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TRENDS IN NUCLEAR ASTROPHYSICS

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Communication présentée à : 2. IAP Meeting on nuclear astrophysics
Paris (France)
7-11 Jul 1986

Trends in Nuclear Astrophysics.

Institut d'Astrophysique
de Paris. July 1986
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The years 1965 -1975 have witnessed the establishment of the primordial nucleosynthesis, (also called BBN for Big-Bang nucleosynthesis). The problem of the origin of the light elements from ^{2}H to ^{11}B was gradually solved, and it became clear that the four isotopes ^{2}H, ^{3}He, ^{4}He, and ^{7}Li, were bona- fide relics from these ancient hot times. (1 to 5) It is worthwhile, at this point, to say that the solar wind experiment of Johannes Geiss and his Berne collaborators, in giving reliable non-terrestrial values for the helium isotopic ratio, played an important role in the set-up of this achievement (6 to 8).

Following the discovery of the fossil radiation, 9) (also called cosmic background radiation CRB), which was rapidly interpreted as evidence that the cosmic temperature had been up to, at least, a few thousand degrees, theoretical calculations of primordial nucleosynthesis, showed that reasonable account of the abundances of the light isotopes could be obtained if it was futher assumed that the scale of past temperatures had reached the 10^{10} degrees (one MeV) mark.

This calculation also provides an estimate of the baryonic density the universe. The baryonic density is between three and twelve percent of the closure density .(The main uncertainty is due to the poorly known distances of remote galaxies)(fig 1). The best estimates of the total (bayonic and non-baryonic) cosmic density, from dynamic effects on galactic motions, yields values around ten to twenty per cent of the closure density . Thus there is no disagreement between the (baryonic) density given by BBN and the dynamic evaluation. There is no sound proof of the existence of a non-baryonic matter contributing in a major way to the total density of the universe.

(To avoid confusion one should also make the distinction between luminous and non-luminous matter. The density of shining matter, stars, galaxies, amounts to only one per cent of the closure density. Thus , at least ninety per cent of the matter is invisible - the so-called missing mass - but may well be baryonic).

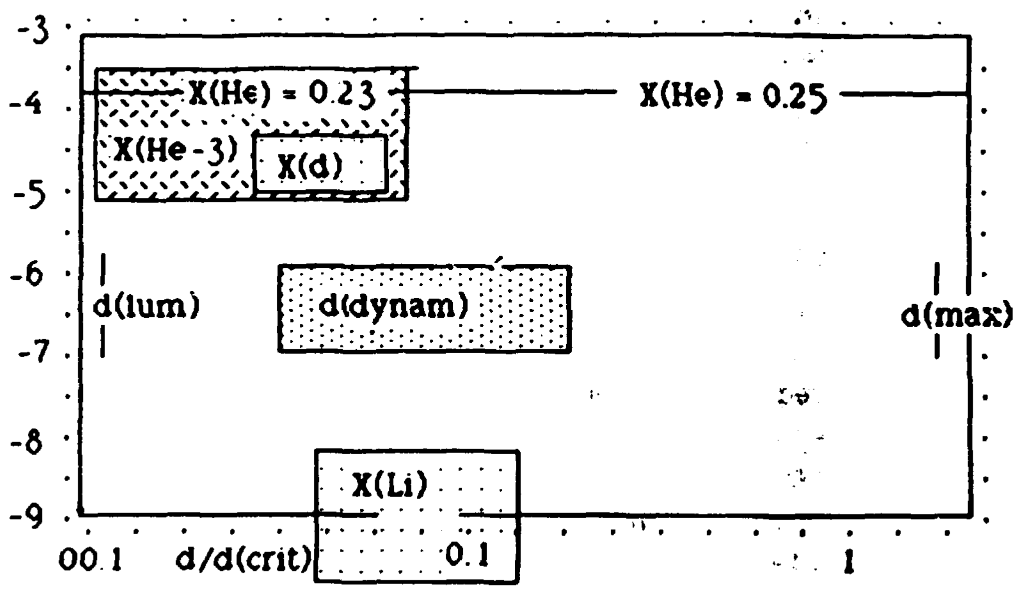

Fig I Estimated cosmic densities . The abcissa is unit of the closure density. On the left, d(lum) is the density of luminous matter . The range of d estimated from dy namical effect is enclosed in a box; Also shown is the upper limit from the search of galaxy deceleration. The light isotopes observational uncertainties and the corresponding uncertainties in the calculated BBN densities are shown in boxes.(fractional mass abundances) (scale on the left).

In the last decade the the success of primordial nucleosynthesis has become a major card in cosmological studies and explorations. It has been used as *ground basis* for testing new hypothesis or even conceptual frameworks. It has served as an "anchor" for theories -and theorists- to keep contact with observations, (a fundamental but sometimes overlooked condition for successful scientific progresses). There is already a large cemetery of cosmological models, brillant or not, which have died because they could not reproduce, in a convincing matter, the success of the simple BBN. In this review iI want to discuss two areas of research in which primordial nucleosynthesis has played a proeminent role.

