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Technical Memorandum **80562**

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(NASA-TM-80562) ASYMPTOTIC FREEDOM IN THE EARLY BIG-BANG AND THE ISOTROPY OF THE COSMIC MICROWAVE BACKGROUND (NASA) 13 p HC A02/MF A01 CSCL 03B

N79-34155

Unclas

G3/93 38913

SEPTEMBER 1979

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

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ASYMPTOTIC FREEDOM IN THE EARLY BIG BANG AND THE ISOTROPY OF THE COSMIC MICROWAVE BACKGROUND

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Abstract:

It is suggested that a superunified field theory incorporating gravity and possessing asymptotic freedom could provide a solution to the problem of the isotropy of the universal 3K background radiation. Thermal equilibrium could be established in this context through interactions occurring in a temporally indefinite pre-planckian era.

There is a mystery concerning the evolution of the universe which is of profound and fundamental significance. When we look out over the sky, we can see radiation that was emitted when the universe was very young and which last scattered off the matter content of the universe some 15×10^9 years ago. At that time, it had a temperature some $\sim 10^3$ times its present temperature of $\sim$ 3K, i.e., it last scattered at a redshift $z \simeq 10^3$, orders of magnitude higher than the redshift of the furthest quasar. But the ultimate source of the radiation, annihilation of particles and antiparticles with all masses allowable at corresponding temperatures, lies at much earlier, hotter epochs. The 3K microwave background radiation is remarkably isotropic - to within better than one part in a thousand (Alpher and Herman 1975).

The puzzle comes in when we consider that as time goes on we see more and more of the universe as distant regions come within our "particle horizon", i.e., within distances $X \leqslant ct_u \sim c/H(z)$ where $H(z)$ is the age of the universe (e.g., Rindler 1956). Thus, we are now seeing 3K microwave background radiation from parts of the universe which apparently were never in causal contact, since even radiation travelling at the speed of light would not have had time to cross from one region to another. How then could they be in such apparent thermal equilibrium? Or, putting it another way,

how could one region have known to adjust its temperature to that of the unknown other region?

The solution may lie with the very earliest stages of the big-bang and may be supplied by concepts now emerging out of the new unified gauge-field theories. The argument begins with a scenerio of high energy physics as applied to the big-bang as summarized below:

It is by now well known that Weinberg (1967) and Salam (1968) have succeeded in developing a theory unifying the weak and electromagnetic interactions which led to some predictions now confirmed such as neutral current (e.g. $\nu + N \rightarrow \nu + X$) interactions (Barish 1978), and the scattering properties of longitudinally polarized electrons (Prescott et al., 1978). The Weinberg-Salam Theory has been shown by 't Hooft (1971) to be renormalizable and therefore to be just as well defined a theory as quantum electrodynamics, the extremely accurate quantum gauge theory of the electromagnetic field.

A further step toward unification was taken with the proposed grand unified theory of strong, weak, and electromagnetic interactions Georgi and Glashow (1974). This theory enabled one to calculate the value of the very important Weinberg angle parameter expressing the ratio of the strength of neutral current to electromagnetic interactions, left undetermined in the Weinberg-Salam model. This is because the SU(5) group upon which the Georgi-Glashow model is based is a simple group involving only one gauge coupling constant whereas the $SU(2)\otimes U(1)$ model of Weinberg and Salam admits two apparently independent gauge coupling constants. In the Georgi-Glashow model, the coupling constants are related as a result of the symmetry breaking $SU(5)\rightarrow SU(3)\otimes[SU(2)\otimes U(1)]$. The calculated renormalized value of the Weinberg angle agrees beauti-

fully with recent experimental results as do the predicted masses of the φ and Υ mesons (Buras et al. 1978).

