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# Exciting peculiarities of the Planck scale physics

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**Abstract.** By the study of physics at the Planck scale interesting and unusual peculiarities emerge, which make this sector an extremely fascinating field of theoretical investigation; in this paper it is given an overview concerning quantum foam, space rips, branes, duality, mirror symmetry, appeared with the study of the Planck scale physics.

## 1. Introduction

Physics attempts to describe in the most general and mathematical way the laws of nature; during the history one of the objectives of this discipline has been the will to build unifying theories, able to provide an overall description of the universe.

In 1974 scientists discovered a new symmetry, called “supersymmetry” (often abbreviated SUSY). It appeared immediately mathematically very elegant and able to resolve several problems. Supersymmetry has quite different properties with respect to the ordinary known ones and can be used as the basis of a geometric theory of gravity, called “supergravity” (often abbreviated SUGRA); it incorporates and extends the Einstein general relativity. In this theory the number of space-time dimensions is fixed; supergravity theories (there are on fact more versions of it) are not valid for a number of space-time dimensions higher than 11. If that number is exceeded, it does not seem possible to find a mathematically consistent way for correlating the bosonic with the fermionic fields. The extra dimensions would form the analogous of a sphere in 7 dimensions, which is one of the most symmetrical and simple structures. The equations derived from supergravity offer however quantities with infinite values, not having therefore physical interpretation.

Among the attempts to overcome this problem, great importance had in the present extreme physics the so-called “string theories”, or “superstrings”, in their supersymmetric version. In such theories the coordinates of a point (understood as zero-dimensional) are replaced with the coordinates of a 1-D structure, called string [1].

The most promising string theories are formulated in 10 dimensions. The dimensions exceeding the 3+1 spacetime ones are compactified, closed on themselves, giving rise in each point to an internal space. These theories appear to be finite, solving the problem of infinities, which afflicts the supergravity theories; theorists have great expectations on them as latest theories describing the reality in the natural language of quantum field theories. The other followed way was the quantum gravity. At this level very small lengths and times are considered, of order of the Planck length unit  $L_{Planck}$  ( $L_{Planck} = 1.61 \cdot 10^{-33} \text{ cm}$ ) and Planck time  $t_{Planck}$  ( $t_{Planck} = 5.36 \cdot 10^{-44} \text{ s}$ ). At such scale the distinction between past and future becomes



uncertain and spacetime is chaotic and fluctuating [2]; special and unusual features appear, which are the subject of current research in the field of speculative physics, also called "extreme physics", with interesting and deep relations with philosophy [3].

## 2. The quantum foam

The two pillars of modern physics are Einstein General Relativity (GR), which concerns the gravitation, and Quantum Mechanics (QM), which describes the world at micro-level. These theories had a lot of experimental confirmations and all their predictions have been experimentally confirmed with high accuracy. But there is a big problem afflicting them, their incompatibility.

One of the basis of QM is the uncertainty principle; according to it, everything is subject to quantum fluctuations, the gravitational field too. According to classical physics, the value of the gravitational field in empty space is zero; with QM it becomes oscillating, due to the quantum fluctuations. The uncertainty principle leads to an increase of such oscillations, reducing the size of the regions of considered space. Since the gravitational field is reflected in the space curvature, quantum fluctuations lead to distortions of the space structure, increasing with respect to the decrease of distances. The magnitude order under which the quantum fluctuations are very important is the Planck length  $L_{Planck}$ ; at such length the structure of spacetime is not smooth and regular, the random fluctuations due to quantum effects are so pronounced to give a geometry with irregular curvature. The structure of spacetime results twisted and the conventional notions of displacement in the three ordinary dimensions lose their classical meaning. Theorists call this environment "quantum foam" [4].

Therefore, at ultramicroscopic level, two of the most significant elements of GR and QM, the geometric model of spacetime and the uncertainty principle respectively, come into direct conflict.

String theories, in which the concept of point-like particle is replaced with that of 1-D extended vibrating object, allow an overcoming of the problem of these strong quantum fluctuations.

The string extension implies the impossibility to probe the structure of objects shorter than its length, i.e. to go under  $L_{Planck}$ . Strings, as elementary constituents of the universe, cannot probe lengths smaller than  $L_{Planck}$ , therefore are not influenced by strong quantum fluctuations; so the infinities of quantum theories of gravitation based on the concept of point-like particles are not present at string level. String theories establish that the spatial dimensions cannot become less than  $L_{Planck}$ ; beyond this length the common notion of distance loses meaning, it is studied with a new geometry, the quantum geometry [5,6].