Proliferation of particle families.

In the present standard theory of physics, the elementary particles are grouped in three main families called *electronic, muonic* and *tauonic*. Each family contains four members : two leptons and two quarks .To each member of a given family correspond members in the other two families which, as far as we know, differ only in masses. For instance, to the electron (0.5 MeV) correspond the muon (107 MeV), and the tauon (1.5 GeV).

The families are shown in the table with the best estimates of the masses.We have, so far, no evidence of any meutrino masses, only upper limits are quoted. The existence of the t-quark has not yet been firmly estabiished.

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FAMILY BOOK.

electronic	muonic	tauonic	?onic	?onic
electron-neutrino <10 eV	muon-neutrino <25 MeV	tauon-neutrino <100MeV	?	?
electron 0.5 MeV	muon 0.1 GeV	tauon 1.5 GeV	?	?
quark-u 0.3 GeV	quark-c 1.5 GeV	quark-t 40 GeV (?)	?	?
quark-d 0.3 GeV	quark-s 0.5 GeV	quark-b 5.0 GeV	?	?

The question in every one's mind is how many more families are there in our big blue world. As a few years ago, high energy physics had hardly anything to say about this question.

Big-bang nucleosynthesis , on the other hand, was making very definite predictions. The number of extra families could not be very large. At best, one or two. More probaly , in fact, we already have come to the end of the list with our three families.

The experiments leading to the discovery of the W and Z particles (responsible for carrying the weak interaction) have confirmed this prediction of primordial nucleosynthesis in limiting the number of new families to three at most. In the following paragraphs, I will present the physical arguments behind these statements. Here I want to take the occasion to put some emphasis on the importance of the event I am talking about , because it seems to have passed largely unnoticed in the astrophysics community.

We should keep in mind that Big-Bang is , in the usual scientific context , quite an extravagant theory. Contrary to the scientific paradigm held unequivocally from the time of the ancient Greeks,throughout the Renaissance, until quite recently, it places the universe in an histortical framework. Instead of being the observer of an eternal unchanging realities, the astrophysicist becomes an historian exploring the past in search of events which have given the world the properties it has today.

A similar transition had already taken place in the life sciences ,one

IFP.1-3

century ago , when Darwin denied the "fixity of the animal and plant species to introduce the notion of biological evolution. With the Big-Bang this notion is enlarged to the whole physical universe.

The more extravagant, (or out-of-the-beaten- path), a theory is, the stronger should be the proofs in his favour, before it is accepted. Confirmed predictions are always of prime values here, as it is always easier to find explanations to known facts than to predict correctly the result of a future observation or experimentation . After correctly predicting the existence of the fossil radiation ,the theory has also passed successfully the test of the family proliferation.This is worth a double mention.

Evidence from the width of the Z

Figure 2 gives the experimental basis for the detection of the Z particle (carrier of the neutral weak interaction) at CERN in 1984 [i to j]. The curve shows the large resonance in the electron-positron cross-section around 93 GeV (the mass of the Z). The energy width of this resonance is , according to the Heisenberg principle , related to the lifetime of this particle. And the lifetime is related to the number of channels (partial widths) in which the Z can decay.

Contrary to us, the Z "knows" how many families there are : it decays in all possible channels open to him . Hence the observed width of the resonance gives us a measure of the total number of families.

Numerically, the energy width of the Z, computed taking into account the three family we already know, turns out to be 2.63 GeV. Each unknown neutrino would contribute an additional 180 MeV to the width. Comparison with the increasingly accurate observational data shows that the upper limit on unknown channels corresponds to the equivalent of less than three neutrino types, with a 90%percent degree confidence.

There are some restrictions . The Z particle is a left-handed weak interacting particle. It cannot decay in righ-handed neutrinos (if they exist). Nor can it decay in particles of more than half of its mass (46 GeV). Its width would not reveal the existence of such hypothetical particles.

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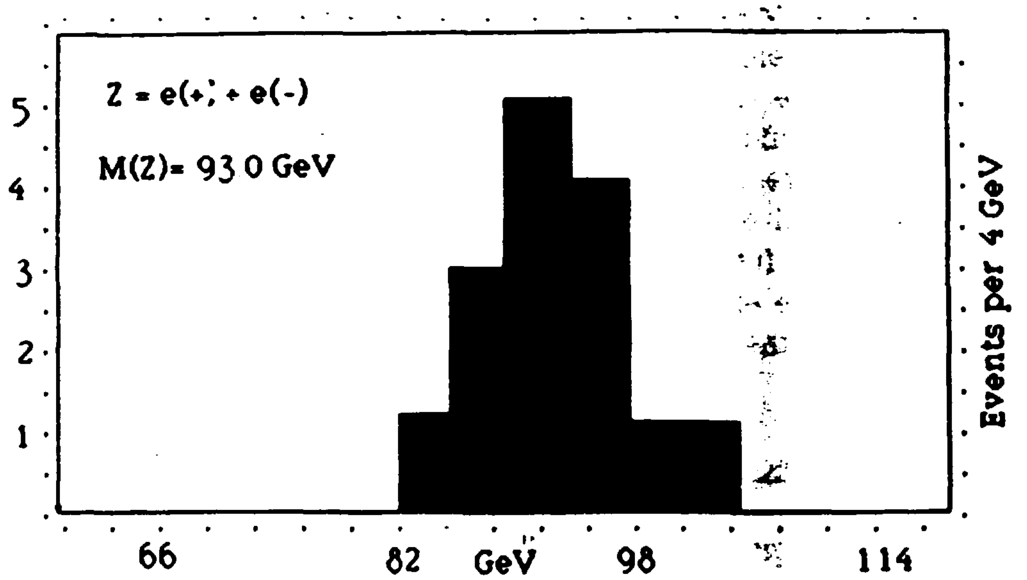

