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COSMOLOGY AND PARTICLE PHYSICS

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INTRODUCTION

The study of the physics of the early evolution of the Universe is at the border--indeed, the frontiers--of astrophysics and particle physics. The last five to seven years have witnessed a remarkable explosion of interest in and work on problems of the early Universe. In this brief period there has been great progress, not only in terms of problems "solved" but, in learning to pose--scientifically--problems which, only recently, were outside our science.

The subject of Cosmology and Particle Physics has grown so rapidly that neither one hour, nor one day, nor even one week would suffice for me to cover the field in any detail. Instead, I will lead you on a brief tour, pointing out a few of the landmarks which are of central interest to our exciting and dynamic discipline.

The Hot Big Bang Cosmology is the generally accepted "Standard" Model for describing the evolution of the Universe. The reasons for this are clear. The standard model provides a natural framework for understanding-- quantitatively as well as qualitatively--the observed expansion of the Universe. The Hot Big Bang Model also accounts for the thermal spectrum of the microwave background radiation. Finally, element synthesis predicted to occur during the early evolution of the Universe in the standard model--Primordial Nucleosynthesis--provides the site for the origin of the light elements in their observed abundances.

The successes of the standard model have encouraged us to be bold and forced us to be honest. There are some problems. There are several cosmological puzzles which, until recently, have either been ignored or blamed on (unknowable) boundary or initial conditions. Occasionally, these problems have been "solved" by appeal to quantum gravity--a theory which, though conceived, is yet to be born. In our tour through the Early Universe the landmarks will be the description of these Cosmological Puzzles and an outline of the solutions which have been proposed via the Particle Physics/Cosmology Connection. The puzzles have been described previously (Steigman 1981, 1984); for a review of the solutions see Turner (1983, 1984) and the Proceedings of the Fermilab Inner Space/Outer Space Workshop (Fermilab, May 1984).

Our excursion begins with an overview of the Cosmological Puzzles. Next, to provide the basis for a deeper appreciation of the puzzles, we make an excursion into the Geometry of the Universe--Cosmography. In particular, this will permit us to formulate the Horizon Puzzle quantitatively. Our route takes us next to a discussion of the dynamics of the evolution of the Universe according to the standard model and to a deeper understanding of the remaining Cosmological Puzzles. Our tour ends with an overview of the solutions provided by the Particle Physics/Cosmology Connection.

COSMOLOGICAL PUZZLES

Baryon Asymmetry

The Universe is made of matter; the Universe is not half matter, half antimatter (Steigman, 1976). Furthermore, the Universe is hot (hence, "Hot Big Bang") since there are at least a billion relic photons for each nucleon in the Universe. How did this baryon (nucleon) asymmetry arise and why are there so many ($\gtrsim 10^9$) photons per baryon? This is the Baryon Asymmetry Puzzle. We will see that the solution is to be found in the Sakharov (1967) recipe whose ingredients are found in GUTs and the early evolution of the Universe.

Horizon Puzzle

As revealed by the isotropy of the x-ray, radio and microwave radiation backgrounds, the Universe--on its largest scales--is very smooth. But, due to the finite speed of light, there is no way within the context of the standard model that physical (i.e., causal) processes could have homogenized an initially inhomogeneous Universe. How, then, did the Universe get to be so smooth on large scales? How was it arranged that the same physical conditions were attained in parts of the Universe which were never in causal contact? This is the Horizon or, Homogeneity Puzzle. Its proposed solution, "Inflation" (Guth, 1981), is also the solution suggested for the last puzzle to be described next.

Age-Flatness-Entropy Puzzle

There are several cosmological puzzles which, under closer scrutiny, are revealed to be different aspects of one problem. These are the Age, Flatness and Entropy Puzzles. The "typical" cosmological timescale is the "Planck time" $t_P \simeq 10^{-43}$ sec. The present Universe ($t_0 \gtrsim 10$ billion years) is some 10^{60} Planck times old. Why is the Universe so old? The 3-space sections of our cosmological space-time are, in general, curved. Current observations, however, fail to reveal any curvature. How is it that the Universe - 10^{60} t_P old - is so flat? Finally, if we estimate the number of relic photons per unit comoving volume in the Universe, we find the enormous number $\mathcal{N} \gtrsim 10^{95}$. Not only are relic photons abundant compared to nucleons ($\eta^{-1} \equiv \gamma/N \gtrsim 10^9$), they are abundant in an absolute sense. Since the entropy per unit comoving volume (divided by Boltzmann's constant) is, up to numerical factors of order unity, equal to $\mathcal{N}$, the universal entropy is enormous. Where did the entropy come from? These are the Age-Flatness-Entropy Puzzles. We will see that they are really one problem, that a Universe with enormous entropy (per unit comoving volume) can live to be very, very old and can be very, very flat. The origin of the entropy is in the reheating of the Universe when "Inflation" ends (new photons are minted); the source of the entropy is in the free energy of the "vacuum".

