Grand Unification signal from ultrahigh energy cosmic rays?

Z. Fodor and S.D. Katz

Institute for Theoretical Physics, Eötvös University, Pázmány 1, H-1117 Budapest, Hungary

(March 25, 2022)

The spectrum of ultrahigh energy (above $\approx 10^9$ GeV) cosmic rays is consistent with the decay of GUT scale particles. The predicted mass is $m_X = 10^9$ GeV, where $b = 14.6^{+1.5}_{-1.7}$.

PACS numbers: 98.70.Sa, 96.40.Pq, 13.87.Fh

The interaction of protons with photons of the cosmic microwave background radiation (CMBR) predicts a sharp drop in the cosmic ray flux above the Greisen-Zatsepin-Kuzmin (GZK) cutoff around $5 \times 10^{19}$ eV [1]. The available data shows no such drop. About 20 events above $10^{20}$ eV were observed by experiments such as Akeno Giant Air Shower Array (AGASA) [2], Fly’s Eye [3], Haverah Park [4], Yakutsk [5] and HiRes [6]. Future experiments, particularly Pierre Auger [7], will have a much higher statistics.



SPs are very efficiently produced by the various mechanisms at post inflationary epochs [22]. Note, that our analysis of SP decay covers a much broader class of possible sources. Several non-conventional UHECR sources (e.g. EG long ordinary strings [20] or galactic vortons [21], monopole-antimonopole pairs connected by strings [22]) produce the same UHECR spectra as decaying SPs.

In this letter we study the scenario that the UHECRs are coming from decaying SPs and we determine the mass of this $X$ particle $m_X$ by a detailed analysis of the observed UHECR spectrum. We discuss both possibilities that the UHECR protons are produced in the halo of our galaxy and that they are of EG origin and their propagation is affected by CMBR. Here we do not investigate how can they be of halo or EG origin, we just analyze their effect on the observed spectrum instead. We assume that the SP decays into two quarks (other decay modes would increase $m_X$ in our conclusion). After hadronization these quarks yield protons. The result is characterized by the fragmentation function (FF) $D(x,Q^2)$ which gives the number of produced protons with momentum fraction $x$ at energy scale $Q$. For the proton’s FF at present accelerator energies we use ref. [23]. We evolve the FFs in ordinary [24] and in supersymmetric [25] QCD to the energies of the SPs. This result can be combined with the prediction of the MLLA technique, which gives the initial spectrum of UHECRs at the energy $m_X$. Altogether we study four different models: halo-SM, halo-MSSM, EG-SM and EG-MSSM.

Ref. [26] showed that both AGASA and Fly’s Eye data demonstrated a change of composition, a shift from heavy –iron– at $10^{17}$ eV to light –proton– at $10^{19}$ eV. Thus the UHECRs are most likely to be dominated by protons and in our analysis we use them exclusively.

The FF of the proton can be determined from present experiments [23]. (Note, that QCD event generators e.g. HERWIG [27] predict the overall proton multiplicity correctly, however they describe the large $x$ region of the FF inaccurately.) The FFs at $Q_0$ energy scale are $D_i(x, Q_0^2)$, where $i$ represents the different partons (quark/squark or gluon/gluino). The FFs can not be determined in perturbative QCD; however, their evolution in $Q^2$ is governed by the DGLAP equations [28]:

$$g_\nu \propto \int \frac{d^2 Q}{Q^2} \frac{1}{x} \frac{d^2 D_i(x, Q^2)}{d^2 x}$$

where $D_i(x, Q^2)$ gives the number of produced protons with momentum $x$ at energy scale $Q$. The FFs at $Q_0^2$ are then determined by the DGLAP equations, which can be solved numerically. The resulting FFs for ordinary [24] and supersymmetric [25] QCD are shown in figure 1. The resulting $m_X$ is consistent with the decay of GUT scale particles. The predicted mass is $m_X = 10^9$ GeV, where $b = 14.6^{+1.5}_{-1.7}$. 

The available data shows no such drop. About 20 events above $10^{20}$ eV were observed by experiments such as Akeno Giant Air Shower Array (AGASA) [2], Fly’s Eye [3], Haverah Park [4], Yakutsk [5] and HiRes [6]. Future experiments, particularly Pierre Auger [7], will have a much higher statistics.

SPs are very efficiently produced by the various mechanisms at post inflationary epochs [22]. Note, that our analysis of SP decay covers a much broader class of possible sources. Several non-conventional UHECR sources (e.g. EG long ordinary strings [20] or galactic vortons [21], monopole-antimonopole pairs connected by strings [22]) produce the same UHECR spectra as decaying SPs.