FIG 2 Electron-positron resonance manifesting the existence of the Z particle at CERN. The width of the resonance is a function of the number of decay channel hence of the number of unknown families of elementary particles. The observed width can not accomodate more than three undetected families over and above the three known families.

Evidence from mass renormalisation

Another test comes from a combination of the masses of the W and the Z , together with the Weinberg mixing angle θ between the EM and the W interactions . In the first approximation, these quantities are related by the equation:

$$M_W^2 = M_Z^2 \cos^2\theta \qquad (1)$$

When radiative corrections are taken into account however, this expression is no more exact because of the renormalisation it imposes on the masses of these particles. The important corrections come from the inclusions of closed loops of fermions, especially those which are widely split in masses (as the b and the t quark whose mass difference is several tens of GeV).

The experimetal ratio of the L.H.S over the R.H.S of equation (1) differs from one by less than five percent. This is enough to exclude new families with quark mass splitting of the same order or larger than the b and the t. Inspection of the data on the table shows that the quark mass splitting increases as we move from left to right. We can exclude the presence of new families in which this trends would continue.

Evidence from primordial nucleosynthesis.

Most of the story is illustrated in the figure 3. Here is plotted first the run of cosmic temperature(in ordinate) as a function of time (in abcissa) as obtained from the Einstein equation describing the early radiation-dominated universe:

$$(R / R)^2 = (8/3)\, G_N\, \rho = (1 / t_{exp})^2 \qquad (2)$$

where R is the distance scale , and ρ is the total energy density. At the high temperatures of the early universe, the particles are relativstic and they contribute in a democratic way to the density , each species being represented by its multiplicity number:

$$\rho = g^* (\pi^2 / 30)\, T^4 \qquad (3)$$

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$$g^* = [\,7/8(\Sigma_f\, g_f) + (\Sigma_b\, g_b)] \qquad (4)$$

In these expression $h=c=k=1$; f stands for fermions and b for bosons. Hence we may write:

$$t_{exp} \cong (\,1/(g^* G_N)^{1/2})\; T^2. \qquad (5)$$

The corresponding curve is plotted in fig 3, with the g^* value corresponding to the three standard families of physics. ($g^* = 9.75$). Adding new families would increase the value of g^*, hence increase the total density through equation (3), and consequently increase the rate of expansion through equation (2) . In fig 3 the resulting curve t'_{exp} (for $g^{*'}$ larger than g^*) is shifted below the standard one.

Consider, next the timescale of weak interactions. For instance, the timescale for the capture of a neutrino to react with a neutron and give a proton and an electron. This reaction is fundamental in keeping the neutron-proton abundance Boltzman equilibrium at high temperatures ($n/p \cong \exp(-\Delta M/kT)$ where ΔM is the neutron-proton mass difference (1.293 MeV)

The neutrino capture probability is proportional to the number of neutrons per unit volume, times the mean thermal cross-section for this event.

$$P_\nu = N(n) \;\langle \sigma v \rangle \qquad (6)$$

The neutron number density decreases with R^{-3} and hence with T^3 ($T \propto R^{-1}$ in the expansion). The mean thermal cross-section is $\propto$ to E^2_ν (hence to T^2) and also the Fermi coupling constant square (G_F^2).

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$$t_{reac} = P_\nu^{-1} \propto \;1/\,G_F^2\, T^5 \qquad (7).$$

The two curves (t_{exp} and t_{reac}) meet around 1 MeV ,called the decoupling temperature(T_d). Below this temperature the reaction rate is too slow to follow the expansion rate and the equilibrium is lost. After