COSMOGRAPHY

To explore the Cosmological Puzzles in more detail requires an understanding of the geometry and dynamics of the expanding Universe as described by the Standard, Hot Big Bang model. First, let us concentrate on the geometry.

The presently observed large scale homogeneity of the Universe and the isotropy of its expansion suggest that the geometry of space-time may be described by a unique metric: the Robertson-Walker metric.

$$ds^2 = (cdt)^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2\, d\Omega^2\right] \qquad (1)$$

In (1), $a = a(t)$ is the scale factor whose time dependence describes the evolution of the Universe; r, θ, ϕ (where $d\Omega^2 = d\theta^2 + \sin^2\theta d\phi^2$) are comoving coordinates--they follow the expansion of the Universe; k is the dimensionless, 3-space curvature constant. The quantities in (1) may be rescaled so that,

$$ds^2 = (cdt)^2 - R^2(t)[d\Theta^2 + \text{----}], \qquad (1')$$

where: $R(t) = a(t)/|k|^{\frac{1}{2}}$ and $d\Theta^2 = |k|\, dr^2/(1-kr^2)$. $R = R(t)$ is the new scale factor and Θ is the new comoving radial coordinate.

From the form of the metric we see that the comoving volume at some time t can be written as, $V(\Theta,t) = 2\pi R^3(t)\, \Phi(\Theta;\, k)$. (2)

The equation of motion for a photon ($ds = 0$) moving along the radial direction ($d\theta = d\phi = 0$) is: $d\Theta = \pm cdt/R(t)$. For example, a photon emitted at t_e from a comoving galaxy (g) whose redshift is z, will be received by us (at the origin) today (t_o), having travelled a comoving radial distance Θ_g,

$$\Theta g = \Theta(t_e,\, t_o) = \int_{t_e}^{t_o} cdt/R(t). \qquad (3)$$

Since the galaxy is comoving, Θ_g is constant so that,

$$R_o/R_e = dt_o/dt_e = \nu_e/\nu_o = 1 + z. \qquad (4)$$

The "Causal" Horizon is the total comoving radial distance (Θ_H) a photon could have travelled since the Big Bang.

$$\Theta_H(t) = \int_0^t cdt/R(t). \qquad (5)$$

Horizon Puzzle

We are now in a position to restate the Horizon Puzzle quantitatively. Consider a piece of the Universe which just barely fit within the horizon at some time t in the past

$(t < t_0)$. The present size of that region is

$$L = L(t; t_0) = R(t_0)\ \Theta_H(t) = (1 + z)R(t)\Theta_H(t). \quad (6)$$

For $R \propto t^n$, where $n < 1$, $R(t)\Theta_H(t) = ct/(1-n)$ so that: $L(t; t_0) \approx (1 + z)\,ct$.
At present, though, the size of the horizon is,

$$d_H(t_0) = R(t_0)\ \Theta_H(t_0) \approx ct_0. \quad (7)$$

Thus, the piece of the Universe which entered the horizon at t in the past now subtends an angle θ in the sky,

$$\theta = L(t; t_0)/d_H(t_0) \approx (1 + z)\ (t/t_0). \quad (8)$$

For the present (matter-dominated) Universe, $n \approx 2/3$ so that, $\theta \approx (1 + z)^{-\frac{1}{2}}$.

Consider, now the epoch of recombination: $z_{rec} \approx 10^3$. Those regions of the Universe which could have been in causal contact prior to recombination now occupy only $\theta \approx 2^\circ$. The observed large scale isotropy of the microwave background radiation is a puzzle.