## 3. Space rips

According to GR, it does not possible that the geometric texture of the space tears; the metric relations of this theory require a smooth space, i.e. without sharp tips and folds, framed distinct pieces, rips. At the Planck scale, holes and rips might on the contrary represent a rather common characteristic of the space structure. String theories show that particular physical circumstances can tear the space. In 1987 it was discovered that it is possible to transform some Calabi-Yau (C-Y) spaces (spaces in which are compactified the extra dimensions) in others by making a puncture on their surface and then mending the hole according to a precise mathematical process.

The procedure can be simply described as follows: it shrinks a sphere inside a C-Y space to the size of a point, operating a sort of bottleneck in space; space tears and produces a sphere which, by swelling, makes again smooth its surface. The original (initial) sphere has in this way undergone a procedure called "flop". In some cases the new C-Y space produced by a flop is topologically different by the initial one, which means that it is impossible to obtain a final

C-Y space deforming the initial one, without producing rips in any intermediate step of the previously indicated operation. There occur therefore transitions with topology change via a flop; flop transitions produce rips in the space texture. The theorist Edward Witten, among the first scientists to study this peculiarity, has proved that the universe sheet described by a string provides a shield which erases the potentially damage effects associated with a rip of the space texture. A string can perform two different types of motion near a rip, whereas a particle can move in one way only; the string can on fact move also forming a circumference around the rip, surrounding it. So the world sheet of the string constitutes a protective barrier able to neutralize exactly the consequences of the geometric space degeneration. According to the Feynman's quantum mechanics formulation, the string moves "sniffing" all possible trajectories; the observed motion results by the combination of all possible paths. Among all the possible string trajectories, it must be considered also the ones wrapping around the rip. QM takes into account the physical effects arising from all possible trajectories, resulting so infinite "protective" ways surrounding the rip. These pathways contribute neutralizing the possible "cosmic catastrophe" produced by the rip.

The transformations which produce the above described rips are technically called "topology changing transitions". As a further consequence, the geometric degeneration predicts no particular effect from the physical point of view. Rips can occur also in the 3 extended dimensions, not only in the extra dimensions of the C-Y compactification. It happens that the mass values of the individual particles change, i.e. the energies of the possible vibration modes, but without discontinuity. Experimental measures of the masses of elementary particles in the most important experimental research centers show actually that these masses are significantly stable in time. In the first instants after the Big Bang the masses of particles changed in time; so there is the probability that during this period occurred rips, with consequent change in topology. If actually the space texture is undergoing a rip, it should happen very slowly, so that the effects on the masses are less than the resolving power of the current experimental devices [2,4].

#### 4. The branes

String theories involve a different spacetime with respect to the common ideas, with very particular characteristics, such as a greater number of dimensions, some of which "rolled" on themselves forming particular subspaces, which can have incredible transformations, such as to shoot up, tear, selfsaw.

Advanced research on the M-theory, result of the second superstring revolution, theory that unifies the previous indicated string theories into a comprehensive conceptual framework, provides an 11-D spacetime. The branes are extended objects appearing in string theories, p-branes in general (p-dimensional objects), basic constituents behaving for some aspects as point particles at large scales, but with different properties at microscopic level. Increasing the string coupling  $\alpha'$ , fundamental parameter of string theories, related to the string tension by the relation  $T_{string} = 1/2\pi\alpha'$ , a new dimension becomes visible. The string expands into a membrane, whose width is controlled by the value of the coupling constant. The perturbative scheme (with  $\alpha' < 1$ ) leads to a 10-D universe with 1-D strings; this picture seems to be the approximation of a 11-D universe with 2-D membranes [7].

The configuration studies of such theories (the BPS states) (with properties determined by means of arguments based on symmetry) led to the evaluation of their masses, charges and geometrical shape. Some BPS states are 1-D strings, other states are 2-D membranes and there are also higher dimensional objects. The possibilities match the number of spatial dimensions.

Despite the presence of these extended objects with a different number of spatial dimensions, strings (or 1-branes) maintain a particular role; it has been shown that the mass of the extended objects of any size, with the only exception of strings, is inversely proportional to the value of

the coupling constant of the respective theory.