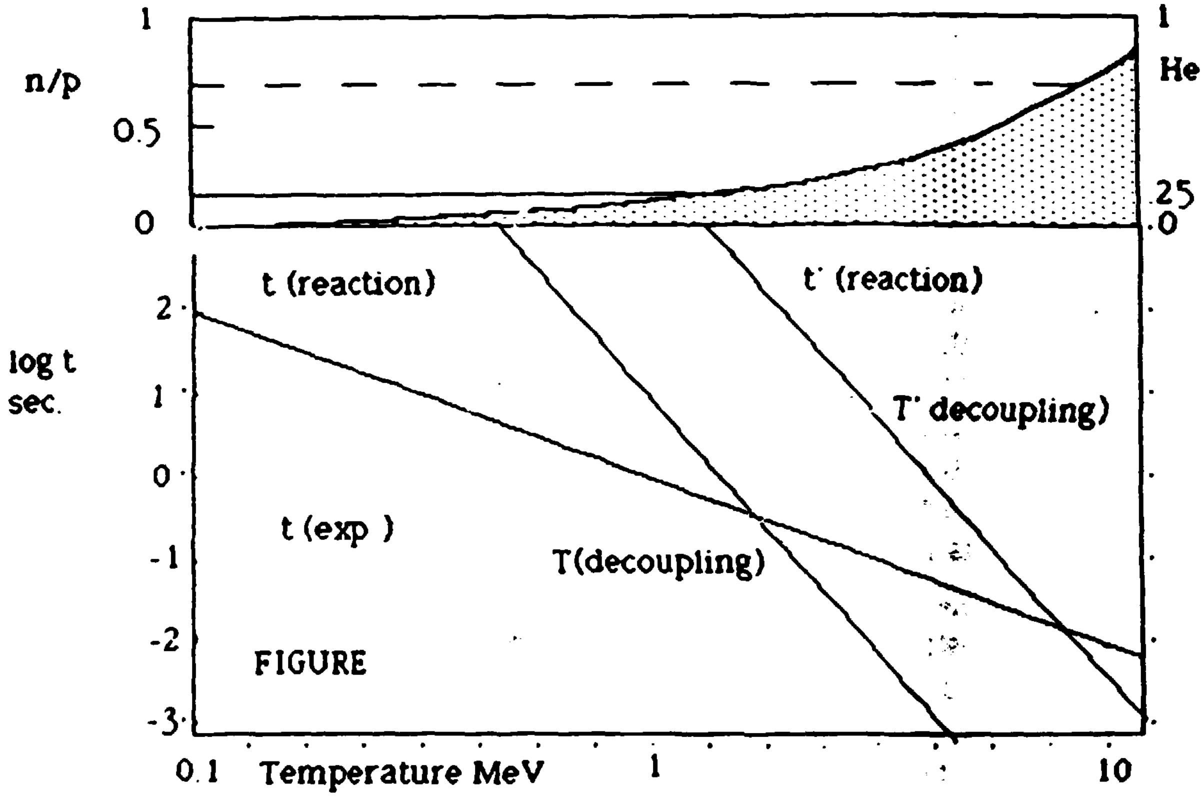

Figure no 3 Decoupling of the neutrino interactions. The abcissa gives the cosmic temperature and the ordinate, the age of the universe in seconds. The curve t (exp) gives the relation between cosmic age and temperature ($t\ (exp) \propto 1/[(g^{*}G_N)^{1/2}\ T^2]$) in the standard Big-Bang. The t (reaction) curve is the mean reaction time for weak interactions involving neutrino capture and emission, ($t\ (reaction) \propto 1/(G_F^2\ T^5)$). At temperatures below the crossing of the curves (at the decoupling temperature T(decoupling) ≅ 1 MeV), the neutrino interactions are too slow to keep pace with the expansion and the neutron-proton equilibrium abundance is no more insured.

An increase in the mass of the W particle would decrease the value of the Fermi constant ($G_F \propto M_W^{-2}$) and shift the reaction-time curve t'(reaction) to the right in the diagram, leading to a higher decoupling temperature T'(decoupling).

On the upper part of the diagram, the n/p ratio is shown as a function of temperature. On the right side of the figure, the abundances are given by the Boltzman equilibrium equation; on the left side, the neutrons are freely decaying. On the scale at the right is given the resulting helium abundance. The position of the decoupling T can be altered by changing g^*, G_F or G_N as seen from the expressions for the timescales. The BBN turns out to be a very sensitive test of the "constancy" of the coupling constants.

this time, the neutron essentially freely decay (lifetime of about one thousand sec). Around T = 0.1 MeV, (one hundred seconds later) the deuterons manage to resist photodisintegration. Essentially all the surviving neutrons are then captured by protons and transformed gradually in mostly helium-4 (BBN).

In a nutshell, the junction of the timescales curves fixes the **n/p ratio** at decoupling (upper part of figure 3). Very few neutrons decay before BBN, and the rest results in helium. Thus, assuming the existence of new families results in an increase in g^* which increases T_d and hence the abundance of He.

The best estimate of the helium cosmic abundance after BB (obtained from observations of galaxies with very low metal abundance) is 0.245 ± 0.01. This is best reproduced in the calculations if we assume three families with neutrinos of masses less than 0.5 MeV(to insure that they are relativistic and "weigh " a full T^4 term in the density balance of equation 3). With the uncertainty on the data , it is possible to include one more family ,perhaps even two ,but certainly not more . It is on the basis of these arguments that BBN did make its successful prediction on the limitation of the number of families of elementray particles.

Let us discuss again the factor g^*. The expression given in equation (4) should be corrected for the factor to be presently discussed . Below the decoupling temperature the neutrinos do not interact anymore with the other particles . They live a separate life and are only affected by the expansion which increases all wavelengths and hence shifts their temperature downward (while respecting their Bose-Einstein energy distribution).

