Before the Bang

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Abstract

While inflation has been an extremely successful cosmological paradigm, almost certainly something have had to have happened before it began. Can the pre-inflationary phase be of any theoretical or phenomenological significance? Could Quantum Gravity have played any interesting role in this story? These are some of the questions we want to explore in this essay written for the Gravity Research Foundation 2013 “Awards for Essays on Gravitation” competition.
The global dynamics of our observable universe is well approximated by the homogeneous isotropic FLRW cosmology, the approximation becoming increasing better as one goes back in the past. This is verified by the one part in a million temperature fluctuations observed in the CMB which formed $\sim eV$ temperatures. According to General theory of Relativity (GR) and standard fluid/thermodynamics, this uniformity should continue as we go further back in time, the success of the Big Bang Nucleosynthesis (BBN), operating at temperatures of around a MeV, corroborates this picture.

Now, GR itself has only been tested directly up to around $\mu m \sim (mev)^{−1}$ [1–3], and therefore gravity may yet surprise us, say, before we hit TeV. However, the phenomenological success of inflation [4, 5] gives us another reason to believe in GR potentially all the way up to $\sim 10^{14}$ GeV, the typical scale of inflation: the generation of nearly scale-invariant fluctuations and its subsequent propagation to the CMB epoch, the phase of inflation itself and the subsequent conversion of inflaton energy into particle excitations through reheating, are all primarily based on GR in the broad sense (which may include extra scalars, for instance). Thus, if we continue to trust GR all the way up to $\sim 10^{14}$ GeV, at this epoch our observable universe had to have been around the size of a soccer ball, and more importantly, still containing only tiny fluctuations in energy density. For a perfectly efficient “reheating mechanism”, $10^{14}$ GeV is also approximately the reheat temperature and in many ways it is this “moment” which can be considered as the hot “Bang” of modern cosmology; beyond this we supposedly had a cold and dark universe.

So, what happened before this new Bang? Well, according to the standard lore, at least around 60 efoldings of near exponential inflationary growth which takes our observable universe at least down to the size of $\sim 10^{−25}$ cm, still mostly homogeneous and isotropic. How far back can we continue to go?

This is where conjectures start to creep in as the threat of the Big Bang singularity looms large. Although the inflationary growth, $a(t) \sim e^{\lambda t}$, may seem to be able to avoid the singularity by stretching time all the way back to past infinity, this is only an illusion as illustrated in some of the classic papers by Guth, Borde, Vilenkin and Linde [6–8]: inflationary space-times are not geodesically complete in the past, if we follow any particle trajectory, at some finite proper time in the past the particle trajectory ends abruptly; something else had to have occurred before inflation! In fact, the separation of scales between the inflationary dynamics and the Planck scale ($\sim 10^{19}$ GeV) suggests a pre-inflationary phase where the GR description of space-time was still valid. Perhaps, we just had a matter/radiation/stringy phase lasting all the way to the Planck scale where the effective space-time description of our patch broke down, and we simply accept the fact that we don’t yet know the language of the Planckian era. The Big Bang singularity is not resolved, the question of how or why time (or more generally any dynamics) began is left unanswered, but in spite of these pesky questions this is probably the best cosmological paradigm we have got!

Let us though humor ourselves for the next few pages; what if an effec-
tive/approximate spacetime description is always possible, what if Quantum Gravity (QG) simply provides us with a “Bounce” where a phase of contraction smoothly transitions into a phase of expansion whenever some Planckian energy density is breached, see [9–15] for efforts to realize such mechanisms. The Big Bounce now becomes the new Bang, or does it?

Let us step back for a second and try to guess what our observational patch would look like at Planckian energy densities. Note, the FRW metric should still be a reasonable description of our cosmology because if the anisotropies were too large we would possibly forever be stuck in a chaotic Mixmaster behavior, while if the inhomogeneities were too large, “all” of us would likely be sitting inside a black hole! So a priori, what could a Planckian patch contain? (i) Vacuum energy, $\Lambda$, which could be positive or negative, (ii) Spatial curvature, $\rho_k \sim a^{-2}$, which again could contribute positively (open) or negatively (closed) to the energy budget, (iii) some massless degrees of freedom or radiation, $\rho_r \sim a^{-4}$, (iv) perhaps some massive modes as well, $\rho_m \sim a^{-3}$, lets just stick to these for simplicity.

