Solitons as Key Parts to Produce a Universe in the Laboratory

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14th September 2006

Abstract

Cosmology is usually understood as an observational science, where experimentation plays no role. It is interesting, nevertheless, to change this perspective addressing the following question: what should we do to create a universe, in a laboratory? It appears, in fact, that this is, in principle, possible according to at least two different paradigms; both allow to circumvent singularity theorems, i.e. the necessity of singularities in the past of inflating domains which have the required properties to generate a universe similar to ours.

The first of them is substantially classical, and is built up considering solitons which collide with surrounding topological defects, generating an inflationary domain of space-time.

The second is, instead, partly quantum and considers the possibility of tunnelling of past-non-singular regions of spacetime into an inflating universe, following a well-known instanton proposal.

We are, here, going to review some of these models, as well as highlight possible extensions, generalizations and the open issues (as for instance the detectability of child universes and the properties of quantum tunnelling processes) that still affect the description of their dynamics. In doing so we will remark how the works on this subject can represent virtual laboratories to test the role that fundamental principles of physics (particularly, the interplay of quantum and general relativistic realms) played in the formation of our universe.

1 State of the Art of Universe Creation in the Laboratory

Cosmology is usually considered as an observational discipline, not susceptible of a direct experimental approach. This seems, of course, quite intrinsic to the discipline itself, which deals with problems related to the birth of our universe and its evolution in the present state; in fact the very meaning of the word

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1 arXiv:gr-qc/0609050v1 14 Sep 2006
cosmology (stemming from the Greek word cosmos, which meant beauty, harmony) seems to bind us to a passive, contemplative attitude in the study of the universe.

On the other hand, even without considering phenomena proper of the quantum world, already General Relativity, a classical theory, brings a challenge to the above perspective, by raising for the first time the concept of causality as a central one in physics. Because of causal relationships, the domain of what can be experienced/observed might be, or more likely is, only a subset of what is existing. At the same time the very concept of causality and its relationship with the global spacetime structure brings up another problem in the scenario of cosmology. In fact, the simplest models of the universe built according to General Relativity and with an at least reasonable degree of consistency with what we observe, seem doomed to begin with an initial singularity. The breakdown of field equations at the very first event of our history (universe creation) is very unfortunate for our description in terms of differential equations, since field equations break down exactly where we would like to set up the initial conditions.

At the same time, if we trace the life of our universe back in time closer and closer to its very beginning, for instance at the exit of the inflationary era, we will see that many parameters describing it are quite far from the domain of “very large scales” which characterizes the present observable universe. In fact for a Grand Unified Theory scale of $10^{14}$ Gev the universe could emerge from a classical bubble which starts from a very small size if the mass of the bubble is of the order of about $10^4$ Kg (by using quantum tunnelling the mass of the bubble could be arbitrarily small, but the probability of production of a new universe out of it would be reduced). Although the density of the universe would have been quite higher than what we can realize with present technologies, the orders of magnitude of the other parameters make not unreasonable to ask the question: might we be able to build a universe in the laboratory? Already years ago it was, in fact, recognized that this question can have, in principle, a positive answer and a simple model of the creation process involving semiclassical effects was suggested. Since then, further decisive developments of those early results have not appeared; there have been a few more proposals, addressing with simple models some qualitative issues, but the problems which emerged in the earliest formulations are, somehow, still open. In our opinion, it is certainly interesting, if not necessary, to study in more detail and with systematic rigor these problems as well as other realistic answers to the above question. As we pointed out, this question is not a purely academic one and we think that a different perspective (an experimental rather than observational one) has interesting consequences. In the rest of this section we are then going to give a concise review of the state of the art in the field according to this point of view. It is worthwhile to remark that, this perspective can be considered much more promising nowadays, since observations have pushed our eyes further back in time, providing us with information about our universe in its earliest stages of life. This has allowed tighter constrains on the parameters of models describing the early universe, so that most of the problems can now be attacked more easily. For example, it
is now easier to identify the fundamental elements (building blocks) which we can use to model the creation of a universe that will evolve in something similar to the present one. At the same time, we could have a deeper insight of the fundamental principles that forged the earliest evolution of the universe, with more hope to enlighten a crucial one, which is the interplay between General Relativity and Quantum Theory.