Around 0.5 MeV, the positron-electron annihilation takes place transforming all their masses in radiations, essentially all in thermal photons since the neutrinos have no possibility in sharing the bounty. The corresponding temperature effect in the photon gas can be computed through photon entropy conservation (initial and final) during the annihilation.

$$S_i = g_i^*(T^3_i) = S_f = g_f(T^3_f) \qquad (8)$$

$$g^*_i = [(2 \quad + \quad 7/3 (2+2)] \qquad (9)$$

photons   positrons and electrons

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$g^*_f = [2]$ (photons only) (10)

thus $T_f/T_i = (11/4)^{1/3} = 1.31$ (11)

This numerical ratio is also the present ratio of the photon to neutrino cosmic background radiation since the neutrino gas did not undergo this temperature effect . With the observed value of 2.7 K for the CMB the big-bang theory is therefore predicting the existence of a cosmic neutrino background of 2.1 K. Such a detection is presently out of the reach of existing technology

This discussion introduces the possibility that some species of particle may not weigh as much as others in the cosmic density balance if they decouple before the onset of massive annihilation chapters.

The expression for g* in equation (4) should thus be corrected in the following way:

$$g = (\Sigma g_b[T^4(b)/T^4(\text{photons})] + 7/8\ \Sigma (g_f[T^4(f)/T^4(\text{photons})]) \quad (11)$$

At the moment of decoupling, the photons and the neutrinos had the same temperature so that eqn (4) and (11) are equal. But let assume that there exist very-weakly interacting particles i characterized by a $G_{Fi}' < G_F$ (an hypothetical right-handed neutrino for example). The corresponding curve in figure 3 would be shifted to the right , leading to a larger decoupling temperature for this particle. Assume for instance, that this decoupling occurs before the muon anti-muon annihilation around one hundred MeV. The released energy would be shared amongst the electrons and left-handed neutrinos (all these particles seeing their temperature go up by a factor of 1.3) but not with this i particle which should be included in the expression of g* , but weighted with a factor of $T^4(i)/T^4(\text{photons}) = 1/2.95$. A similar computation could be made for particles decoupling before the nucleon masses ; their contribution would be correspondingly smaller.

Big-bang nucleosynthesis specifies that the value of g* is somewhere between 9 and 13. Although this range limits the number of particles interacting with the standard Fermi interaction, it clearly does not preclude the existence of a large number of other species ,provided their interaction strength is weak enough not to contribute to the g* in an exagerate way.

IAD-I

A multidimensional universe.

Cosmologies with extra geometric dimensions have been the center of much interest in recent years. The most popular version noway day involves ten dimensions, thus adding six new compact dimensions, over and above the familiar three-space and one-time dimensions.

The radius of curvature of these extra-dimensions would be of the order of the Planck length (10^{-33}cm) , far smaller than the smallest dimensions within reach of presently operating accelerators (the TeV accelerator of Fermilab can probe to a few 10^{-18} cm). Energies of the order of the Planck mass (10^{19}GeV) would be required to excite the corresonding modes. This is the reason why we can spend our life without being aware of the existence of these compact dimensions .

However they express themselves in properties that we are just reckognizing as related to the existence of these extra- dimensions. Here I will discuss one of these manifestations which will bring us back to big-bang nucleosynthesis. In these cosmological models *the values of the coupling constants of the various forces depend upon the radius of curvature of these compact dimensions* . If , as is the case in our familiar 3-D geometry, these radii are changing with time, the coupling constants would also vary with time.

We have much evidence today that these coupling "constants" are faithful to their name. Again we can take advantage of the success of BBN to study the question . To what extent can we alter the value of these constants without " messing up" the good agreement with the simple theory (Kolb 1986)? The answer is the following : since the universe cooled off to less than one MeV some ten billion years ago (after the first minutes in the standard chronology), *the coupling constants have not changed by more than one percent.*

We are not used to question the constancy of the "laws of nature". We usually take this fact for granted , or at least as "natural. The situation is changed when the extra-dimensions are added, and the observed constancy become a property of the model. This characteristics · severely constrains the choices of acceptable theories, just as renormalisabilities of gauge theories have been most useful guides in elementary physics research.

I will try to illustrate the situation by a simple case : the historical Kaluza-Klein model published in 1921. The aim of this model was to formulate an unified theory of gravitation and electromagnetism. One extra space dimension is added to the standard 3-D geometry. This space,