DYNAMICS

To follow the evolution of the Universe we must determine the time dependence of the scale factor R(t). The dynamics of the evolution are determined by the Friedman equations which follow when the Robertson-Walker metric is substituted in the Einstein equations. For the Robertson-Walker- Friedman models the expansion rate - the Hubble parameter - is given by,

$$H^2 = \left[\frac{1}{R}\frac{dR}{dt}\right]^2 = \frac{8\pi}{3}G\rho \pm \left(\frac{k}{R}\right)^2 + \frac{\Lambda}{3}. \quad (9)$$

$\rho = \rho(t)$ is the total mass-energy density and Λ is the cosmological constant. The second term on the right hand side of (9) is due to the 3-space curvature; if $k = 0$, the second term would vanish. A second equation, which follows from the conservation of the stress-energy tensor, may be written as $dS = 0$, where the entropy S is,

$$S = \frac{(P + \varepsilon)}{T} V \approx \left[\frac{(P + \varepsilon)}{T}\ R^3\right] \Phi. \quad (10)$$

As long as the stress-energy tensor describes a perfect fluid, the expansion is adiabatic and $dS = 0$.

The entropy density is dominated by the contribution from relativistic particles for which $P = 1/3\ \varepsilon$ and $\varepsilon \approx 3Tn$; n is the number density and T the temperature of the relativistic particles (e.g., photons, neutrinos, etc.). Up to numerical factors of order unity (and, in units with the Boltzmann constant equal to unity), the total entropy is essentially the total number of relativistic particles.

$$S \approx 4N \equiv 4\mathcal{N}\Phi(\Theta). \quad (11)$$

$\mathcal{N}$ is the number of relativistic particles per unit comoving volume; $\mathcal{N}$ is a constant, independent of t and Θ .

Since relativistic particles dominate the total mass-energy density ($\rho \propto T^4$) during the early evolution of the Universe, the equation for the Hubble parameter may be rewritten as,

$$(Ht_p)^2 \approx (T/T_p)^4 \pm \mathcal{N}^{-2/3} (T/T_p)^2 + (T_V/T_p)^4. \qquad (12)$$

In equation (12), we have introduced the "natural" units for cosmology--the Planck units. The Planck mass is defined by $M_p = (\hbar c/G)^{1/2}$, so that,

$$M_pc^2 \approx 1.2 \times 10^{19} \text{ GeV}, \qquad (13a)$$

$$T_p = M_pc^2/k \approx 1.4 \times 10^{32}\text{K}, \qquad (13b)$$

$$t_p = \hbar/M_pc^2 \approx 5 \times 10^{-44} \text{ sec.}, \qquad (13c)$$

$$l_p = ct_p \approx 1.6 \times 10^{-33}\text{cm}. \qquad (13d)$$

Also, in equation (12), we have rewritten the cosmological constant (Λ) in terms of the "vacuum temperature" (T_V) where,

$$\Lambda \equiv t_\Lambda^{-2} \equiv t_p^{-2} (T_V/T_p)^4. \qquad (14)$$

Notice that, in Planck units, the present Universe ($t_o \gtrsim 10^{10}$ years; $ct_o \approx 10^{28}$cm) is very old ($t_o \gtrsim 6 \times 10^{60}\ t_p$) and very big ($ct_o \gtrsim 6 \times 10^{60}\ l_p$); also, the Universe is very cold ($T_o \approx 3\text{K} \approx 2 \times 10^{-32} T_p$).

Notice, too, that Λ is very, very small. To see this, return to equation (9) from which it follows that $\Lambda \lesssim H_o^2$. Thus, $\Lambda t_p^2 \lesssim (H_o t_p)^2 \approx (t_p/t_o)^2 \lesssim 10^{-120}$. Equivalently, $t_\Lambda \gtrsim 10^{61}\ t_p$ or $T_V \lesssim 30\text{K} \lesssim 10^{-31}\ T_p$. The extreme smallness of Λ should be added to the list of cosmological puzzles. Since I am unaware of any, even modestly convincing, proposals to solve this problem, I'll have nothing further to say about Λ in this talk.

With the above diversion completed, we may now return to the main road and resume our tour by viewing, once again, the cosmological puzzles of age- flatness-entropy.