The SU(5) Georgi-Glashow theory incorporates within it the SU(3) gauge theory of strong (or, more properly, quark-gluon color) interactions known as quantum chromodynamics (QCD). This theory has the peculiar (but for our purposes here essential) property called asymptotic freedom (Politzer 1973) which is experimentally supported by the observations of Bjorken scaling and certain nucleon structure functions measured in high energy neutrino-nucleon interactions. (Bjorken 1969, Bosetti et al., 1978). Asymptotic freedom, i.e. the weakening of the color force at small distances (or equivalently higher energies), is one side of the mathematical relationship that requires such forces to become strong at "large" distances (of the order of the size of the nucleon), a phenomenon sometimes called "infrared slavery". Indeed, Weinberg (1977) has remarked that we would have to postulate asymptotic freedom in order to allow a gauge field to become strong at hadron distances.

Work is now progressing on what may be the final unification of the "grand unified theory" with a quantum gauge theory of gravity. Such theories are called "supergravity" theories. (Wess and Zumino 1974; Salam and Strathdee 1974, Nath and Arnowitt 1975). While many problems remain, let us for the moment assume that they can be overcome and that a quantum unified field theory can be constructed. We can then put together an outline of the evolution of the big-bang.

The renormalization group equation for QCD yields the energy dependent relation for the color coupling strength which exhibits asymptotic freedom

$$\alpha_c(-q^2) = \frac{\pi}{(\frac{11}{4} - \frac{N_f}{6}) \ln (-\frac{q^2}{\Lambda^2})} \tag{1}$$

where q^2 is the square of the momentum transfer of the interaction which scales like the square of the temperature of the thermal radiation T, N_f is the number of quark flavors with mass $m \ll |q|$ and Λ is a constant which must be determined experimentally. For example, $N_f=6$ would correspond to the quarks u, d, s, c, b and t.

The strength of the weak force at energies below the mass of the W boson M_W is of order

$$\alpha_W = \mathcal{O}\{\alpha (\frac{T}{M_W})^2\} \tag{2}$$

where $\alpha \simeq 1/137$ is the fine structure constant.

(We have set here c = k = 1).

In the case of the leptoquark interactions responsible for proton decay,

$$\alpha_{lq} = \mathcal{O}\{\alpha (\frac{T}{M_X})^2\} \tag{3}$$

where, $M_X \sim 5 \times 10^{14}$ GeV (Goldman and Ross 1979) is the mass of the intermediate boson involved in the interactions. In the case of gravity, the same type of energy dependence occurs, since mass and energy are proportional, and we may write

$$\alpha_g = \mathcal{O}\{\alpha(\frac{T}{M_{pl}})^2\} \tag{4}$$

with the Planck mass $M_{pl} \sim 10^{19}$ GeV/c^2 (cf. Zee 1979).

In the grand unified theory of Georgi and Glashow, the coupling strengths are related through implicit renormalization group relations. At the grand unification temperature, $\sim 10^{28}$K, $\alpha_{GU} \sim 0.22$ (Buras et al., 1978).

Figure 1 shows the strengths of the various interactions predicted by these models and the unification energies given as temperatures in

the early big-bang and corresponding time scales. The interaction strengths are given with the low-energy electromagnetic strength $\alpha = e^2/hc \sim 1/137$ and the other strengths also as pure numbers. The "leptoquark force", an interaction predicted by the Georgi-Glashow model which can change quarks into leptons and vice versa, is too weak to have been observed. However, searches are underway to look for evidence of the decay of protons into leptons (e.g. Sulak 1979) for which the SU(5) model predicts a proton lifetime of $\sim 10^{32}$ yrs. (Goldman and Ross, 1979).

Going back in time we see that about 10^{-8}s after the big-bang, the weak and electromagnetic forces were unified into one force with strength $\sim\alpha$. At this time nucleons and mesons did not exist and in their place was a gas of quarks. These quarks and leptons look like "point particles". For this reason, we can continue talking about particles even for times when the particle horizon was less than $\sim 10^{-13}$cm, the size of a typical present-day hadron. (Such a situation has been called the "hadron barrier" (Bahcall and Frautschi 1971)).