In this letter we study the scenario that the UHECRs are coming from decaying SPs and we determine the mass of this $X$ particle $m_X$ by a detailed analysis of the observed UHECR spectrum. We discuss both possibilities that the UHECR protons are produced in the halo of our galaxy and that they are of EG origin and their propagation is affected by CMBR. Here we do not investigate how can they be of halo or EG origin, we just analyze their effect on the observed spectrum instead. We assume that the SP decays into two quarks (other decay modes would increase $m_X$ in our conclusion). After hadronization these quarks yield protons. The result is characterized by the fragmentation function (FF) $D(x,Q^2)$ which gives the number of produced protons with momentum fraction $x$ at energy scale $Q$. For the proton’s FF at present accelerator energies we use ref. [23]. We evolve the FFs in ordinary [24] and in supersymmetric [25] QCD to the energies of the SPs. This result can be combined with the prediction of the MLLA technique, which gives the initial spectrum of UHECRs at the energy $m_X$. Altogether we study four different models: halo-SM, halo-MSSM, EG-SM and EG-MSSM.

Ref. [26] showed that both AGASA and Fly’s Eye data demonstrated a change of composition, a shift from heavy –iron– at $10^{17}$ eV to light –proton– at $10^{19}$ eV. Thus the UHECRs are most likely to be dominated by protons and in our analysis we use them exclusively.

The FF of the proton can be determined from present experiments [23]. (Note, that QCD event generators e.g. HERWIG [27] predict the overall proton multiplicity correctly, however they describe the large $x$ region of the FF inaccurately.) The FFs at $Q_0$ energy scale are $D_i(x, Q_0^2)$, where $i$ represents the different partons (quark/squark or gluon/gluino). The FFs can not be determined in perturbative QCD; however, their evolution in $Q^2$ is governed by the DGLAP equations [28]:
\begin{tabular}{|c|c|c|c|c|}
\hline
flavor & Q(GeV) & N & \alpha & \beta \\
\hline
u = 2d & 1.41 & 0.402 & -0.860 & 2.80 \\
s & 1.41 & 4.08 & -0.0974 & 4.99 \\
c & 2.9 & 0.111 & -1.54 & 7.69 \\
b & 9.46 & 40.1 & 0.742 & 11.4 \\
t & 350 & 1.11 & -2.05 & 3.74 \\
g & 1.41 & 0.740 & -0.770 & 7.69 \\
\hat{q}, \hat{g} & 1000 & 0.82 & -2.15 & 10.8 \\
\hline
\end{tabular}

Table I. The fragmentation functions of the different partons using the parametrization \( D(x) = N x^\alpha (1 - x)^\beta \) at different energy scales (second column).

\[
\frac{\partial D_j(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{j_1}(z, \alpha_s(Q^2)) D_j(x, Q^2).
\]

One can interpret \( P_{j_1}(z) \), the splitting function, as the probability density that a parton \( i \) produces a parton \( j \) with momentum fraction \( z \). Analogous evolution equations can be obtained by using coherent branching (angular ordering) for the emitted gluons. We use this technique too. Results of direct Monte-Carlo jet simulations are also available (cf. [28]). We include the uncertainties coming from the different choices of evolution in our final error estimates. We solve the DGLAP equations numerically with the conventional QCD (SM case) splitting functions and with the supersymmetric (MSSM case) ones [35]. For the top and the MSSM partons we used the FFs of ref. [28]. While solving the DGLAP equations each parton is included at its own threshold energy. The uncertainties of the different energies each parton is included at its own threshold energy. We solve the DGLAP equations and the MLLA result at a given \( x \), \( \alpha \), \( \beta \) value. Our final result on \( x \) is rather insensitive to the choice of \( x, \alpha, \beta \), the uncertainty is included in our error estimate. We also determined the FF of the proton and the MSSM partons using the parametrization \( D(x) = N x^\alpha (1 - x)^\beta \), where \( N = 1, \alpha = 0, \beta = 1 \). The MLLA describes the observed hadroproduction quite accurately in the small \( x \) region [41]. For large values of \( x \) the MLLA should not be used. We smoothly connect the solution for the FF obtained by the DGLAP equations and the MLLA result at a given \( x \). Our final result on \( m_X \) is rather insensitive to the choice of \( x, \alpha, \beta \), the uncertainty is included in our error estimate. We also determined the FF of the pion. The FF shows the FF for the proton and pion at \( Q = 10^{16} \) GeV in SM and MSSM.