This said, we are now going to make a closer contact with some of the models for the formation of the universe. These are the ones studying the dynamics of vacuum bubbles and those developing the idea of topological inflation (both aspects considered also in a semiclassical framework).

The study of vacuum decay initiated more than 30 years ago with the work of Callan and Coleman [13, 12]; in the following years the interest in the subject increased and the possible interplay of true vacuum bubbles with gravitation was also studied [14, 35]. At the same time, and as opposed with the true vacuum bubbles of Coleman et al., false vacuum bubbles were also considered. In connection with gravity, the classical behavior of regions of false vacuum, first studied by Sato et al. [43, 31, 41, 37, 42, 30], was for example analyzed in [6, 8] and in [7].

From the classical point of view, false vacuum bubbles have an energy density which is higher than that of the surrounding spacetime. Because of this, although the space inside the bubble can undergo an exponential inflation, the pressure difference with respect to the outside implies that the bubble cannot displace the external space. The child universe solutions appear then as expanding bubbles of false vacuum which disconnect from the exterior region. These solutions contain a wormhole and also a white-hole like initial singularity. They are allowed under general relativistic settings, where, in the simplest case, the region inside the bubble can be modelled by a domain of de Sitter spacetime and the outside by a domain of Schwarzschild spacetime; these two regions are then joined across the bubble surface, using the well known junction conditions [28, 29, 5]; on the bubble Einstein equations, which also hold separately in the two domains, are satisfied when interpreted in a distributional way and determine the motion (embedding) of the bubble itself in the two domains of spacetime. Although there are configurations of this system (and of more elaborate generalizations) that are appropriate to describe the evolution of a newly formed universe (in the sense that the expanding bubble can become very large) these models are affected by some pathologies. In particular:

- only bubbles with masses above some critical value can expand from very small size to infinity;
- all the solutions, which can expand enough to represent a new universe starting from a very small size, have a singularity (white-hole) in their past, since, for them, all hypotheses of singularity theorems are satisfied.

In connection with the first problem it was observed in [26] that in theories

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1The subject of inflation assisted by topological defects was also studied later in [10] and [30].
with multiple scalars, like a triplet of scalars, all bubbles that start evolving from zero radius can inflate to infinity, provided the scalars are in a “hedgehog” configuration or global monopole of big enough strength. This effect also holds in the gauged case for magnetic monopoles with large enough magnetic charge.

A possible connection of this with the second problem mentioned above, appears from the discussion of Borde et al. [9]: they proposed the possibility of a mechanism by means of which two regular magnetic monopoles (with below critical magnetic charge) could coalesce and form a supercritical one, which then inflates and gives rise to a child universe. This process might help addressing the singularity problem. In this context it is very interesting the work of Sakai et al. [40] in which the interaction of a magnetic monopole with a collapsing surrounding membrane is considered; also in this case a new universe can be created.

Related to the solution of this second issue are a number of other approaches that propose to use quantum effects. In particular when describing the bubble separating the inflating spacetime domain from the surrounding spacetime in terms of Israel junction conditions [28, 29, 5] (and under the additional assumption of spherical symmetry) it is possible to reduce the problem to the study of a system with only one degree of freedom: this is the so called minisuperspace approximation, which has been adopted to address the problem of the semiclassical quantization of the system even in the absence of an underlying quantum gravity theory. This has been the approach by2 Farhi et al. [15] and by Fishler et al. [18, 17]. One difficulty that these approaches faced was that the initial state was not a classically stable one. This was resolved by the introduction of massless scalars or gauge fields that live on the shell and produce classical stabilization of false vacuum bubbles. These bubbles can then, by quantum tunnelling, become child universes [21]. In a 2 + 1-dimensional example [24] the tunnelling can be arbitrarily small.

