Centauros and/or Chirons as evaporating mini black holes

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It is argued that the signals expected from the evaporation of mini black holes - predicted in TeV-scale gravity models with large extra dimensions, and possibly produced in ultra high energy collisions in the atmosphere - have characteristics quite similar to the ones of the Centauro events, an old mystery of cosmic-ray physics.

1. Introduction

The theoretical framework of this talk is the TeV-scale gravity with large extra dimensions. The basic assumption, easily accommodated in Superstring Theory, is that our spacetime is a 4 dimensional hypersurface (a D3-brane) embedded in a 10 dimensional world (the bulk), with the additional feature that all known matter (quarks, leptons, higgses), as well as the carriers of the fundamental interactions of the Standard Model of Particle Physics (photon, W, Z, gluons) are confined on our 4 dimensional subspace. Only gravity can propagate in the bulk. The fact that the only communication with the bulk is via the gravitational force, allows for a fundamental gravitational scale to be of \( \mathcal{O}(1 \text{TeV}) \), while at the same time the size of the extra spatial dimensions may be as large as a fraction of a mm.

Clearly, such a scenario, if true, leads to the exciting prospect of observing string physics, large higher dimensions and quantum gravity effects, within the next few years in the forthcoming accelerator (LHC), neutrino and cosmic-ray experiments.

Even better, in this talk I will argue that the long known Centauro-like events (CLEs) may be due to the formation and subsequent evaporation of mini black holes (MBHs), predicted in the context of the above scenario \cite{[1]}. After a quick review of the relevant scales and of the main features of MBHs in TeV-gravity, as well as of the basic characteristics of the Centauro events, I present in Section 5 the somewhat qualitative arguments that support our interpretation. The talk ends with a critical discussion.

The first steps towards a more quantitative analytical/Monte Carlo investigation of the mini black hole picture are described in \cite{[2]} and \cite{[3]}.

2. TeV-scale gravity models

Even though non-compact extra dimensions are not a priori excluded, the most straightforward realization of the above theoretical scenario is to neglect the tension on the brane, which would modify the gravitational background, and to consider the extra dimensions compact and forming a higher dimensional torus \( T^n \), with equal radii \( R \).

In the simplest case of \( n = 1 \), one is dealing with a 4 dimensional Minkowski space with one extra transverse dimension, a circle of radius \( R \). One may compute the gravitational potential \( \Phi(x, \theta) \) (in the Newtonian approximation) of a point mass \( M \) at the origin, by solving the corresponding Poisson equation

\[
\nabla^2 \Phi + \frac{1}{R^2} \frac{\partial^2 \Phi}{\partial \theta^2} = -G^{(4)} M \delta(x) \frac{\delta(\theta)}{2\pi R}
\]

where \( G^{(4)} \equiv 1/M^3 \) is the 4 dimensional gravitational constant, with fundamental gravitational

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Thus, it is reasonable to expect that for a light black hole the mass is of the order of the weak interaction scale. Lighter black holes cannot exist. At least a few times the fundamental gravitational scale. Near the mass $M$, i.e. for $r \ll R$ and $\theta \ll \pi$ it gives $\Phi \sim 4\pi MC^4/(r^2 + R^2\theta^2)$, the correct expression for a 4 dimensional gravitational potential. At large distances ($r \gg R$) from the mass $M$, on the other hand, one obtains $\Phi \sim 2\pi MG^4/Rr$, the correct 3 dimensional Newtonian potential with Newton’s constant $G_N = 2\pi G^4/R = 2\pi/RM^3$.