UHECR protons produced in the halo of our galaxy can propagate practically unaffected and the production spectrum should be compared with the observations.

Particles of EG origin and energies above \( \approx 5 \times 10^{19} \) eV loose a large fraction of their energies due to interactions with CMBR [1]. This effect can be quantitatively described by the function \( P(\tau, E, E_c) \), the probability that a proton created at a distance \( \tau \) with energy \( E \) arrives at Earth above the threshold energy \( E_c \) [11]. This function has been calculated for a wide range of parameters in [42], which we use in the present calculation. The original UHECR spectrum is changed at least by two different ways: (a) there should be a steepening due to the GZK effect; (b) particles losing their energy are accumulated just before the cutoff and produce a bump. We study the observed spectrum by assuming a uniform source distribution for UHECRs.

Our analysis includes the published and the unpublished (from the www pages of the experiments on 17/08/00) UHECR data of [2–4, 6]. Due to normalization difficulties we did not use the Yakutsk results. We also performed the analysis using the AGASA data only and found the same value (well within the error bars) for \( m_X \). Since the decay of SPs results in a non-negligible flux for lower energies \( \log(E_{\text{min}}/\text{eV}) = 18.5 \) is used as a lower end for the UHECR spectrum. Our results are insensitive to the definition of the upper end (the flux is extremely small there) for which we choose \( \log(E_{\text{max}}/\text{eV}) = 26 \). As it is usual we divided each logarithmic unit into ten bins. The integrated flux gives the total number of events in a bin. The uncertainties of the measured energies are about 30% which is one bin. Using a Monte-Carlo method we included this uncertainty in the final error estimates. The predicted number of events in a bin is given by

![Graph](https://via.placeholder.com/150)

FIG. 1. The FFs averaged over the quark flavors at \( Q = 10^{16} \) GeV for proton/pion in SM (solid/dotted line) and in MSSM (dashed/dashed-dotted line) in the relevant \( x \) region. To show both the small and large \( x \) behavior we change from logarithmic scale to linear at \( x = 0.01 \).
The best fit in the EG-MSSM scenario. The first bump for $\chi^2$ value for the mass, whereas $\chi^2$ consistent with the SP decay.

Clearly, the error bars are large enough to be depicted in full. Clearly, the error bars are large enough to be consistent with the SP decay.

$$N(i) = \int_{E_i}^{E_{i+1}} \left[ A \cdot E^{-3.16} + B \cdot j(E, m_X) \right],$$  \hspace{1cm} (2)

where $E_i$ is the lower bound of the $i^{th}$ energy bin. The first term describes the data below $10^{19}$ eV according to $\chi^2$ where the SP decay gives negligible contribution. The second one corresponds to the spectrum of the decaying SPs. A and B are normalization factors.

The expectation value for the number of events in a bin is given by eqn. (2) and it is Poisson distributed. To determine the most probable $m_X$ value we used the maximum-likelihood method by minimalizing the $\chi^2(A, B, m_X)$ for Poisson distributed data $\chi^2$

$$\chi^2 = \sum_{i=18.5}^{26.0} 2 \left[ N(i) - N_o(i) + N_o(i) \ln \left( N_o(i)/N(i) \right) \right],$$  \hspace{1cm} (3)

where $N_o(i)$ is the total number of observed events in the $i^{th}$ bin. In our fitting procedure we have three parameters: $A$, $B$ and $m_X$. The minimum of the $\chi^2(A, B, m_X)$ function is $\chi^2_{min}$ at $m_{X_{min}}$ which is the most probable value for the mass, whereas $\chi^2(A', B', m_X) \equiv \chi^2_{\min}(m_X) = \chi^2_{\min} + 1$ gives the one-sigma (68%) confidence interval for $m_X$. Here $A'$, $B'$ are defined in such a way that the $\chi^2(A, B, m_X)$ function is minimalized in $A$ and $B$ at fixed $m_X$. Fig. 2 shows the measured UHECR spectrum and the best fit in the EG-MSSM scenario. The first bump of the fit represents particles produced at high energies and accumulated just above the GZK cutoff due to their energy losses. The bump at higher energy is a remnant of $m_X$. In the halo models there is no GZK bump, so the relatively large $x$ part of the FF moves to the bump around $5 \times 10^{19}$ GeV resulting in a much smaller $m_X$ than in the EG case. An interesting feature of the GZK effect is that the shape of the produced GZK bump is rather insensitive to the injected spectrum so the dependence of $\chi^2$ on the choice of the FF is small. The experimental data is far more accurately described by the GZK effect (dominant feature of the EG fit) than by the FF itself (dominant for halo scenarios).