Going further back, Figure 1 indicates that $\sim 10^{-36}$s after the big-bang all of the forces except gravity were unified. At this time, the universal "soup" consisted of unified leptoquarks and the various gauge bosons - photon, gluons, weak intermediate vector bosons ($W^{\pm}$, Z^{o}), leptoquark intermediate vector bosons (X, Y) gravitons and possibly Higgs bosons and gravitinos. The X and Y bosons have masses $\sim 10^{15}$ GeV/c^2.

Finally, we arrive back at a time $\sim 5\times10^{-44}$s after the big-bang when gravitation was as strong as the other forces (Zee 1979) and may have been unified with them. This is the Planck time $t_{pl} = (h\ G/c^5)^{1/2}$ at which the full quantum effects of gravity come into play (Harrison et al.,

1965; Misner, Thorne and Wheeler 1967; Harrison 1967).

What happened earlier? It is in this "preplankian era" that a possible solution to the microwave background isotropy problem may be found. Two points in the above discussion are crucial.

(1) All fields at that time could have been unified into one "force".

(2) The color field exhibits asymptotic freedom. Asymptotic freedom also holds for various classes of grand unified theories of strong, weak and electromagnetic interactions (Vaughn 1978), and has been recently shown to hold for one model of quantum gravity (Smolin 1979).

Combining these points, it is plausible to suppose that <u>the completely unified force possesses asymptotic freedom</u>, i.e., $\alpha_U \to 0$ as $T \to \infty$.

It has hitherto been assumed (although we have no satisfactory theory of gravity at these energies) that gravitational forces blow up as $T \to \infty$ (i.e., $t \to 0$). It has also been speculated that at the Planck time t_{pl} there existed unified gauge bosons having the Planck mass $M_{pl} = (hc/G)^{1/2}$ $\sim 1.2 \times 10^{19}$ GeV/c^2 existing as their own independent "black holes". At t_{pl} space-time would then have been discontinuous. In this situation we can then no longer speak of a space-time continuum whose properties define the gravitational field (Einstein 1956) or indeed the behavior of a particle in any unified field. Thus, without space time there is no gravity (or unified gravity). Remaining physical concepts would of necessity be expressed in such pretopological terminology as Borel rings (Hausdorff 1957).

However, the concepts discussed above suggest an alternative picture of the initial stage of the big-bang, <u>viz</u>., the curvature of space-time could have been smaller than the inverse Planck length because of asymptotic freedom.

It is also possible that before the breakdown of full symmetry, the gauge bosons were massless, their huge masses being the result of spontaneous symmetry breaking in the post-planckian era corresponding to the expansion (and cooling) phase of the big-bang. We can thus envision a "preplanckian era" as being a pre-expansion stage in the history of the universe when quantum effects were important but when field theory concepts were also applicable.

The concept of time ordering, however, would not have been meaningful at this stage. With the strength of the unified field being small (rather than divergently large), owing to the uncertainty principle, time fluctuations can have occurred about t=0 until a fluctuation occurred which was large enough to "set off" the big-bang. Indeed, with a time-symmetric superunified field existing before the cooling expansion stage resulted in spontaneous symmetry breaking, it would have been impossible to define a unique global direction of time. It has been suggested that the big-bang could have arisen as a vacuum fluctuation provided that the universe initially had a vanishing net baryon number (Tryon 1973). Such a situation arises naturally within the context of baryon symmetric cosmology (Stecker 1978, Brown and Stecker 1979). Thus, a temporally indefinite preplanckian era would have possessed a very large effective particle horizon within which thermodynamic equilibrium would have occurred through reversable particle-field interactions (e.g.,pair production and annihilation). This would account for the isotropy of the 3K microwave background radiation. Owing to the temporally indefinite state of the preplanckian era,it is not possible to calculate the ultimate scale over which this isotropization would occur for an open universe, but it must, of course, be greater than the present particle horizon in order to be consistent with observational data.

