CAUSAL STRUCTURE OF THE EARLY UNIVERSE

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The standard big bang model has always had a couple of fundamental problems: the universe's matter excess and the isotropy of the cosmic microwave background radiation. Recent developments in particle physics now point to answers to these problems and lead to new models for the causal structure of the early universe. One interesting possibility is the formation of multiple bubble universes. In such models there exist event horizons and the thermal background radiation can be produced by the Hawking mechanism.

Grand Unified Theories (GUT's) now provide an explanation for the universe's matter excess. If the cosmic blackbody radiation was initially pure thermal radiation with exactly equal amounts of matter and anti-matter at an initial temperature higher than $T \sim 10^{14}$ Gev then the GUT's now show that the observed baryon excess $n_b/n_\gamma \sim 10^{-9}$ can be produced from CP violations at later epochs (Weinberg 1979, Toussaint et al. 1979).

The other development of importance for cosmology in particle physics is the idea of "false vacuum" epochs in the early universe where $P = -\rho$ and the universe expands exponentially. Such false vacuum epochs may occur at the Planck density $T \sim 10^{19}$ Gev as proposed by Brout, Englert and Spindel (BES) (1979), Gott (1982) and Zeldovich (1981) or at the GUT transition $T \sim 10^{14}$ Gev as proposed by Guth (1981). By allowing more time for different regions to come into causal contact these models can all solve the isotropy problem. We shall discuss each of these models and their causal structure.

Figure 1 shows a Penrose diagram of an open, negatively curved, k = -1 standard big bang cosmology (see Hawking and Ellis 1973 for description). χ is a spacelike coordinate and η is a timelike coordinate, light travels at 45°. The big bang singularity at t = 0 is shown as a serrated line. Spacelike and timelike infinity i^0, i^+ are shown as well as future null infinity $\mathscr{I}^+$. A typical hypersurface

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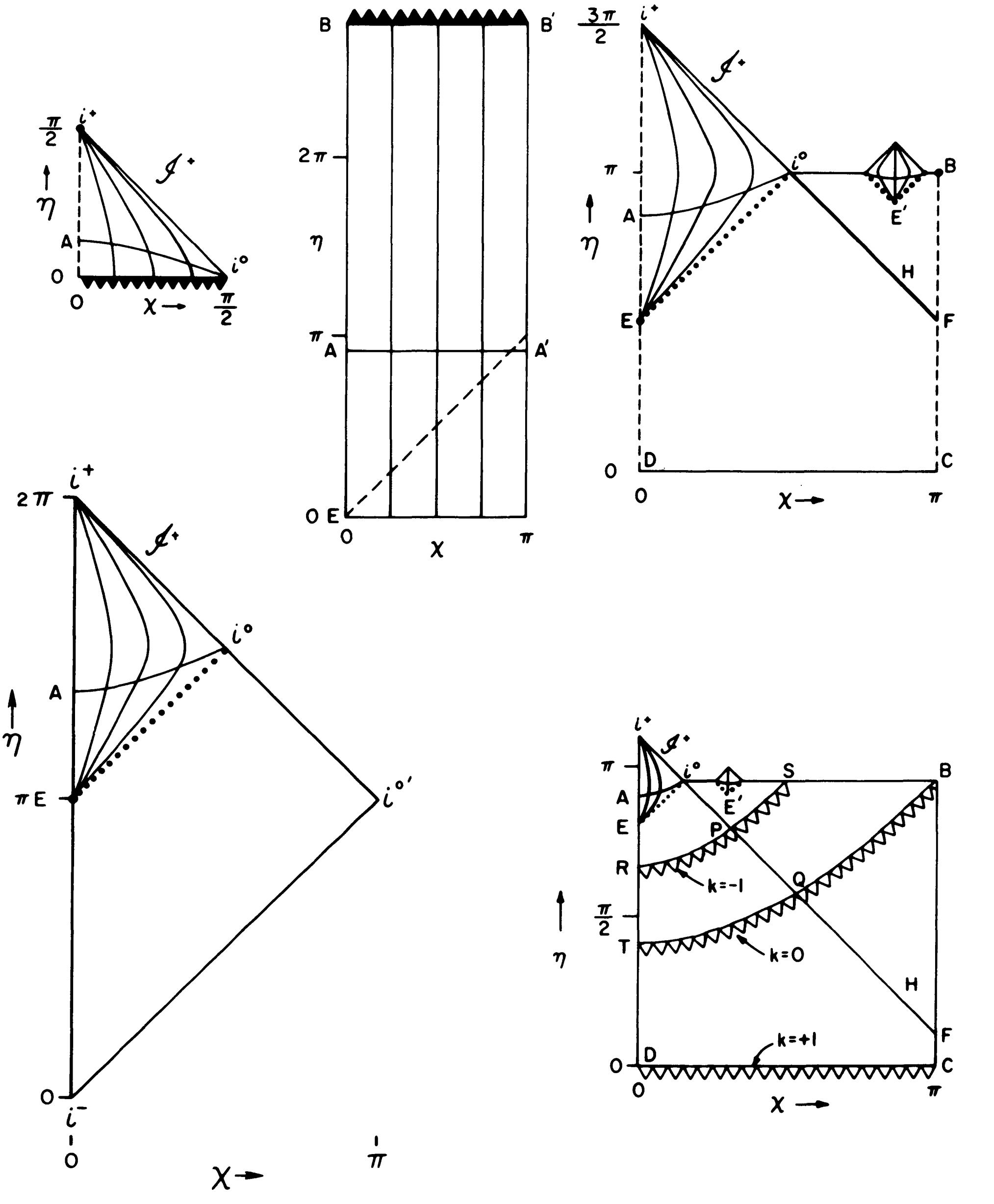