These formulas generalize trivially to n toroidal transverse dimensions, in which case Newton’s constant is given by

$$G_N \sim \frac{1}{M^2_N} \frac{1}{(RM^3)^n}$$ (3)

Assume that the fundamental scale $M_N$ of gravity is of the order of the weak interaction scale $M_N \sim O(1 \text{TeV})$. Then, (3) leads to the correct value $G_N \simeq 10^{-38}\text{GeV}^{-2}$ for a value of $R$ given by $R_\pi \simeq 1/(M_N(M_N^2 G_N)^{1/n})$. The value $n = 1$ is excluded, since it leads to $R$ of the order of the size of the solar system. For $n = 2$ one obtains $R_2 \sim 2\text{mm}$. Accelerator and astrophysical constraints lead to a preferred value of $n \geq 4$ with a corresponding value for $R$, much larger than the usual value $10^{-33}\text{cm}$.

3. Mini black holes

As described, the world contains black holes, generalizations to $D = 4 + n$ space-time dimensions of the well known Schwarzschild metric. They are characterized by their mass $M_{BH}$, and can exist as long as $M_{BH}$ is at least a few times the fundamental gravity scale. Lighter black holes cannot exist. Thus, it is reasonable to expect that for $M_*$ a fraction of a TeV, the black hole masses are $M_{BH} \geq 2\text{TeV}$. If, in addition, $M_{BH} \ll M_* (G_N M^2_N)^{-1/n}$, the black hole is essentially 4+n-dimensional, since its Schwarzschild radius $R_S^{-1} \sim M_*(M_/M_{BH})^{(1/n-1)} \sim M_*$ is much smaller than the radius of the large extra dimensions. Black holes are expected to be produced in the collision of any two particles, as long as their impact parameter is smaller than the Schwarzschild radius corresponding to their center of mass energy. A black hole with mass of the order of the ones discussed here can be produced in the collision of an ultra high energy primary with atmospheric partons. The energy of the primary should exceed 1000 TeV and the cross section of the process is conjectured to be $\sigma \sim \pi R^2 \sim 10^{-37}\text{cm}^2 \sim \sigma_{\nu N}$, comparable to the neutrino-nucleon weak interaction cross section at these energies.

Once produced, black holes are believed to evaporate. Even though none has worked out the details of the evaporation process for such light black holes, we shall assume the semiclassical formulas of the standard treatment. So, within $\tau_{BH} \sim M^{-n+2}_*/(4\pi R_S)^{n+3}/(n+1)^{n+3} \sim 10^{-27}$ seconds the black hole decays "democratically" into all kinds of quarks, leptons, gauge bosons, gravitons, higgses. It is a fireball of temperature $T_{BH} = (n+1)/4\pi R_S \sim 1 \text{TeV}$. The number of initial particles emitted by the black hole is determined by its entropy $S_{BH} = \pi M_{BH} R_S/2$. For the case of black holes with mass of order 1-2 TeV of interest here and $n = 4$, this number is of the order of $O(10)$.

4. The Centauro-like events (CLEs)

A normal high energy cosmic ray event is created by the collision of a primary particle with a particle in the atmosphere. Typically a couple of leading partons emerge from the interaction region with high transverse momenta, leaving behind a number of soft fragments, mainly pions with relative abundance 1:1:1. The neutral pions subsequently decay to photons and the shower ends up consisting of low $p_T < 1 \text{GeV/c}$ particles with $N_{hadron}/N_{em} \sim 1$ or even less, if one takes into account the extra photons that will be produced as the shower develops even further.

In contrast to the above picture, several events have been observed since 1972 with the following main characteristics [4]: (a) They were claimed to have taken place at distances smaller than 500 m above the detectors at Pamir and Chacaltaya. It should be pointed out, however, that the altitude was measured directly only for one of these
events, and even that has been questioned recently \cite{5}. (b) They are hadron rich, with typically \( N_{\text{hadron}}/N_{\text{em}} \gg 1 \), (c) have fragments with high \( p_T \gg 1 \) GeV/c, (d) have in many cases a heavy central core with tiny angular opening (halo) and finally, (e) have all been observed with energies above a threshold around 500 TeV in the lab frame.