2 Outlook and Prospects for Future Research

Most of the models that have been developed to describe the process of universe creation are based on a very well-known and studied classical system, usually known as a general relativistic shell [28, 29, 5]. General relativistic shells provide an excellent, non-trivial, gravitational system, whose dynamics can be described by an extremely intuitive set of equations with a clear geometrical meaning. In situations with high symmetry the number of equations of motion of the system is drastically reduced (and often we are left with just one non-linear equation). In this sense, the classical dynamics of the system is “under control”; there are then many analytical results that can be derived and numerical methods have

2 Apart from the papers already cited above, the semiclassical approach has also been discussed by other authors (see for instance [32, 33, 39]) and we would also like to recall the suggestive relationship between the decay of the cosmological constant, membranes generated by higher rank gauge potentials and black holes, which have appeared in many papers in the literature [1, 26, 10, 11, 32, 16, 29, 19].
also been employed (see the introduction of [1] for additional references). What is, somehow, surprising is that little progress has been made in the development of the quantized theory, which still remains a non-systematized research field. A progress in this direction would be very important to be able to analyze, for instance, the semiclassical process of universe creation.

Let us first concentrate our attention on the classical creation process. We especially remember, in this context, the works of Borde et al. [9] and of Sakai et al. [40], which suggest many interesting ideas for further developments in the field.

- For instance, it would be possible to extend the analysis in [9], which is mainly qualitative in nature: in fact, the process of collision of two magnetic monopoles and the formation, by means of it, of a supercritical one, is highly non-linear; the detailed analysis of this non-linearity is instrumental for a quantitatively meaningful use of the idea of topological inflation.

- Also one could extend the study performed in [40], making a complete analysis of all the possible choices of the parameters of the model and of the related spacetime structures; this should help to draw a definitive conclusion about the classical stability of the initial configuration, i.e. to determine if this is a general feature of monopole models or if it appears only for a restricted subset in the full parameter space.

In both the above mentioned classical models another crucial problem is the one about the causal structure of the resulting spacetime describing the universe creation. In fact the global spacetime structure can be obtained by well-known techniques. Again a full classification of all the possibilities that can arise is certainly necessary to gain evidence in favor or against the proposed mechanisms. It is already known that subtleties can appear in some of these cases, as, for example, the presence of singularities in the causal past of the created universe but not in the past of the experimenter creating the universe in the laboratory. Also the presence of timelike singularities, that in some cases are not hidden behind horizons (i.e. are naked), makes interesting a discussion, in this context, of the problem of initial conditions. The proper analysis of the Cauchy problem will, in fact, involve resolution or proper handling of these singularities.

After discussing the classical aspects, we now come to the quantum (more precisely semiclassical) ones. Let us first recall that the semiclassical picture invokes quantum effects to justify the tunnelling between a classical solution, that can be formed without an initial singularity, and another classical solution, which can describe an inflating universe. In this way, the creation of the inflating universe via quantum tunnelling, could evade the consequences of singularity theorems, i.e. the initial singularity. A first problem which has already been partly studied is the stability of the initial classical configuration [21]. It is interesting then to consider the tunnelling process in more general situations, where, for example, the stabilization can be still classical in origin. In [40] it is shown that it is possible to obtain this solution in the context of monopole configurations, although, as we mentioned above, the analysis should be extended.
to the whole of the parameter space. At the same time it can also be interesting to consider the possibility that semiclassical effects might stabilize the initial configuration. In particular, closely related to the problem of instabilities present in many models, is the fact that the spacetime surrounding the vacuum bubble (which is often chosen to be Schwarzschild spacetime or generalizations of it) has itself an instability due to presence of the white hole region (see, for instance, [11]). Also in this context quantum effects might stabilize the system and help solving the issue. A possible suggestion in this direction, requires the determination of the stationary states in the WKB approximation, so we propose to generalize the procedure presented in [11] (where this analysis was performed for the first time in a simplified model) to the configurations that we considered above.

Another important point for further investigations, could be to address with a critical spirit the issues related with the semiclassical tunnelling procedure. About this, we are now going to follow, for definiteness, the clear, but non-conclusive, analysis developed by Farhi et al. [15]: they show that, when considering the tunnelling process, it is not possible to devise a clear procedure to build the manifold interpolating between the two (initial and final) classical configurations; this manifold would describe the instanton that is assumed to mediate the process. In particular, Farhi et al. show that it seems possible to build only what they call a pseudo-manifold, i.e. a manifold in which various points have multiple covering. To make sense of this, they are forced to introduce a ‘covering space’ different from the standard spacetime manifold, in which they allow for a change of sign of the volume of integration required for the calculation of the tunnelling action and thus of tunnelling probabilities. It is suggestive to consider other approaches which might give a more precise meaning to the concept of a pseudo-manifold. In this context we would like to recall two possibilities.