If $\Lambda > 0$, then it is obvious that for an open or a flat universe, we have what is called a bouncing cosmology where way back in the past our universe starts out infinite and in a phase of contraction. Now, one of the virtues of inflation was to be able to wash away any “initial condition effect” by expanding the universe exponentially and making it uniform, but now one has to first arise at a sufficiently smooth universe at the bounce point starting from a large contracting universe. This requires an impossible fine-tuning, let us remind our readers that anisotropies increase as $a^{-6}$ and inhomogeneities are not far behind; one of the biggest virtues of inflation seems to be under a serious threat! Perhaps our universe is closed. Unfortunately, this does not change the scenario. Either the negative curvature density always remains small as compared to all the other components, or it cancels all the positive energy components before the quantum bounce. In either case we are stuck with a bouncing universe, only in the latter case the bounce is mediated by curvature and not QG.

In the bouncing scenario it also becomes unclear why one should use the Bunch-Davis vacuum initial conditions for the calculation of the primordial spectrum of fluctuations seeding the CMBR anisotropies. These calculations agree remarkably well with the observations [11], but if one has a prior contracting phase, one ought to start with initial seed fluctuations in that phase, track it through the bounce, and then along the inflationary expansion; there are no general arguments known to the author which demonstrate that the resulting spectrum in such a case will still be nearly scale-invariant as observed in CMBR. In fact, cosmologists have been looking at non-inflationary mechanisms to generate the desired near scale-invariant spectrum utilizing the contraction/bounce phase, some notable examples being the ekpyrotic [16], matter-bounce [17] and Hagedorn-bounce [18] scenarios. So, have we run out of options?

What if $\Lambda < 0$? If $|\Lambda| > \rho_r + \rho_m + \rho_k$, FRW evolution is inconsistent, most likely the universe would be stuck in a static anti-de Sitter like vacuum with massless and
massive excitations, not our kind of universe. So, let us look at $|\Lambda| < \rho_r + \rho_m + \rho_k$ case. As the universe expands, all the matter components dilute and eventually cancel the negative cosmological constant causing the universe to turnaround and start contracting. The contraction lasts till the universe bounces back to expansion at Planckian energy densities, the story repeating itself periodically. The trouble however is that, ever since the advent of supernova data \cite{19}, having a small negative $\Lambda$ is no longer an option, and a large $|\Lambda|$ only makes matters worse. For instance, if we take $|\Lambda| \sim (10^{14} \text{GeV})^4$ motivated by string/GUT scale physics, each of these cycles would only last a very short time, $\tau \sim M_p/\sqrt{\Lambda} \sim 10^{-33}$ s, an impossible cosmology for us to ever exist in.

Did we miss something? Interactions between different species? That generally creates entropy which can only increase monotonically thereby breaking the periodicity of the evolution. This was precisely what Tolman pointed out in the 1930s giving rise to Tolman’s famous entropy problem \cite{20,21}. Ironically, that now turns out to be a great savior! As discussed in \cite{22}, entropy tends to increase by the same factor in every cycle while the time periods of the cycles remain a constant being governed by $\Lambda$. Therefore this leads to an overall inflationary growth.

A simple illustrative example is to consider some massive species interacting with massless particles via scattering and decay processes. In a given cycle, equilibrium can be maintained up to a certain temperature in the expanding branch, below which the massive species falls out of equilibrium. A subsequent out-of-equilibrium decay into radiation creates entropy. After the turnaround, once the temperature becomes sufficiently high, the massive particles are recreated from radiation via the scattering processes re-establishing thermal equilibrium before the next cycle commences. The dynamics of matter density, $\rho_m$, can be captured by Boltzman equation of the form

$$\dot{\rho}_m + 3H\rho_m = -\Gamma\rho_m + \frac{\sigma(T)}{m}[\bar{\rho}^2_m - \rho^2_m] ,$$

where $\sigma$ is the scattering cross-section, $\Gamma$ is the decay rate, and $\bar{\rho}$ is the equilibrium matter density. Fig. 1 (left) shows the numerical behavior of $\rho_m$ in a single cycle \cite{23} giving rise to an exponential growth over the course of many many cycles \cite{23}, see Fig. 1 (right).