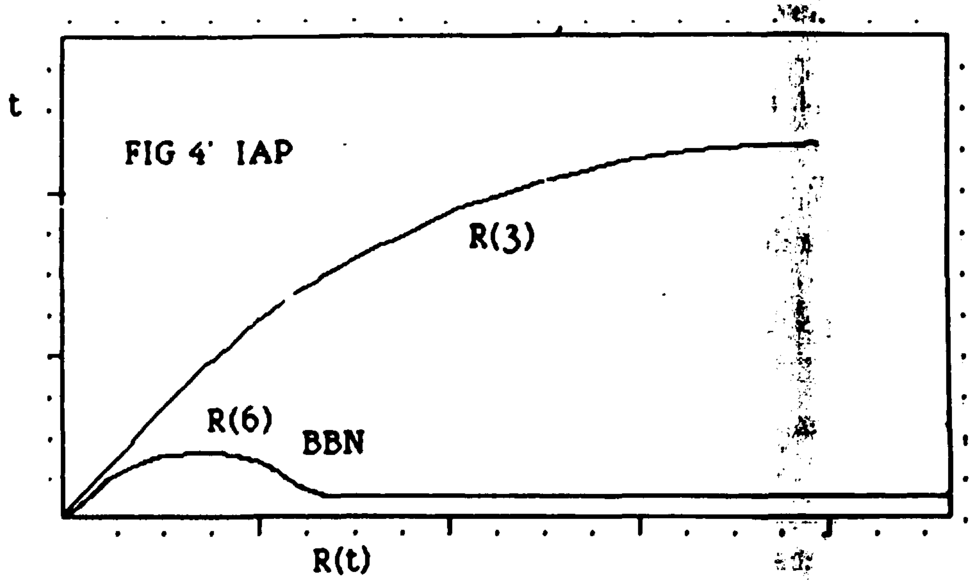

FIG 4'
Cosmological evolution . of space in a 10-D universe. Our familiar 3-D space is expanding with time, while the 6-D compact space rapidly reaches very small radii. The success of Big-Bang nucleosynthesis implies that these radii have not varied by more than a few percent since the first minutes. This constancy imposes severe constraints on superstring theories, and in general on all multidimensional cosmologies.

with radius D too small to be detect able, is responsible for the electromagnetic force through which it manifests itself.

Assume a Fourier decomposition of a field $\Phi(x,t)$ in 5-D, where x represents the 4 familiar dimensions and y is the fifth one.

$$\Phi(x,y) = \int \Phi^k(x) \exp(iky/D) \qquad (12)$$

The 5-D (del_5) Laplacian applied to this field will give the equivalent of a Klein -Gordon equation for massive particles:

$$(del_5)\Phi^2 = [(del_4) - m_k^2]\Phi^2 \qquad (13)$$

where $m_k = k/D$ with $k=0, \pm 1, \pm 2$ ....

If D is chosen as the Planck mass , the different modes corresponds to integers of the Planck mass,needless to say unobservable today .

Our everyday physics involves only the k = 0 mode. It is to be derived from the 5-D action integral:

$$S_5=(1/16\pi G_5)\int d^5(-g^5)^{1/2}\, R(N)+R(EM) \qquad (14)$$

where G_5 is the fundamental Newton constant of the (real) 5-D world . The number 5 on the other letters of this expression are a remainder of the presence of the fifth dimension. R is the curvature tensor which includes both a gravitational(N) and an electromagnetic(EM) term related to Maxwell's equation.

By confining ourselves to the k=0 mode of the field , it is clear from equation (12) that the fields are no more functions of y. This dimension gets out of the dynamics, In consequence, we may simply integrate equation (14) over y, to obtain:

$$S_5 = (2\pi D/16\pi G_5)\int d_4(-g_4)(R_N+R_{EM}) \qquad (15)$$

or

$$S_5 = (1/16\pi G_4)[S_4(N) + S_4(EM)] \qquad (16)$$

Thus we recover the standard 4-D physics if we identify the observed Newton's constant G_4 with G_5/D, where G_5 is the really

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fundamental constant of the theory. Hence the need to keep D constant to explain the observed constancy of G_4.

Since the years of the Kaluza-Klein theory, the gauge theories of weak and nuclear interactions have been developped successfully. The forces of nature are now seen as resulting from group symmetry operations in internal (isospin) spaces. The EM force correspond to an U(1) group, the full electro-weak force to an SU(2) X U(1) and the nuclear force to an SU(3).

In analogy with the K-K model , the present view of multidimensional cosmologies involves the identification of the internal spaces of the standard gauge theories with geometric spatial dimensions on which the corresponding group operators would act. The motivation for this identification is related to the many difficulties of the standard models (divergencies , anomalies etc,) together with the hope of formulating a realistic theory of quantum gravity. There appears to be no other ways, known at the present time, to reach these goals.

The problem of the variability of the coupling constants with the volumes of the compact spaces is met in higher -D spaces just as in the 5-D space of K-K. In the Einstein cosmological versions of expanding universe, all the radii are coupled together so that variation of any one dimension always results in variation of the others. We know that our familar 3 dimensions have expanded to some 10^{60} times the Planck length in the last ten billion years. It is usually assumed that the other six dimensions have contracted upon themselves after a few Planck times (10^{-43}sec). The situation is described in fig 4. The question in everyone's mind is : how did these dimensions managed to remain so amazingly stable (at least after the BBN) while the others underwent such a large modification? It is fair to say that no satisfactory answer have yet (in 1986) be given to that question.

One popular way of stabilizing the compactification of these spaces is to introduce an appropriate cosmological constant in the Einstein equation. This brings reminiscence of the situation met by Einstein in 1915 when he first investigated the cosmological problem.