To determine the most probable value for the mass of the SP we studied 4 scenarios. Fig. 3 contains the $\chi^2_{\min}$ values and the most probable masses with their errors for these scenarios. (The uncertainties coming from the FFs are included in our error estimates on $m_X$.)

The UHECR data favors the EG-MSSM scenario. The goodnesses of the fits for the halo models are far worse. The SM and MSSM cases do not differ significantly. The most important message is that the masses of the best fits (EG cases) are compatible within the error bars with the MSSM gauge coupling unification GUT scale.

The SP decay will also produce a huge number of pions which will decay into photons. Our spectrum contains 94% of pions and 6% of protons. This $\pi/p$ ratio is in agreement with which showed that for different classes of models $m_X \lesssim 10^{16}$ GeV, which is the upper boundary of our confidence intervals, the generated gamma spectrum is still consistent with the observational constraints. We performed the whole analysis including the pion produced $\gamma$s in eqn. (3). The results agree with our results of Fig. 3 within errorbars, which is easy
to understand. For the EG case high energy $\gamma$-s dominate at energies where the observed flux is zero [25]. For the halo case the agreement is resulted by the similarity (except normalization) between $D_p$ and $D_\gamma$ (cf. Fig. 8).

In the near future the UHECR statistics will probably be increased by an order of magnitude [7]. Performing our analysis for such a statistics the uncertainty of $m_\chi$ was found to be reduced by two orders of magnitude.

Since the decay time should be at least the age of the universe it might happen that such SPs overclose the universe. Due to the large mass of the SPs a single decay results in a large number of UHECRs, thus a relatively small number of SPs can describe the observations. We checked that in all of the four scenarios the minimum density required for the best-fit spectrum is more than ten orders of magnitude smaller than the critical one.

Details will be presented in a subsequent paper [46].

We thank B.A. Kniehl for providing us with the proton’s FF prior to its publication and F. Csikor for useful comments. This work was partially supported by Hungarian Science Foundation grants No. OTKA-T29803/T22929-FKP-0128/1997.