Figure 1. Top left: Standard big bang model, also Guth model. Bottom left: Brout, Englert, Spindel model. Top center: Zeldovich model. Top right: Gott model. Bottom right: Gott model with a finite past de Sitter phase.

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at time $t = \tau$ is shown as Ai^0, the timelike worldlines of co-moving observers are shown as lines connecting the singularity to i^+. This is a big bang model that expands forever, it is only the conformal map projection that makes it appear contracting. Our galaxy's world line from $t = 0$ to $t = \infty$ is $\chi = 0$ from $\eta = 0$ to $\eta = \pi/2$. Our current position at $t = t_0$ is at $\eta = \eta_0$. Let Ai^0 for the moment stand for the epoch of recombination. Let A^1 be the intersection of the past light cone of ($\eta = \eta_0$ and $\chi = 0$) and the line Ai^0, i.e. $\eta(A^1) + \chi(A^1) = \eta_0$. In the standard big bang model $\eta_0 > 2\eta(A^1)$ so that when we look back to recombination we see a region so large that it could not have been causally connected in the past.

The Guth model at early times is radiation dominated: $P = 1/3\ \rho$ and $\rho \propto a^{-4}$; when $\rho = \rho_c$ it enters a "false vacuum" phase where $P = -\rho_c$, $\rho = \rho_c$ and $a \propto \exp(t/t_{ex})$. During this phase $T_{\mu\nu} = -\rho_c g_{\mu\nu}$, and the geometry approximates a piece of deSitter space. Finally it exits the deSitter phase and becomes a standard radiation dominated big bang model again: $P = 1/3\ \rho$, $\rho \propto a^{-4}$. (Linde 1981). The Penrose diagram of the Guth model is exactly the same as the standard big bang model. If the deSitter phase lasts $\tau > 65t_{ex}$ then the recombination epoch Ai^0 is pushed upward so that $\eta_0 < 2\eta(A^1)$ and the region we can see is causally connected. But if we wait long enough we will eventually expect to see a chaotic universe just as in the big bang model.

The BES model proposes that one starts with an empty Minkowski space with $\rho = 0$. There is a quantum tunnelling event that within the future light cone of an event E produces an open $k = -1$ universe with a deSitter $\rho = \rho_c$ phase, finally leading at the epoch Ai^0 to a standard radiation dominated $P = 1/3\ \rho$ phase. In this model $t = 0$ at E and $a \sim t_{ex} \sinh(t/t_{ex})$ for small t. The Penrose diagram of the BES model is shown in Figure 1. The region Ai^0i^+ in the diagram is equivalent to the same region in the standard big bang model (Fig. 1). Now however note that for any η_0 in the range 0 to π, $\eta_0 < 2\eta(A^1)$ so the observer always sees uniform background radiation no matter how long he waits. The entire hypersurface Ai^0, at which the phase transition occurs, is causally connected to the event E.