THE UNIVERSE IS OLD AND FLAT; THE ENTROPY IS LARGE

It is clear from equation (12) that--in the absence of a cosmological term--the Universe becomes "Curvature Dominated" when the temperature drops below $T_{CD} = \mathcal{N}^{-1/3} T_p$. If it were the case that $\mathcal{N} \approx 0(1)$, then $T_{CD} \approx T_p$ and the Universe would have become Curvature Dominated very early in its evolution. Indeed, if the space were positively curved ($k > 0$), the Universe would have completed its entire evolution--expansion and collapse--in a few Planck times. Clearly, that hasn't happened. Observationally, we are--at present--unable to determine with any confidence whether or not the Universe has yet become Curvature Dominated. Since $T_{CD} \lesssim 0$ (3K), $\mathcal{N} \gtrsim 10^{95}$; the entropy per unit comoving volume of our Universe is enormous. This has direct consequences for the age and flatness of the Universe.

As a measure of the curvature, compare the "Hubble Distance", c/H, with the scale factor R; recall that $(R/l_p)(T/T_p) \approx \mathcal{N}^{1/3}$.

$$\frac{c/H}{R} \approx [\mathcal{N}^{2/3} (T/T_p)^2 \pm 1]^{-1/2}. \quad (15)$$

If we evaluate this quantity during the Planck epoch, when $T \approx T_p$, we find,

$$\left(\frac{c/H}{R}\right)_p \approx (\mathcal{N}^{2/3} \pm 1)^{-1/2} \approx \mathcal{N}^{-1/3} \lesssim 2 \times 10^{-32}. \quad (16)$$

Early on, the Universe was very, very flat.

A Universe with such a large entropy evolves for a very long time before becoming Curvature Dominated.

$$t_{CD}/t_P \approx (T_P/T_{CD})^2 \approx \mathcal{N}^{2/3} \approx 2 \times 10^{63}. \quad (17)$$

Of course, our Universe is, at present, (most likely) "Matter Dominated"; the total mass-energy density is dominated by nonrelativistic particles (nucleons, massive neutrinos, monopoles, etc.). If the Universe is dominated by a particle of mass M and number density $n = \eta T^3$, then,

$$t/t_p = 2/3(T_p/T)^{3/2}(M_p/M\eta)^{1/2}. \quad (18)$$

If the present Universe is (still) Matter Dominated,

$$t_0/10^{10}\ \text{yr} \approx 4 \times 10^{-14} (M_p/M\eta)^{1/2}. \quad (19)$$

For example, for either nucleons ($M \approx 10^{-19} M_p$, $\eta \approx 10^{-9}$) $M\eta/M_p \approx 10^{-28}$, or for neutrinos ($M \approx 10^{-27} M_p$, $\eta \approx 1$) $M\eta/M_p \approx 10^{-27}$, $t_0 \approx 0\,(10^{10})$ (up to numerical factors of order unity). However, for superheavy Grand Unified Monopoles ($M \approx 10^{-3} M_p$, $\eta \approx 10^{-11}$), $M\eta/M_p \approx 10^{-14}$ (Zeldovich and Khlopov 1978; Preskill 1979) and $t_0 \approx 4{,}000$ years! A monopole dominated Universe expands so fast that, at present (when $T = T_0 \approx 3K$), it is much too young. This is the well-known "Monopole Problem"; not, as is usually stated, that monopoles "close" the Universe--the curvature of the Universe neither knows nor cares about the existence of monopoles.

THE PARTICLE PHYSICS/COSMOLOGY CONNECTION

Our tour so far has highlighted the Cosmological Puzzles which arise within the context of the standard, Hot Big Bang cosmological model. The solutions which have been proposed for these problems have involved a symbiotic relation between Particle Physics and Cosmology. In our final excursion I shall describe, qualitatively, this connection; for further detail and references to the original work, the following articles are highly recommended: Turner (1983, 1984), Kolb and Turner (1983), Linde (1984).