[1] K.Greisen, Phys.Rev.Lett. 16, 748 (1966); G.T.Zatsepin, V.A.Kuzmin, Pisma Zh.Exp.Teor.Fiz. 4, 114 (1966).
[2] M.Takeda et al., Phys. Rev. Lett. 81, 1163 (1998); astro-ph/9902238 www-akeno.icrr.u-tokyo.ac.jp/AGASA/
[3] D.J.Bird et al., Phys. Rev. Lett. 71, 3401 (1993); Astrophys. J. 424, 491 (1994); ibid 441, 144 (1995).
[4] M.A.Lawrence, R.J.O. Reid and A.A. Watson, J. Phys. G17, 773 (1991).
[5] N.N.Efimov et al., "Proc. Astrophysical Aspectes ...", M. Nagano and F. Takahara, World Sci., Singapore, 1991.
[6] D.Kieda et al., to appear in Proc. of the 26th ICRC, Salt Lake, 1999; www.physics.utah.edu/Resrch.html.
[7] M.Boratav, Nucl. Phys. Proc. 48, 488 (1996); C.K. Guerard, ibid 75A, 380 (1999); X. Berton, M. Boratav, A. Letessier-Selvon, astro-ph/0001516.
[8] N.Hayashida et al., Phys. Rev. Lett. 77, 1000 (1996).
[9] Y. Uchihori et al., Astropart. Phys. 13, 151 (2000).
[10] S.L.Dubovskiy, P.G.Tinyakov, JETP Lett. 68, 107 (1998); V.Berezinsky, A.A. Mikhailov, Phys. Lett. B449, 61 (1999); C.A. Medina Tanco, A.A. Watson, Astrop. Phys. 12, 25 (1999).
[11] S. Yoshida, M. Teshima, Prog. Theor. Phys. 89, 833 (1993); F.A.Aharonian, J.W. Cronin, Phys. Rev. D50, 1892 (1994); R.J. Protheroe, P. Johnson, Astropart. Phys. 4, 253 (1996).
[12] P.Bhattacharjee and G.Sigl, Phys. Rep. 327, 109 (2000).
[13] A.Achterberg et al., astro-ph/9907069.
[14] T.Stanek et al., astro-ph/0003484.
[15] G.Domokos, S.Nussinov, Phys. Lett. B187, 372 (1987); D.Fargion, B. Mele, A. Salis, Astrophys. J. 517, 725 (1999); T.J. Weiler, Astropart. Phys. 11 (1999) 303, Astropart. Phys. 12, 379 (2000) (Erratum); G. Domokos, S. Kovesi-Domokos, Phys. Rev. Lett. 82, 1366 (1999).
[16] P.L.Biermann, P.A. Strittmatter, Astrophys. J. 322, 643 (1987).
[17] C.T.Hill, D.N. Schramm, T.P. Walker, Phys. Rev. D36, 1007 (1987); P. Bhattacharjee, C.T. Hill, D.N. Schramm, Phys. Rev. Lett. 69, 56 (1992); G. Sigl astro-ph/9611190.
[18] V.Berezinsky, A. Vilenkin, astro-ph/9704255.
[19] V.S.Berezinsky, S.I. Grigorieva, in Proc. of the 16th Int. Cosmic Ray Conf., Kyoto 1979, Vol. 2, p. 84.
[20] B.R.Dhandford, Phys. Scr. T85, 191 (2000).
[21] V.Berezinsky, M. Kachelrieß and A. Vilenkin, Phys. Rev. Lett. 79, 4302 (1997).
[22] V.A.Kuzmin, V.A. Rubakov, Phys. Atom. Nucl. 61, 1028 (1998).
[23] J.Ellis et al., Phys. Lett. B247, 257 (1990); Nucl. Phys. B373, 399 (1992); P. Gondolo, G.B. Gelmini, S. Sarkar, Nucl. Phys. B392, 111 (1993).
[24] Ya.I. Azimov, Yu.L. Dokshitzer, V.A. Khoze, S.I. Troyan, Phys. Lett. B165, 147 (1985); Z. Phys. C27, 65 (1985); ibid C31, 213 (1986); C.P. Fong, B.R. Webber, Nucl. Phys. B355, 54 (1991).
[25] V.Berezinsky, M.Kachelriess, Phys.Lett.B434, 61 (1998).
[26] V.Berezinsky, P. Blasi, A. Vilenkin, Phys. Rev. D58, 103515 (1998).
[27] M.Birkel and S. Sarkar, Astropart. Phys. 9, 297 (1998).
[28] S. Sarkar, hep-ph/0005256.
[29] N. Rubin, www.stanford.edu/~rubin/Thesis.ps
[30] for a review see V. Berezinsky, astro-ph/0001163.
[31] G. Vincent, N. Antunes, M. Hindmarsh, Phys. Rev. Lett. 80, 2277 (1998); M. Hindmarsh, hep-ph/9806469.
[32] L.Masperi, G. Silva, Astrop. Phys. 8, 173 (1998).
[33] J.J. Blanco-Pillado, K.D. Olum, astro-ph/9909143.
[34] J.Binnenwies, B.A.Kniehl, G. Kramer, Phys. Rev. D52, 4947 (1995); B.A. Kniehl, G. Kramer, B. Potter, Phys. Rev. Lett. 85, 5288 (2000);Nucl. Phys. B582, 514 (2000).
[35] V.N. Gribov, L.N. Lipatov, Sov. J. Nucl. Phys. 15, 438 (1972); L.N. Lipatov, ibid 20, 94 (1975); G. Altarelli, G. Parisi, Nucl. Phys. B126, 298 (1977); Yu.L. Dokshitzer, Sov. Phys. JETP 46, 641 (1977).
[36] S.K. Jones, C.H. Llewellyn Smith, Nucl. Phys. B217, 145 (1983).
[37] B.R. Dawson, R. Meyhander and K.M. Simpson, Astropart. Phys. 9, 331 (1998).
[38] G. Marchesini et al. Comp. Phys. Comm. 67, 465 (1992).
[39] G. Marchesini and B. R. Webber, Nucl. Phys. B330, 261 (1990). S. Catani, B. R. Webber and G. Marchesini, Nucl. Phys. B439, 655 (1991).
[40] V. Berezinsky and M. Kachelries, hep-ph/0009053.
[41] see eg. P. Abreu et al. Phys.Lett. B459, 397 (1999); G. Abbiendi et al. hep-ex/0002012.
[42] J.N. Bahcall and E. Waxman, hep-ph/9912326.
[43] Z. Fodor, S.D. Katz, hep-ph/0001153.
[44] C. Caso et al., Eur. Phys. J. C3, 172 (1998).
[45] U. Amaldi, W. de Boer, H. Furstenau, Phys. Lett. B260, 441 (1991).
[46] Z. Fodor, S.D. Katz, in preparation.