This implies that in the case of “weakly coupled” theories all the extended objects (except strings) have “enormous” masses (of order of  $10^{-4} \div 10^{-5} g$ , i.e. heavier than the Planck mass  $m_{Planck} = 2.18 \cdot 10^{-5} g$ ). It follows that very high energies are required for producing them, thus they have a negligible effect on a great part of physics. Increasing the constant, on the contrary, the multidimensional branes become lighter and therefore more important.

The appearance of the new dimension changes the structure of the string, transforming it in a 2-D “belt”. At dimensionality level, an interesting analogy can be done:

- (i) the membrane has a so small “width” to seem a string;
- (ii) the 11<sup>th</sup> dimension is so small to be undetectable using the perturbative equations.

P-branes play an important role in string theory, related to the fact that the approximate equations (result of perturbative methods) indicate as possible the collapse of a 4-sphere in a C-Y space. It would give rise to serious negative consequences, i.e. the creation of a bottleneck in the space structure with consequent production of unwanted infinities. P-branes can wrap and completely cover a part of a (p-1)-D space, avoiding therefore this problem [8,9].

## 5. Mirror symmetry and duality

String theories increase the connections between physics and geometry; the properties of vibrating strings are largely determined by the properties of the compactified space components. In such theories it is possible that a circle with radius  $R$  and another with radius  $1/R$  are undistinguished from a physical point of view; the particles masses and charges in a universe of radius  $R$  are the same as those of a universe of radius  $1/R$ . This particular aspect derives by considerations regarding the string states spectrum. The two universes (with supposed circular dimension) are geometrically different, but physically undistinguishable.

If  $R$  is of order of  $15 \cdot 10^9 ly$ , such scenario results to be physically equivalent to a universe with the 3 spatial dimensions as ordinary circumferences of radius  $R$  of order of  $10^{-61} L_{Planck}$ . The pairs of C-Y spaces, physically equivalent but mathematically different, are indicated as “mirror manifolds”. Two spaces with this feature are not the mirror images of each other in the ordinary sense; they have different geometrical properties, but give rise to the same universe when used for the compactification of the extra dimensions of string theories; in this case there is a “mirror symmetry”.

The concept of duality is also referred to theoretical models which, although quite distinct, describe exactly the same physics, for example two universes with a circular dimension of radius  $R$  and  $1/R$  respectively: the properties of strings imply the same physical situation.

This duality symmetry, which prevent us from distinguishing between large and small distance scales, is called “T-duality”; it comes from the compactification of extra space dimensions in a 10-D superstring theory. In general, we can exchange the compactification radius  $R$  with a  $\alpha' / R$  radius, exchanging the winding modes of a string with the quantized momentum modes. T-duality is referred only to string physics; for point-like particles it is not possible, because in this case there aren't winding modes. String theory implies that the separation between large vs. small distance scales in physics is not a fixed separation, but dependent upon the type of probe used for measuring the distances.

In relation to the mirror symmetry we can think to two different compactification ways of the extra dimensions in a C-Y space; the two universes will have the same physical properties.

Theorists showed that the five developed string theories are different ways to describe the same fundamental physical theory. The duality implies that, considering two of them, one changes into another if we vary their coupling constants. Considering also the dualities concerning the spacetime geometry, the five theories and M-theory are connected by a duality network.

The six theories can be graphically visualized with a pentagonal structure, with M-theory at the center.

Among the SUGRA theories, as possible reconciliation elements between GR and QM, the closest to this big objective are formulated in 10 or 11 dimensions. A greater number of dimensions was excluded for both theoretical and experimental reasons. In the "low energy" processes, where the "extended" character of the string is not detectable, it is possible to approximate a string with a point-like particle without internal structure, using the usual scheme of quantum field theories.

Supergravity theory is thus the quantum field theory which best approximates the string theory. Considering this theory too, the unified scheme becomes an hexagonal-type structure, always with the M-theory at the center [6,8,10].

## 6. Closing remarks

String theories have allowed extraordinary advances in the description of an ultimate theory of the universe. They have motivated an understanding of black holes in higher dimensions and of extended objects such as strings and branes.

The study of these theories has opened the way to exciting scenarios, in which unusual situations, as quantum foam, space rips, branes, duality, mirror symmetry appear, characterizing the Planck scale physics.

Perhaps spacetime geometry is not something of a fundamental nature in string theory, but it emerges in the theory at large distance scales or weak coupling. This and all the previously mentioned Planck scale phenomena are ideas with fascinating philosophical implications.

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