Baryon Asymmetry

As advertised, the Particle Physics/Cosmology Connection is responsible for the)posed solutions to the Cosmological Puzzles. The most dramatic example is the solution the problem of the Universal Baryon Asymmetry (Why is the Hot Big Bang Hot?). The lution was actually proposed many years prior to the current interest in ·ticle-Astrophysics (Sakharov 1967). The recipe for cooking a universal baryon asymmetry :icipated later developments in Grand Unified Theories. Clearly, one ingredient must be)cesses in which Baryon Number conservation is violated. This ingredient is provided :urally by GUTs which unify quarks, antiquarks, leptons and antileptons. For example, in ıy GUTs, two quarks can, via the exchange of a superheavy gauge (or Higgs) boson (X: $\approx M_{GUT} \gtrsim 10^{14}$ GeV), turn into an antiquark and a lepton ($q + q \overset{X}{\rightarrow} \bar{q} + l$). ıonconservation is, however, only one of the essential ingredients for producing a iversal baryon asymmetry. Another essential ingredient is violation of C and CP ıservation so that reactions among antiparticles don't undo what particle reactions have ıe. Again, GUTs provide a natural mechanism for violating C and CP; however, the amount C and CP violation is very model dependent and, often very small. If equilibrium among ; various B-, C- and CP- violating interactions were maintained, the presence of the above ıredients would be of no avail. Detailed balance would conspire to drive the net Baryon nber to zero and, to keep it there. Fortunately, here, cosmology comes to the rescue. ; Universe is expanding and cooling. Therefore, reactions--especially those mediated by ; exchange of a superheavy particle--find it harder and harder to maintain equilibrium; ; reaction rates become small compared to the expansion rate. It is, then, the marriage Particle Physics and Cosmology which provides the ingredients necessary for producing the :ter-antimatter asymmetry observed in the Universe today.

To illustrate one of the ways in which the universal baryon asymmetry may have ın produced, consider the model of "out-of equilibrium decay". Suppose the X (gauge or ıgs) bosons live sufficiently long that they decay when $T < M_X$; in this case, the Xs are :-of-equilibrium when they decay ($n_X \approx n_\gamma$ rather than $n_X/n_\gamma \approx \exp(-M_X/T)$). Suppose ıt, due to C and CP non- conservation, when each X and $\bar{X}$ pair decay, a net baryon number ε produced. Then, after the Xs have decayed away, the Universe will be left with an excess baryons; the resulting universal ratio of nucleons-to-photons ll be, roughly,

$$N/\gamma = \eta \approx \varepsilon\ (n_X/n_\gamma)_D. \tag{20}$$

:hough $(n_X/n_\gamma)_D \approx 0\ (1)$, ε - in most GUTs - is very small. GUTs and Cosmology ıvide the mechanism for producing a net baryon asymmetry. Although there are too many justable parameters in most GUTs to claim that η is predicted, it is clear that it is ıtural" for ε to be small and, hence, for the Universe to be hot ($\eta^{-1} \gtrsim 10^9$).

Inflation

Spontaneous Symmetry Breakdown is fundamental to GUTs. Crudely speaking, the idea is that at very high temperatures ($T > T_{GUT}$) the full symmetry of the theory is manifest. The vacuum state corresponds to, for example, SU(5) or SO(10), etc. As is common in quantum field theory, the vacuum energy density does not necessarily vanish. At low temperatures ($T < T_{GUT}$), the symmetry is broken; now the vacuum state corresponds to a lower symmetry, for example, one which distinguishes between the Strong and the Electroweak interactions (SU(3) x SU(2) x U(1)). The energy difference between the high temperature and low temperature vacua is of order T_V^4 ($T_V \approx T_{GUT}$). Since the vacuum energy density behaves like a cosmological constant, the present vacuum energy density must be very small ($\Lambda \lesssim H_0^2 \Rightarrow T_V \lesssim 30K$). As a result, the vacuum energy density during very early, high temperature epochs in the evolution of the Universe must have been very large.

$$\rho_V \approx \Delta\rho_V \approx T_V^4 \tag{21}$$

Since $\rho_R \propto T^4$, the Universe will be dominated by the vacuum energy density if, when $T \lesssim O(T_V)$, the Universe is "trapped" in the symmetric ("false vacuum") state. If the symmetry breaking transition is a first order phase transition, the Universe expands and supercools, trapped in the higher symmetry state; this indeed occurs for most GUTs.

During this epoch, when the Universe is trapped in (or, is evolving slowly from) the false vacuum, the Universe "Inflates"; that is, the expansion is exponential.

$$H \approx H_V \approx t_P^{-1} (T_V/T_P)^2 \tag{22a}$$

$$R \approx R_i \exp(H_V t) \gg R_i \tag{22b}$$

Since the temperature drops exponentially ($T \propto R^{-1}$), the Universe supercools.