Realizing that the model implied a global motion of cosmic matter , and having strong dislike for this effect, he introduced the cosmological constant precisely to stop this motion. However it was soon shown that this solution would be of no avail since it is unstable to small perturbations. The problem disappeared ,at any rate, after the Hubble observations of the recessing galaxies.

Present efforts to stabilize the extra dimensions by introducing a cosmological constant are facing the same stability requirements , which again can be considered as a constraint that a successful model should meet.

Summary.

I have described two instances in which the good success of standard Big Bang nucleosynthesis in reproducing the abundance observations of the light elements has been used for the developpment of high energy physics and of early cosmological models. The first case is in relation with the families of elementary particles ,the other case is in the formulation of multidimensional cosmologies (as superstring theories) taking into account the observed constancies of the 4-D versions of the coupling constants.

Light elements as probe of stellar physics.

To end up this review of " recent trends in nuclear astrophysics" I want to talk shortly on a new development of so great pedagogical interest that it should soon find its way into physics textbooks.

Boesgard and Tripicco (1986) have recently reported a rather astonishing feature of the abundance curve of Li in the Hyades cluster (age 8×10^{8} years) as a function of surface temperature. When completed with the data of the Cayrel (1986), the curve shows a deep dip around 6600 degrees, followed by the well known decreasing slope at lower temperature (fig 5).

This low-temperature slope is understood as being due to the nuclear destruction of lithium, by proton-induced reactions, at the bottom of the surface convective zone (b.s.c.z.) of the star. As we go to the right of the diagram, the b.s.c.z. becomes deeper and its mean temperature increases with decreasing surface T, resulting, after eight hundred million years, in a gradual destruction of Li , more pronounced to the right.

According to Michaud (1986) the dip could be understood in terms of atomic (not nuclear) phenomena, in relation with photon-atom collisions *below* the convective zone. The differential light presure on the atoms in their various ionization states have been computed with realistic stellar models, and compared with the force of gravity.

For surface stellar T above 6800K, the net force upward on the lithium ions situated just below the b.s.c.z. is stronger than the gravity force pushing downward. The ions are pushed up into the convective zone. Below 6800 K, the opposite situation holds and the convective zone is gradually depleted in lithium ions.

Depletion takes time. The deeper the layer(in other words, the lower the T (surf)), the longer is the timescale for appreciable depletion. Fig 6 shows the computed depletion timescale as a function of T(surface). For T < 6600 or so, no depletion due to the sinking of the ions is expected ,since the timescale is comparable to the age of the cluster.

The nuclear timescale of Li destruction at the b.s.c.z. is shown in the same figure (adapted to the data with some degree of overshooting). The remarkable feature is the fact that the two depletion processes (nuclear and atomic) are manifesting themselves side by side with no

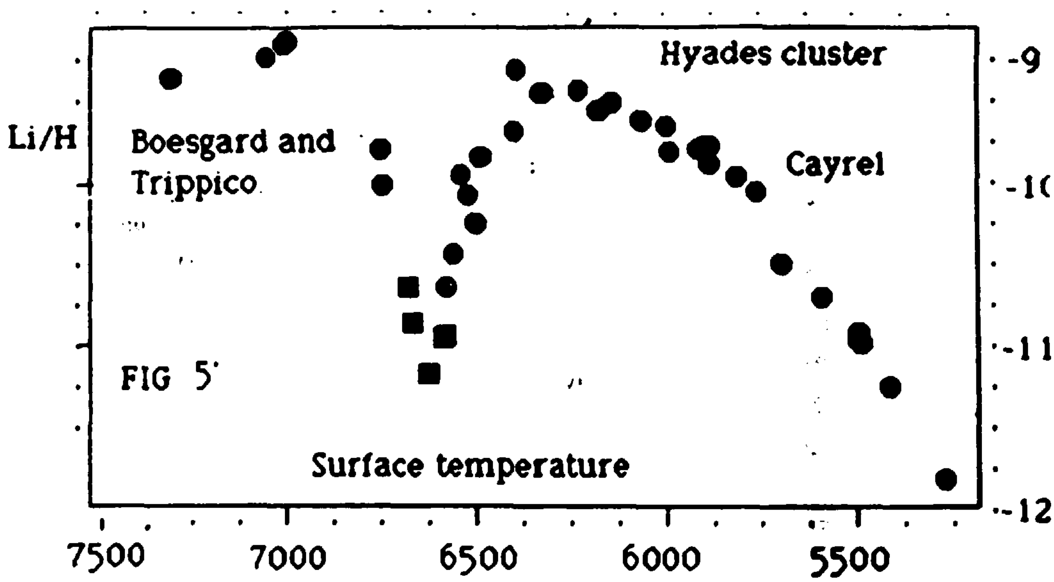

FIG 5'
Lithium observations in the Hyades cluster. The data is form Boesgard and Trippico (1986) and also of the Cayrel (1986) Square dots are upper limits.

In ordinate, the abundance Li/H .In abcissa, the stellar surface temperature.

