TeV String Theories, Mini Black Holes and Trans-GZK Cosmic Rays

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We review the proposal that trans-GZK cosmic ray interactions are caused by neutrino primaries. The primaries cause excitations of strings and give rise to extensive air showers (EAS) resembling EAS induced by nuclei. We also show that in “low scale” ($M_* \approx 70$ TeV) string models the excited string and the mini black hole pictures are equivalent.

1. Introduction

The existence of cosmic rays transcending the Greisen-Zatsepin-Kuzmin (GZK) cutoff appear to be a fact of life. While there is still some controversy regarding the observational data, it appears that opinions converge toward acknowledging the existence of trans-GZK events. Clearly, the issue will be satisfactorily clarified once future detectors, such as OWL, EUSO, the Pierre Auger Observatory, various neutrino telescopes, etc. will begin to take data. In the meantime, one may rely upon the existing set of observations and seek an understanding of the phenomenon. It is to be emphasized that if indeed trans-GZK cosmic ray events exist, they pose a serious challenge either to our current understanding of particle physics, or of astrophysics (or, perhaps, both).

• From the particle physics point of view, it is to be noted that the well-known GZK cutoff is a low energy effect: at the GZK energy (of a few times $10^{19}$ eV), the average CMS energy in the interaction of a high energy proton with a photon in the CMB is of the order of the mass of the $\Delta$ resonance. This energy region has been extensively studied for the past half century or so and it is well understood.

• From the astrophysics point of view, starting with the famous search of Elbert and Sommers [1] for possible sources of trans-GZK cosmic rays within the the so called GZK sphere, astrophysicists have been looking at the sky, but, in essence, found no good candidates. The astrophysics problem has been somewhat aggravated by the work of Stanev et al. [2]. Those authors showed that random intergalactic magnetic fields cause the high energy protons to undergo a Brownian motion. As a consequence, the distance along the line of sight of a candidate source for emitting trans-GZK protons has to be less than about $14$ Mpc as opposed to $\approx 50$ Mpc as previously believed on the basis of assuming propagation along a straight line.

There has been no dearth of theoretical schemes proposing to understand the existence of trans-GZK CR events. In fact, currently, the number of theoretical papers on this subject is about an order of magnitude larger then the number of such events observed. This is clearly a very unhealthy situation; however, it will change once the new detectors start collecting data.

Fortunately, a substantial number of the proposed explanations is dead: they are, by now, excluded by accelerator based data, data on the CMB, etc. See the talk of S. Kovesi-Domokos [3] discussing this issue.

In this talk we mainly follow a recent paper of ours [4], where a more detailed discussion of the issues and a more complete list of references can be found.
2. The Survivors

In essence, there are two proposals which have not been excluded by new data or consistency requirements. Both of them assume that the primaries of trans-GZK cosmic rays are neutrinos\(^3\) and both of them rely upon the notion that the characteristic scale of the “new physics” beyond the Standard Model can be in the TeV range, instead of \(10^{13}\) to \(10^{16}\) TeV \([7]\).

- The excited string picture\([6]\)
- The mini black hole picture as applied to cosmic rays\([8]\)

Let us briefly review the main problems any successful model of trans-GZK cosmic rays should solve.

- **The penetration problem.** In the absence of nearby sources, one has to make sure that the primary can penetrate the CMB over large distances. For neutrinos, this requirement is beautifully satisfied: in an interaction of a neutrino having an energy, say, \(10^{20}\) eV, with a typical CMB photon, the CMS energy is of the order of a few hundred MeV. Consequently, one does not even have to now about the existence of the \(W\) and \(Z\) bosons. This is low energy physics: the mean free path of the neutrino is comparable with the horizon size. By contrast, in an interaction with a nucleus in the atmosphere, the CMS energy is in the range of hundreds of TeV. Consequently, one does not even have to now about the existence of the \(W\) and \(Z\) bosons. This is low energy physics: the mean free path of the neutrino is comparable with the horizon size. By contrast, in an interaction with a nucleus in the atmosphere, the CMS energy is in the range of hundreds of TeV. Thus, if indeed the onset of the “new physics” is around a TeV to a few tens of a TeV, one is well in the new physics regime there.

- **The interaction problem.** All observed trans-GZK events are “hadron-like”: it appears that the observed showers have a normal development, with an \(X_{\text{max}}\) (where known) as in a hadronic shower. Hence, if the primaries are neutrinos, the new physics has to have the property that in the new physics regime, neutrinos have a large cross section, about the size of a hadronic one. This is plausible: in string models, once the string is excited, the interactions are unified: all interactions have the same strength.

The surprising fact is that the black hole and string pictures are, in essence, different facets of the same scheme, even though they seem to be based on very different physics.