Gott (1982) and Zeldovich (1981) have proposed models intermediate between the Guth and BES models that simply begin the universe with a deSitter state. A complete deSitter space may be embedded as the hyperboloid $X^2 + Y^2 + Z^2 + W^2 - V^2 = r_0^2$ in a 5 dimensional space with metric $ds^2 = -dV^2 + dX^2 + dY^2 + dZ^2 + dW^2$ where $T_{\mu\nu} = -\rho_c g_{\mu\nu}$, $\rho_c = 3/8\pi r_0^2$, $P = -\rho_c$. This solves Einstein's field equations with zero cosmological constant. In the Zeldovich model there is a phase transition to $P = 1/3\ \rho$ along the 3-sphere $V = V_0 > 0$. This leads to creation of one closed positively curved $k = +1$ universe. The Penrose diagram of a complete deSitter space is a square $0 < \chi < \pi$, $0 < \eta < \pi$. $\eta = 0$ corresponds to $t = -\infty$, $V = -\infty$; $\eta = \pi$ corresponds to $t = +\infty$, $V = +\infty$; $\chi = 0$ and $\chi = \pi$ correspond to opposite poles where $X = Y = Z = 0$. The Zeldovich model is given by a rectangle $0 < \chi < \pi$, $0 < \eta < \eta_{BB}$, (Figure 1). There is a big crunch

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singularity at $\eta_{BB'} < 3\pi$ and the phase transition occurs at $\eta = \eta_{AA'} < \pi$. The phase transition is acausal because one can not find any event in the deSitter space which can causally communicate with all of $\eta = \eta_{AA'}$, $0 < \chi < \pi$. The Zeldovich model can solve the observed isotropy of the cosmic background but if one waits long enough one will eventually see chaotic conditions. Zeldovich does not believe that the deSitter space existed for all time in the past, he thinks it likely that it originated from singular initial conditions.

The Gott model starts with the same initial deSitter space but the phase transition to $P = 1/3\ \rho$ occurs along a 3-hyperboloid given by $W = W_0 > r_0$ and $V > 0$. This creates an open negatively curved universe with $k = -1$ and $\Omega < 1$ which will continue to expand forever. The Penrose diagram for the Gott model is shown in Figure 1. The phase transition occurs along Ai^0. The region Ai^0i^+ can be mapped directly into the corresponding region of a standard big bang model (Fig. 1). This is a low density bubble universe in a high density deSitter space.

The Gott model contains an event horizon (boundary of past of $\mathcal{I}^+$) shown by the line H in Figure 1. None of the other models we have discussed have an event horizon. Hawking (1974) has shown that in the black hole case the existence of an event horizon leads to production of pure thermal radiation. The GUT's theories now allow us to start the universe with pure thermal radiation so Hawking radiation is ideal. DeSitter phases have been introduced in order to explain the isotropy of the cosmic background radiation. But one of the most famous properties of a complete deSitter space is that it has event horizons and is filled with Hawking radiation at a temperature of $T = 1/2\pi r_0$ (Planck units) [c.f. Gibbons and Hawking (1977)]. In fact the total energy momentum tensor for the Gibbons and Hawking thermal state has the required $P = -\rho$ form in a curved deSitter space because of trace anomalies (Gott (1982), deWitt (1982), Page (1982)). A self-consistent state is achieved at a density of $\rho_c \sim 135/2N$ (Planck units) where N is the number of spin states (Gott 1982). The diagram shows how another bubble universe (starting at E') can form behind the event horizon which is causally disconnected from our universe. The causal structure depends on the structure of deSitter space at late times and does not require that the deSitter space exist since $t = -\infty$. It can begin with singular or chaotic initial conditions. As an example of this consider a Guth type model in which the deSitter phase ends not with a smooth transition but by breaking into Gott type bubble universes (Fig. 1): $k = -1$ bubble universes can form from $k = -1$, $k = 0$ and $k = +1$ initial Guth type initial models. In each case consider only the appropriate singularity and ignore any parts of the diagram to the past of it. The event horizon for our universe is shown (H) as well as another universe beyond it.