Eventually, the transition to the "true" (lower symmetry) vacuum is completed and the "free energy" (the vacuum energy density) is released, reheating the Universe to a very high temperature: $T_f \lesssim O(T_V)$. There is, then, a double meaning to "Inflation"; not only does the Universe expand exponentially but, new photons are created ("new money is minted"). These dual aspects of Inflation permit a solution to the Age-Flatness-Entropy Puzzle, as well as the Horizon-Homogeneity Puzzle.

The Horizon-Homogeneity Puzzle is solved by the exponential expansion. If the duration (Δt) of the vacuum driven expansion is sufficiently large ($H_V \Delta t \gg 1$) then, at the end of the inflationary epoch, all scales will be stretched enormously.

$$L_f/L_i = \exp(H_V \Delta t) \gg 1. \tag{23}$$

It is thus possible to imagine that inflation began in a patch of the Universe whose size was sufficiently small ($L_i \ll d_H(t_i)$) that the region was completely homogeneous, and, still, today (t_0), that region would be much larger than the presently observable Universe.

$$L_0 = L_f(T_f/T_0) = L_i(T_f/T_0)\ \exp\ (H_v \Delta t) >> c/H_0. \qquad (24)$$

ne initially homogeneous region now encompasses the entire observable Universe--and beyond.

The reheating at the end of the inflationary epoch solves the ge-Flatness-Entropy Puzzle. Compare the entropy (or $\mathcal{N}$) before and after inflation.

$$\mathcal{N}_f/\mathcal{N}_i = [(R_f T_f)/(R_i T_i)]^3 \approx \exp\ (3H_v \Delta t). \qquad (25)$$

n (25), account has been taken of reheating by: $T_f \approx T_i$. For example, if $\Delta t > 70\ H_v^{-1}$, nen, exp $(H_v \Delta t) > 10^{30}$ and $\mathcal{N}_f > 10^{90} \mathcal{N}_i$. It is the "free energy" or the energy ensity difference between the two vacua which is the source of the present Universe's normous entropy. We have already seen that a Universe with such a large entropy will be ery, very old and very, very flat.

For $H_v \Delta t \gtrsim 70$ and $T_f \approx 10^{15}$GeV, $L_0/L_i \gtrsim 10^{58}$. We may estimate $_H(t_i) \approx ct_i \approx l_P(T_P/T_f)^2 \approx 10^8\ l_P \approx 10^{-25}$ cm, so that $_0 \gtrsim 10^{33}[L_i/d_H(t_i)]$ cm or, $L_0/(c/H_0) \gtrsim 10^5[L_i/d_H(t_i)]$. Thus, even or $L_i < d_H/(t_i)$, it is possible that $L_0 >> c/H_0$.

The above discussion of Inflation has been extremely crude, the intent being to xpose the basic essence of the idea. The reader should consult the (very readable) riginal papers (Guth, 1981; Linde, 1982; Albrecht and Steinhardt 1982 and the excellent eviews by Turner (1983; 1984) and by Linde (1984).

IMMARY

During the last hour we've been on a tour through the early Universe, viewing me of the landmarks in the Particle Physics/Cosmology Connection. We have noted that the tandard" Hot Big Bang Model, successful as it is in accounting for the observed expansion the Universe as well as for the thermal spectrum of the microwave background radiation d the abundances of the light elements produced in primordial nucleosynthesis, is faced th several Cosmological Puzzles. The symbiotic relationship between High Energy Physics d the Physics of the Early Universe offers a route to the solution of these puzzles. The zzle of the universal baryon asymmetry--Why is the Big Bang Hot?--is solved by the rriage of GUTs and Cosmology; the baryon asymmetry is generated by B-, C- and CP-olating interactions which drop out of equilibrium very early in the evolution of the iverse. The Age-Flatness-Entropy Puzzles are seen to be different aspects of one puzzle: y does the Universe have so much entropy? Inflation--the exponential expansion and timate reheating associated with spontaneous symmetry breakdown in GUTs in the context of expanding Universe--solves this problem. Inflation, too, solves the Horizon-Homogeneity zzle; the exponential expansion permits the entire observed Universe to have originated om a completely smooth initial region.

Although my description has been qualitative, I have, I believe, dealt with a bject of profound significance. Through the union of Particle Physics and Cosmology, the t Big Bang Model has built on its previous successes. Now, we may pose questions which re, until recently, imponderable. The solutions which have been proposed for the "old" zzles, have a ring of truth. Our subject is at a very exciting threshold.

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