“Cyclic inflation” (CI) can address the usual cosmological puzzles such as the ones associated with isotropy/Mixmaster behavior, horizon, flatness and homogeneity/Black hole over-production in our universe \cite{22}, in manner very similar to the standard inflation. For instance, since anisotropies $\propto a^{-6}$, once the cyclic-inflationary phase is “activated” in a small and sufficiently smooth patch of the universe the chaotic Mixmaster behavior is avoided in subsequent cycles because the scale factor at the consecutive bounce points also keep growing and the universe becomes more and more isotropic. Very similar reasoning also resolves the flatness problem.

What about the graceful exit problem? After all we have been expanding monotonically for the last 13 billion years. In an expanding background it is known that
energy densities can only decrease, and hence once the universe is in a negative energy phase, there is no way for it to claw back up to the positive region. However, in contracting phases the reverse is true, the energy density increases, and in [24] (see also [25,26]) it was demonstrated that our universe could have been “exploring” the negative potential regions coming from the various scalar (moduli) fields, when at some opportune moment it was able to jump up a “potential ladder” to positive potential energy regions hitherto ushering in a monotonic phase of expansion, which is where our familiar universe finds its place, see Fig. 2.

Last but not the least, we need to revisit the issue of geodesic completeness in the context of the CI scenario. If one tracks, say, the maximum of the oscillating space time, then one finds that it has the traditional inflationary trajectory, and the problem of past geodesic incompleteness comes back to haunt us. Fortunately, there appears a natural resolution [27] for a closed universe: As one goes back in cycles, there comes a point when the curvature energy density becomes more important than the vacuum energy density. (Curvature density blue shifts as $a^{-2}$, while the vacuum energy density remains a constant.) Once this happens, the universe no longer turns around due to the negative vacuum energy density, but before, when $\rho_r + \rho_k = 0$. The further back we go in cycles, the universe spends less and less time in the out-of-equilibrium phases thereby decreasing the entropy production, and eventually, the universe asymptotes to a periodic behavior as $t \to -\infty$ [27], see Fig. 3. The space-time is, in fact, very reminiscent of the emergent universe scenario advocated in [28,30], and perhaps the cosmological model should be referred to as emergent-cyclic-inflation.

To summarize, we have seen a viable cosmology emerges once we assume the existence of the QG bounce, the dynamics is certainly more complex than slow-roll inflation, but the conditions required are very reasonable, a closed universe with negative vacuum energy (which incidentally is not particularly rare if String Theory is to be believed), and some massless and massive excitations interacting with each other. A good physics model though should be predictive, so for example, can one
distinguish the CI scenario from ordinary inflation? In principle, the answer is yes. It was found that the “cyclicity” of the inflationary phase leaves its imprint in CMB in the form of small logarithmic oscillations in the primordial spectrum, the fit provided in [31] was not definitive but encouraging. More recently, it was found that interesting thermodynamic features, such as phase transitions, may manifest as nongaussianities in CI models [32]. Intriguingly, the prediction was for low $f_{NL}$ but potentially high $g_{NL}$'s, consistent with Planck observations [5]. These signals do depend on the different model parameters, and one does have to be lucky to be able to observe them in Planck data, but perhaps it is worth investigating a bit more whether, our universe emerged, not just from one but, from multiple bangs; before every bang there was always another waiting right around the corner.

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Figure 3: Qualitative plot of how the scale factor evolves as a function of the conformal time $\tau$. The cycles have the same period in $\tau$, but they grow as a function of proper time. The blue curve denotes the transition between the Hagedorn (below the curve) and the non-thermal (above the curve) phase. The evolution ends in an inflating expanding branch.

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