The detailed bubble formation outcome depends on several factors. Let ε be the probability per unit four volume r_0^4 of forming an event

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E which creates a bubble. If the deSitter space has existed since $t = -\infty$ isolated bubble universes form if ε is infinitesimal. Only a few isolated bubble universes are allowed in this case. If a large number are created they will run into each other and destroy the event horizons and create one frothy chaotic universe. This will also occur if ε is finite. If however the deSitter space is created in the finite past the situation is as follows. If ε is infinitesimal then a finite but arbitrarily large number of bubble universes form each surrounded by an event horizon. If $0 < \varepsilon < \varepsilon_{CRIT}$ (Guth (1982)) has shown $5.8 \times 10^{-9} < \varepsilon_{CRIT} < 0.24$.) then an infinite number of separate bubble cluster universes form. A bubble cluster universe is a bubble with bumps on it and smaller bumps on those bumps ad infinitum so that it looks like a fractal snowflake. A bubble cluster universe is quite acceptable because it is surrounded by its own event horizon and its background radiation stays uniform until times much later than the present if ε is sufficiently small. If $\varepsilon > \varepsilon_{CRIT}$ then the bubbles coalesce to fill the space and create an unacceptable frothy chaotic structure with many wormholes and event horizons (Kodama et al. 1981).

These new developments allow a much greater freedom in the initial conditions of the universe.

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Discussion

Novikov: The probability of the origin of the Friedman universe in the de Sitter universe is constant for all points. The de Sitter model has an infinite past. It means that all space of the de Sitter universe is transformed into the new stage and different Friedman universes collide. Do you agree?

Gott: Yes.

Paal: The isotropy of the cosmic background radiation is uaually described as a consequence of the homogeneity and isotropy of the observable universe. In the standard Big Bang cosmology, this description implies that one has to accept six space-like symmetries in a very large cosmic region, the different parts of which are not yet causally connected. Such symmetries cannot therefore be explained as a result of physical smoothing processes.

In order to avoid this unwanted situation and ensure causal connections, R. Gott proposes a model which uses de Sitter's spacetime, i.e., ten symmetries corresponding to the constant four-dimensional curvature. This means presupposing more regularity to explain less regularity, which is not an obvious progress. The really satisfactory solution would be to start with chaos and deduce regularity. Such an attempt was made, e.g., by Misner, his "mixmaster model"; however, it failed to work without very special and artificial assumptions and has not therefore been accepted as a real physical explanation. Similarly, the different ad hoc constructions of unconventional cosmologies have not clarified so far the mystery of the isotropy of the microwave background radiation.

Gott: I agree that this is a case of broken symmetry where the O(4,1) symmetry of the de Sitter space is broken by bubble formation to leave each bubble with the O(3,1) symmetry of an open universe. However, the de Sitter false vacuum state which is characterized by a T^{μ}_{ν} proportional to the metric is one which can arise naturally from a variety of chaotic or singular initial conditions. As the de Sitter exponential expansion phase sets in, it forgets its initial conditions on an expansion timescale. So starting with random or chaotic initials conditions, this leads at late times to a de Sitter geometry with its associated symmetries.

Segal: As you may be aware, the Einstein universe covariantly contains all the universe you describe, and yields isotropy without any relatively exotic and complex features such as instantaneous symmetry breaking and Hawkins radiation. Therefore, why not just use the Einstein universe?

Gott: The Einstein static universe has no expansion and no event horizons.

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Contopoulos: The "mystery of the microwave isotropy" is a special case of the much more general problem: "Why are the physical laws everywhere the same in the universe?" which is extremely difficult to answer. For example, in an open universe, we cannot have a causal relation between all its parts, whatever the law we adopt for the initial expansion.

Gott: That's not correct. In the model I have proposed (Nature, 1982), as well as in the Brout, Englert, Spindel model, the universe is open and yet all its parts have had a causal relation with each other. In my model, for example, from $t = 0$ to $t = \tau \sim 69t_{ex}$, the expansion law is given by $a(t) = t_{ex} \sinh(t/t_{ex})$ where t_{ex} is the expansion timescale. The comoving distance traveled by a photon is $d\eta = dt/a$ and since $a \sim t$ as $t \to 0$, the integral of $d\eta$ from $t = 0$ to $t = \tau$ is logarithmically divergent. So even two observers who are separated by an arbitrarily large comoving distance at the present epoch have had time to communicate with each other since $t = 0$. Another way to see this is to note that in the Penrose diagram the entire negatively curved open universe hypersurface at epoch $t = \tau$ (Ai°) is causally connected to the event E.

Contopoulos: I notice that most unconventional theories today are much less unconventional than the ones that were fashionable ten or twenty years ago. They depart from the standard big bang only at times prior to the Planck time (10^{-43} s) or the GUT time (10^{-37} s).

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