- A first one uses the two measures theory [22], where one can use four scalar fields and define an integration measure in the action from the determinant of the mapping between these scalar fields and the four spacetime coordinates; there can be configurations where this mapping is not of maximal rank, and this appears to be relevant to the problem we are discussing, if we interpret the scalar fields as coordinates in the pseudo-manifold of [15]. In this picture the non-Riemannian volume element of the two measure theory would be related to the non-Riemannian structure that must be associated to the pseudo-manifold, as recognized by Farhi et al. Thus, it appears that the consideration of non-Riemannian volume elements could be essential to make sense of the quantum creation of a universe in the laboratory, so that it could be important to develop the theory of shell dynamics in the framework described by the two measures theory.

- A second one, likely complementary, can come from a closer study of the Hamiltonian version of the dynamics of the system. To better understand this point, we remember that the Hamiltonian for a general relativistic shell, which we are using as a model for the universe creation process, is
a non quadratic function of the momentum, because of the non-linearities intrinsic to General Relativity; this makes non-standard and subtle the quantization procedure. Although it is possible to determine an expression for the Euclidean momentum which reproduces standard results for the decay of vacuum bubbles, this momentum can have unusual properties along the tunnelling trajectory; it turns out that some of these inconsistencies disappear if we consider the momentum as a function valued on the circle instead than on the real line \[3\]; further investigations in this direction are then likely to give a better understanding of the semiclassical tunnelling creation of a universe in the laboratory.

With the above we have recalled some existing ideas to analyze the creation of a universe by classical or quantum processes; we also presented some significant further developments of these ideas. Another related question is if all creation efforts might end in a baby universe totally disconnected from its creator or not. Since there is not a definitive answer to this problem yet, it is certainly interesting to address the question if, in some way, the new universe might be detectable. There is an indication in this direction from the analysis performed in \[41\], where a junction with a Vaidya radiating metric is employed so that the baby universe would be detectable because of the modifications to the Hawking radiation due to the baby universe creation process. It is natural to think generalizations that apply to solitonic inspired universe creation, for instance extending the metric describing the monopole, i.e. the Reißner-Nordström spacetime, to the Reißner-Nordström-Vaidya case. This question can be important in the perspective of a gravitational scenario where quantum effects are also relevant and in which the exact and definite character of the classical causal relations proper of general relativity, might be altered by quantum effects.

Once one has some detailed model of universe creation, many more phenomenological issues can be analyzed and the differences between purely classical and semiclassical processes can also be better appreciated through this analysis. This is a good reason to consider both procedures explicitly and separately, together with the physical consequences of different values of the parameters characterizing the newly forming/formed universe. In particular it is possible to study how different ways of creating a universe in the laboratory could lead to different resulting universes, with, maybe, different coupling constants, gauge groups, etc.. In this context we would also like to recall the hypothesis of Zee et. al \[27\], that a creator of a universe could pass a message to the future inhabitants of the created universe. In the perspective that we gave in this short review, this is a suggestive way to represent the problem of initial conditions and of the causal structure, which can be of relevance also for the problem of defining probabilities in the context of the multiverse theory and of eternal inflation. Another point of phenomenological relevance, is the connection between universe creation and the current observations that suggest the universe as super-accelerating. It may seem that, if this result will be confirmed, it will support the idea that some very unusual physics could be
governing the universe, in the sense that standard energy conditions might not be satisfied. The process of creation of baby universes in the laboratory without initial singularity deserves closer investigation, since it might seem plausible that the basic behavior of the universe to try to raise its vacuum energy could take a local form, i.e. manifest itself in the creation of bubbles of false vacuum (as seen by the surrounding spacetime), which would then led to child universes. A proposal, based on the two measures theory, for avoiding initial singularities in a homogeneous cosmology, already exists [23] and it would be desirable to apply it to the non-singular baby-universe creation also. Finally it would be also interesting to consider the possibility of producing baby-universes at the TeV scale in theories with large compact extra-dimensions.

Acknowledgements

We would like to thank H. Ishihara and J. Portnoy for conversations.

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