**How can this happen?**

3. Strings and Black Holes: the Equivalence

Let us illustrate the situation on a simple example. Suppose that we want to produce a highly excited string in a neutrino – quark interaction. (This is possible, since the excited string is unstable and it will eventually decay: there is no conflict with the conservation of energy-momentum.) Apart from trivial factors, the probability of this process is given by:

\[
P \propto \sum_{\alpha} \langle i | O^\dagger | N, \alpha \rangle \langle N, \alpha | O | i \rangle \delta (E - NM_s) \quad (1)
\]

In eq. \(1\) \(\alpha\) stands for the collection of labels necessary for the full specification of states at level \(N\): one has to sum over (most of) those, since the quantum numbers carried by \(|i\rangle\) and \(O\) do not fully specify the substate at level \(N\). (We remember that, apart from a constant – the Regge intercept – the mass of string levels is given by \(M^2 \sim M^2_s N\), where \(N\) is a positive integer. Everywhere, \(M_s\) is the characteristic energy scale of the string model.)

We recognize that the quantity in eq. \(1\),

\[
\rho_M = \sum_{\alpha} \langle N, \alpha | N, \alpha \rangle \delta (E - NM_s) \quad (2)
\]

is just the microcanonical density matrix of the final state. (In statistical mechanics, a smoothing of the delta function is necessary in order to define a level density; in the present context, such a smoothing is automatic if the finite width of resonances is taken into account.) The summation

\(^3\)It is interesting to remember that neutrino primaries for the extreme energy cosmic rays were first proposed by G. Cocconi at one of the early Texas Symposia (1967) and soon thereafter by Berezinsky and Zatsepin \([5]\), based on the Fermi theory of weak interactions. Unfortunately, it appears that Cocconi’s conjecture has not been recorded.
over $\alpha$ leads to the information loss discussed by Amati characteristic of a black hole.

Now, it is intuitively clear that a large microcanonical ensemble is like a canonical one: a sufficiently large system acts like its own thermal reservoir. (In ref. [4] we gave a formal proof of this statement, using a saddle point expansion.) In fact, the temperature of the large ensemble is given by the usual formula all of us learned in an undergraduate course on statistical mechanics, viz.

$$\frac{1}{T} = \frac{\partial S}{\partial E},$$

(3)

where $S$ (the entropy) is just the logarithm of the level density as a function of the energy of excitation.

Thus, for a highly excited string, we may assign a temperature to it. Also, since the level density grows as the exponential of the energy of excitation, there is a limiting temperature to which the system converges in the limit of very high ("infinite") excitations. Thus, at very high excitations, strings $\sim$ black holes.

One might say that this is a neat theoretical construction, perhaps satisfying to the purists who do not like two solutions to the same problem, but does it have observable consequences? Remarkably, the answer is "yes". We now turn to explore the consequences of the equivalence of the string and black hole pictures.

4. Observable Consequences

Consider level densities of the asymptotic form:

$$d(E) = \exp S(E) \sim C \left(\frac{E}{M_*}\right)^{-\gamma} \exp (\alpha(E/M_*).$$

(4)

The quantities $C, \gamma, \alpha, \delta$ depend on the specific model considered. This asymptotic form of the level density comprises all known string models.

We now evaluate the microcanonical density matrix, eq. (2) by means of the saddle point method.

The inverse temperature turns out to be:

$$\beta = \frac{\partial S}{\partial E} \sim -\gamma + \frac{3}{2} \frac{\alpha M_*}{E} + \alpha M_*^{-1}$$

(5)

The temperature is asymptotically constant and, hence, its limit as $E \to \infty$ may be identified with the Hagedorn temperature. It is necessary to take Kaluza-Klein (KK) excitations into account: otherwise, the Hagedorn temperature is not the maximal, but a minimal temperature, which is clearly unphysical. The contribution of the KK excitations to the level density is proportional to $(E/M_*)^n$, $n$ being the number of compactified dimensions. The expression of the Hagedorn temperature in terms of $M_*$ is somewhat model dependent: in the calculations cited above, one has, $T_H = M_* / a$, with $a$ ranging, approximately, between 2 and 4 for various string models. For purposes of numerical estimates, we take $a = 3$.

An estimate of the single particle inclusive cross section was given in ref. [4] and we refer the reader to that article for details. The basis of the estimate is that in the rest frame of the excited resonance (a leptoquark in our case) the distribution of the observed particle is given by a Fermi or Bose distribution, respectively.

Here we summarize the salient features of the inclusive distribution as measured in the laboratory frame.

- The distributions are strongly peaked in the forward direction: they are exponentially decreasing with the emission angle of the observed particle.