It should be pointed out that there are severe uncertainties in the observational data. One of the speakers in this meeting presented a reanalysis of the Centauro I and raised serious doubts about the altitudes reported in general for all these events \cite{5}. Others express doubts about the existence of these events altogether, worrying, for instance, about the fact that no such events have been observed yet in Kanbala and Fuji. We shall not take part in this debate at this point. Instead, we shall assume that the events are real and try to interpret them as due to evaporating MBHs, produced by ultra high energy \( E_1 > 1000 \) TeV cosmic ray primaries.

5. CLEs as evaporating mini black holes

The processes of black hole creation, of its subsequent evaporation and, finally of the shower formation in the atmosphere involve all the complications of several different fields, such as cosmic ray physics, quantum gravity/string theory, quantum field theory in curved spacetimes, quark-gluon plasma physics in QCD, low energy non-perturbative QCD, cosmic shower atmospheric physics, of theoretical and experimental high energy physics and astrophysics. Given the incomplete knowledge in all these, a lot has to be done before one can safely confront the observational data. Nevertheless, we shall make a few simplifying assumptions, implicit in the discussion below, and present the arguments in favour of the scenario proposed in \cite{123}.

- **Energy threshold.** The energy threshold of the observed Centauro events, corresponds in the center of mass frame to a mass roughly a few times \( M_\bullet \sim 1 \) TeV. This coincides with the lower bound on the MBH masses, mentioned above. The agreement may be even better, if one takes into account the energy losses into the bulk during the evaporation of the MBH.
- **Production rate.** Assuming that the black holes are produced by primary neutrinos, one may obtain a rough estimate of the number of CLEs based on current figures for the neutrino flux \( \Phi_\nu \).

Since we are interested in neutrino energies of order \( 10^6 - 10^7 \) GeV in the lab frame, one may use the estimates for the gamma-ray burst muon neutrino flux given in \cite{67}. Their analysis leads to \( \sim 20 \) neutrino-induced muon events in a km\(^3\) water or ice per year. Since the cross section of MBH production by neutrinos is of the same order of magnitude as that of muon production, we would expect approximately the above number of black holes for each kind of neutrino. Multiplying by 10-20 (the number of initial jets) and taking into account the lower density of the atmosphere, where the centauros are produced, one ends up with the estimate of about 10-100 events per km\(^2\) per year, which is one to two orders of magnitude smaller than the claimed intensity of the Centauros \cite{4}. However, it seems to us that there is considerable uncertainty in the neutrino flux, which could take care of this discrepancy \cite{8}.

- **Decay products, \( p_T, N_{\text{hadron}}/N_{\text{em}} \).** The black hole, depending on its mass, decays initially to 10-20 fundamental particles of all kinds and with equal probability. Their energies are \( \sim 100 \) GeV each in the black hole frame. The MBH emits almost as a black body of temperature \( \sim 1 \) TeV, all types of matter and force quanta of the Standard Model. The simplest possibility is that these initial partons, with \( p_T \)s also around 50-100 GeV will form hadrons, mostly mesons, of all kinds. The charmed or heavier mesons will decay to lighter ones, the neutral pions will decay to photons almost immediately, but the kaons will survive a distance of a few hundred meters. Since the Ks are counted as hadrons, the ratio of \( N_{\text{hadron}}/N_{\text{em}} \) will be enhanced, if the observation takes place at less than a few hundred meters from the initial interaction. The total multiplicities of the final showers in this case are a few decades \cite{2}.

An alternative possibility is that a hot DCC forms before hadronization of the produced partons. This is known to lead to larger numbers of heavier mesons, which makes it more probable to
obtain a large ratio of the hadronic to the electromagnetic components. However, it is unclear if the system passes through such a DCC state. In any case, it seems that the probability to obtain a superclean Centauro event is rather small.

On the other hand, given the typically large values of $p_T$, the present scenario seems to be the most natural one to explain this feature of the Centauros.

- **Deep penetration.** The deep penetration follows from the assumption of neutrinos, or some other weakly interacting particle (WIMP?), as the primary source of these events. According to the present picture any black holes produced at higher altitudes from the detectors, will give signals similar to standard events. This kind of signature with large hadronic to electromagnetic ratio, could only be obtained from the decay of black holes near the detector.