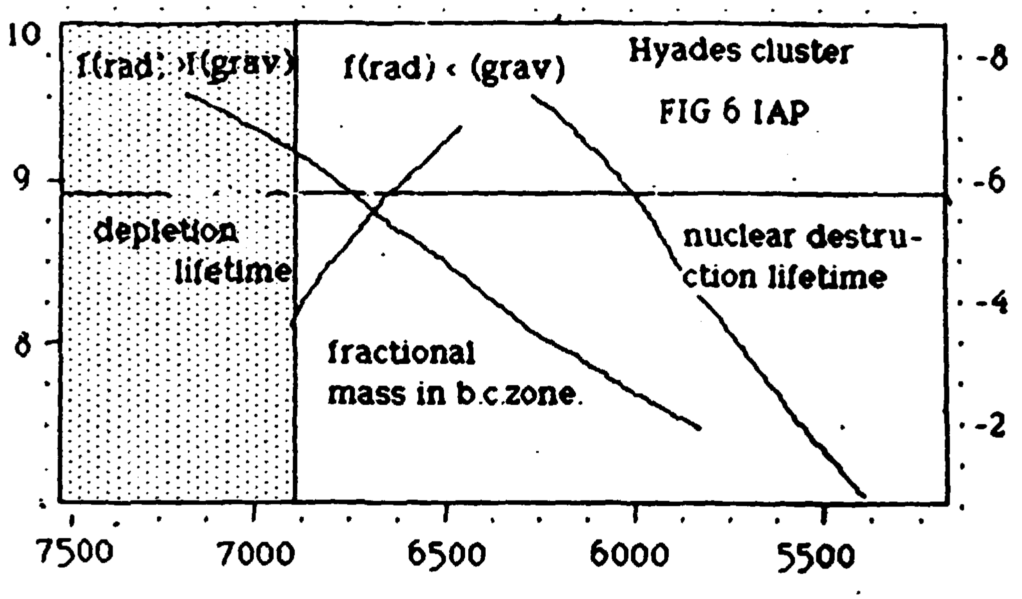

FIG 6 Physical parameters of Hyades stars. On the left (shaded area) thelight pressure on lithium atoms is stronger than the gravitational pull downwars. The depletion lifetime and also the nuclear destrution lifetime are plotted (scale on the left) log of the time in years. On the right, the fractional mass of the star in the convective zone. The age of the cluster is indicated by the horizontal line.

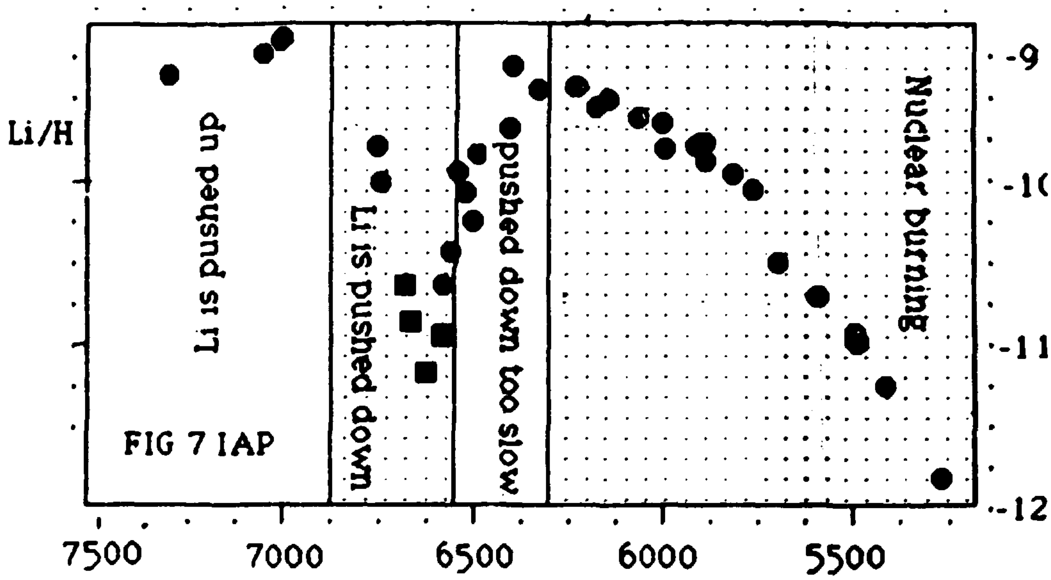

Fig 7 The observational data with the physical phenomena presumed to account for the behaviour of the abundances.

overlap(fig 7).

We are left with a question about the right side of the diagram : why are there no *overabundances* of lithium at T > 6800 K, where the ions are pushed up? Michaud and his collaborators (1986) provide an answer in terms of mass loss through stellar winds. According to their computations, stellar winds of 10^{-14} to 10^{-15} solar masses per year could account for the observations.

Further studies have shown (op.cit.)that other elements would react differently to stellar winds. This opens up a new field of stellar dynamics through stellar abundance determinations.

Similar analyses of clusters of different ages would be welcome to test the validity of these nice ideas.

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