Report 1 (1999); cf. also: CERN Courier, Vol. 39-8, October (1999) 29.
8. T. Saito, Y. Hatano and Y. Fukuda, Phys. Rev. Lett. 65 (1990) 2094.
9. P. B. Price, Phys. Rev. D38 (1988) 3813.
10. M. Ichimura et al., Nuovo Cim. A106 (1993) 843.
11. C. M. G. Lattes, Phys. Rep. 65 (1980) 151; J. D. Bjorken and L. D. McLerran, Phys. Rev. D20 (1979) 2353.
12. G. Wilk and Z. Włodarczyk, Nucl. Phys. B Proc. Suppl. 52 (2001) 215.
13. V. Choutko (AMS Coll.), 28 ICRC (2003) OG1, 1765.
14. A. Wrotniak, Report No. 85-195, Univ. of Maryland (1985).
15. See talk by P. Le Coultre, these proceedings.
16. J. Madesn and J. M. Larsen, Phys. Rev. Lett. 90 (2003) 121102.
17. See talks by: K. Shinozaki (AGASA), S. Westerhoff (HIRES) and K. H. Kampert (AUGER), these proceedings.
18. B. Wiebel-Sooth, Astronomy and Astrophysics 330 (1998) 389; see also A. Dar, astro-ph/0409464.