- **Halo.** At a more speculative level, it has been claimed recently that after evaporation a MBH is expected to leave behind a highly excited string state (a string ball), which in principle will decay to light (compared to $M_*$) particles. Their life-time depends strongly on the excitation level and can be considerably larger than $M_*^{-1}$. These objects may be serious candidates in the context of the present scenario for the projectiles responsible for the halos observed mostly in Chirons.

6. Discussion

On the basis of the above qualitative presentation and of the results of the first numerical steps taken in [2], it seems that the above scenario may account quite successfully (a) for the energy threshold of all these events of order $O$(TeV) in the center of mass frame, (b) the total multiplicities of a few dozen particles, dependent on the number of extra dimensions [2], (c) the large values of $p_T$, and (d) the number and the rough heights of first interaction of the Centauro/Chiron events. It seems less successful in giving the right $N_{\text{hadron}}/N_{\text{em}}$ (especially for the superclean events), even though due to large statistical fluctuations, the numerical simulations [2] have not been conclusive yet.

Several alternative proposals have been put forward to explain these mysterious events [4]. An effort was made in [1] and [9] to compare the various scenarios. It should be clear however, that the study, for instance, of the production and evaporation processes of a MBH or of Strange Quark Matter fireballs, of the potential formation of a high temperature quark-gluon plasma phase or of a DCC, of the hadronization of the 100 GeV partons, all rely on unknown aspects of the physics involved. Much more work is necessary and all possible realizations of a given scenario have to be investigated, before one can safely fit the observational data. The fundamental importance of the issues involved deserves every effort.

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Elsevier instructions for the preparation of a 2-column format camera-ready paper in $\LaTeX$

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The next-to-leading order (NLO) results without the pion field.

| \( \Lambda \) (MeV) | 140 | 150 | 175 | 200 |
|---------------------|-----|-----|-----|-----|
| \( r_d \) (fm)     | 1.973 | 1.972 | 1.974 | 1.978 |
| \( Q_d \) (fm\(^2\)) | 0.259 | 0.268 | 0.287 | 0.302 |
| \( P_D \) (%)      | 2.32 | 2.83 | 4.34 | 6.14 |
| \( \mu_d \)        | 0.867 | 0.864 | 0.855 | 0.845 |
| \( M_{M1} \) (fm)  | 3.995 | 3.989 | 3.973 | 3.955 |
| \( M_{GT} \) (fm)  | 4.887 | 4.881 | 4.864 | 4.846 |
| \( \delta_{VP}^{1B} \) (%) | −0.45 | −0.45 | −0.45 | −0.45 |
| \( \delta_{C2}^{1B} \) (%) | 0.03 | 0.03 | 0.03 | 0.03 |
| \( \delta_{C2}^{N} \) (%) | −0.19 | −0.19 | −0.18 | −0.15 |

The experimental values are given in ref. [4].

packages can be found in \texttt{\LaTeX}'s \texttt{tools} directory.

\textbf{array} Various extensions to \texttt{\LaTeX}'s \texttt{array} and \texttt{tabular} environments.

\textbf{longtable} Automatically break tables over several pages. Put the table in the \texttt{longtable} environment instead of the \texttt{table} environment.

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\textbf{tabularx} Smart column width calculation within a specified table width.

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\texttt{\includegraphics{file}}, which inserts the PostScript file \texttt{file} at its own size. The starred version of this command:

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With the \texttt{graphicx} package one may specify a series of options as a key–value list, e.g.:
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\begin{equation}
H_{\alpha\beta}(\omega) = E^{(0)}(\omega)\delta_{\alpha\beta} + \langle \alpha|W_\pi|\beta \rangle
\end{equation}

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For complex mathematics, use the \texttt{AMSMath} package. This package sets the math indentation to a positive value. To keep the equations flush left, either load the \texttt{espcrc} package after the \texttt{AMSMath} package or set the command
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Above we have listed some references according to the sequential numeric system [1234].