In the early days of dual resonance models (ca. 1968), Gabriele Veneziano pointed out that the fixed angle elastic scattering amplitude was exponentially small away from the forward direction. We now see that this result is much more general and it is, in fact, independent of the tree approximation to a dual amplitude.

- The total particle multiplicities can be estimated by creating a model for the hadronization of quarks and gluons, for instance, as it was done in ref. [4]. One arrives at the conclusion that total multiplicities resemble hadron multiplicities created by an incoming heavy nucleus, e.g. Fe. Of course, since at high string excitations the excited string behaves as a system in a heat bath at the Hagedorn temperature, the relative multiplicity of any particle species is pro-
portional to its statistical weight. Hence, a number of prompt leptons is also created, with a smaller (by about a factor of 3, because of the absence of color) statistical weight. However, once one begins a realistic simulation of $\nu$ induced air showers in this picture, there may be a noticeable (and, perhaps, observable) difference in shower development. At this meeting, Claudio Coriano presented the results of a simulation of showers using the semiclassical black hole picture \[11\]. It is likely that an adaptation of the simulation to the scheme presented in this talk will yield interesting and testable results.

• In order to assess the importance of the multiplicity question, let us adopt the approximations made in ref. \[4\] and list the hadronic multiplicities as a function of $n$, the number of compactified dimensions. (Recall that for superstrings, $n = 6$.) The result is summarized below.

| $n$ | 6          | 7          | 8          |
|-----|------------|------------|------------|
| $N_{\text{had}}$ | $1.76 \times 10^4$ | $4.16 \times 10^4$ | $1.12 \times 10^4$ |

Table 1
Hadron multiplicity for various numbers of extra dimensions

We used a value of the characteristic string scale $M_s \approx 80\text{TeV}$, as estimated in \[10\]. This result is to be compared with an extrapolation of hadronic multiplicities assuming that there is no new physics between present day accelerator energies and the energies of trans-GZK cosmic rays. This is relatively easy: most data listed in the particle data group can be fitted by means of a quadratic polynomial in log $s$. In this way, one obtains a baseline: multiplicities in hadronic interactions assuming no “new physics”. Comparing that to what we obtained in our estimates for neutrino induced showers in the string/black hole picture, we can introduce an “effective atomic number”:

$$A_{\text{eff}} = \frac{\text{multiplicity in the string picture}}{\text{extrapolated multiplicity}}$$ (6)

(Of course, this estimate of $A_{\text{eff}}$ assumes a simple superposition picture of air showers induced by nuclei. In any case, the superposition picture is qualitatively correct.) The result is displayed in the next Table.

| $n$ | 6 | 7 | 8 |
|-----|---|---|---|
| $A_{\text{eff}}$ | 69 | 16 | 4 |

Table 2
Comparison of proton and black hole induced showers at $E_L = 3 \times 10^{11}\text{GeV}$ in terms of an “effective atomic number”.

It is noteworthy that A.A. Watson has emphasized over the years that the mass composition of the extreme energy cosmic rays is uncertain and that, in fact, the data may favor a heavy composition, see \[12\] and references quoted in that paper.

5. Discussion: Can we tell the difference?

We presented a scheme of understanding the events induced by extreme energy (trans-GZK) cosmic rays, based on a scenario involving “new physics” as abstracted from a class of string models. It is to be emphasized that the scheme presented here is more general than any specific string model known today. It is essential that one rely upon the paradigm of strongly coupled string models: the features discussed here, as far as one knows, can be realized in strongly coupled string models (and their future generalizations to a yet better theory) only.

It is pleasing that one can can discern some essential differences between the string/black hole scheme advocated here and the heavy nucleus scheme as advocated by Alan Watson, loc. cit. Both schemes favor “heavy nucleus” primaries of
the trans-GZK cosmic ray interactions, see our Table of effective atomic numbers.

However, if the primaries are, indeed, nuclei, they should undergo photo disintegration in sunlight: this is the celebrated Zatsepin effect \[13\]. (Briefly, heavy nuclei entering the neighborhood of our solar system interact with sunlight and undergo photo disintegration. In the process, one or a few nucleons are broken off and get separated from the incoming nucleus. Thus, one can observe practically simultaneous air showers at detectors separated by distances of the order of \[10^3\text{km}\] or so.) Clearly, no Zatsepin effect can be observed if the primary of a trans-GZK air shower is a strongly interacting neutrino. Thus, the presence or absence of the Zatsepin effect will differentiate between the (conservative) heavy nucleus and the (radical?) strongly interacting neutrino schemes, once new detectors, such as both sites of the Pierre Auger observatory, will become operational.

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