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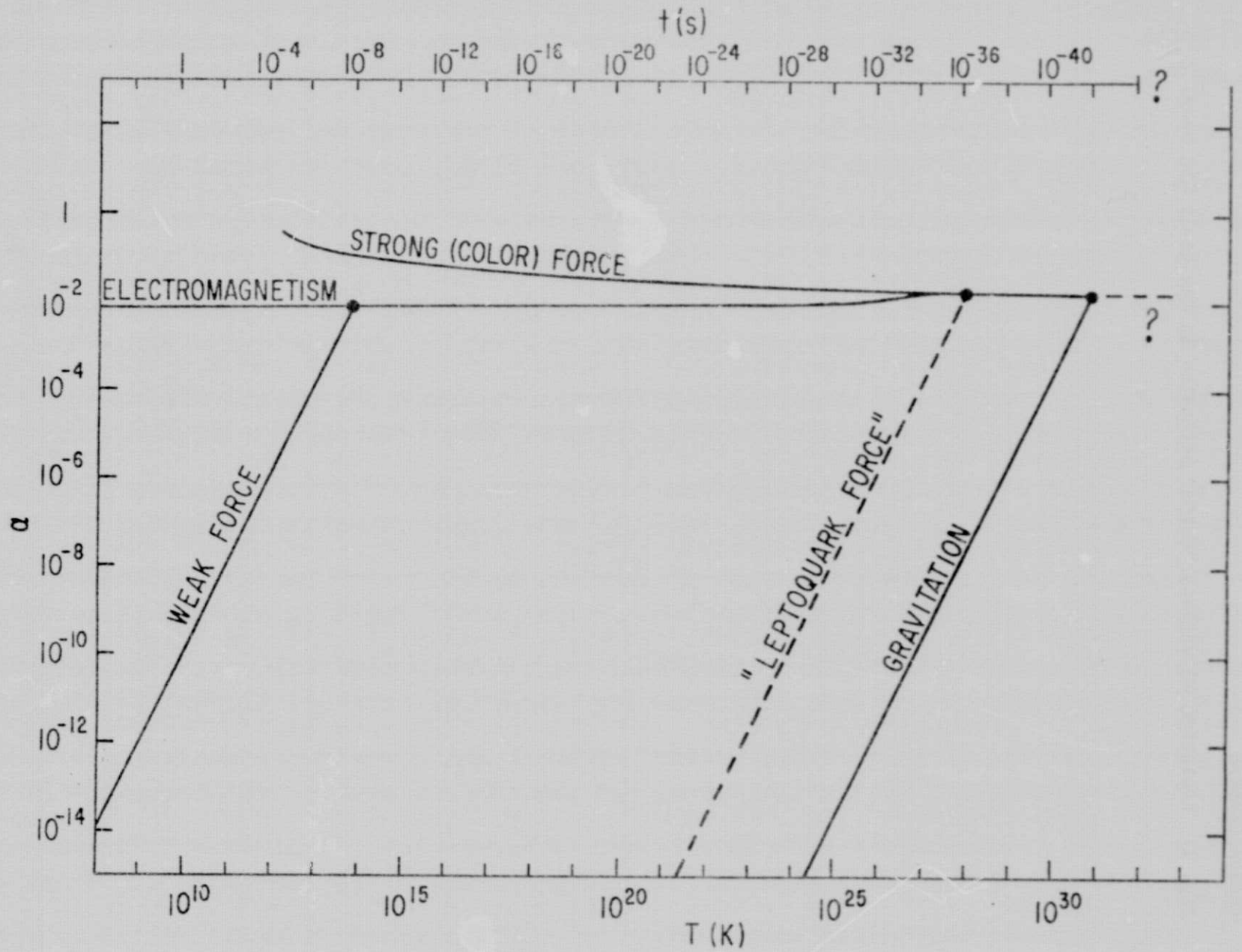
Figure Caption

Fig. 1. Evolution of various "force" strengths in the early big bang.


t (s)
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
10^{-32}
10^{-36}
10^{-40}
?
STRONG (COLOR) FORCE
ELECTROMAGNETISM
?
WEAK FORCE
"LEPTOQUARK FORCE"
GRAVITATION
α
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{10}
10^{15}
10^{20}
10^{25}
10^{30}
T (K)