NUCLEAR CONSTRAINTS ON THE AGE OF THE UNIVERSE

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1. INTRODUCTION

In this paper a review will be made of how one can use nuclear physics to put rather stringent limits on the age of the universe and thus the cosmic distance scale. As the other papers in this session have demonstrated there is some disagreement on the distance scale and thus the limits on the age of the universe (if the cosmological constant $\Lambda = 0$.) However, the disagreement is only over the last factor of 2, the basic timescale seems to really be remarkably well agreed upon. The universe is billions of years old - not thousands, not quintillions but billions of years. That our universe has a finite age is philosophically intriguing. That we can estimate that age to a fair degree of accuracy is truly impressive.

No single measurement of the time since the Big Bang gives a specific, unambiguous age. Fortunately, we have at our disposal several methods that together fix the age with surprising precision.

In particular, as the other papers show, there are three totally independent techniques for estimating an age and a fourth technique which involves finding consistency of the other three in the framework of the standard Big Bang cosmological model. The three independent methods are:

1. Cosmological Dynamics
2. The Age of the Oldest Stars
3. Radioactive Dating

This paper will concentrate on the third of the three methods, as well as go into the consistency technique. Each of these involves nuclear physics, hence the title of the article.

Since other papers in this session dealt with techniques 1 and 2, I will not describe them here. I will instead give an updated review of nucleocosmochronology and of age consistency arguments using Big Bang nucleosynthesis. As such this will be an update of the review

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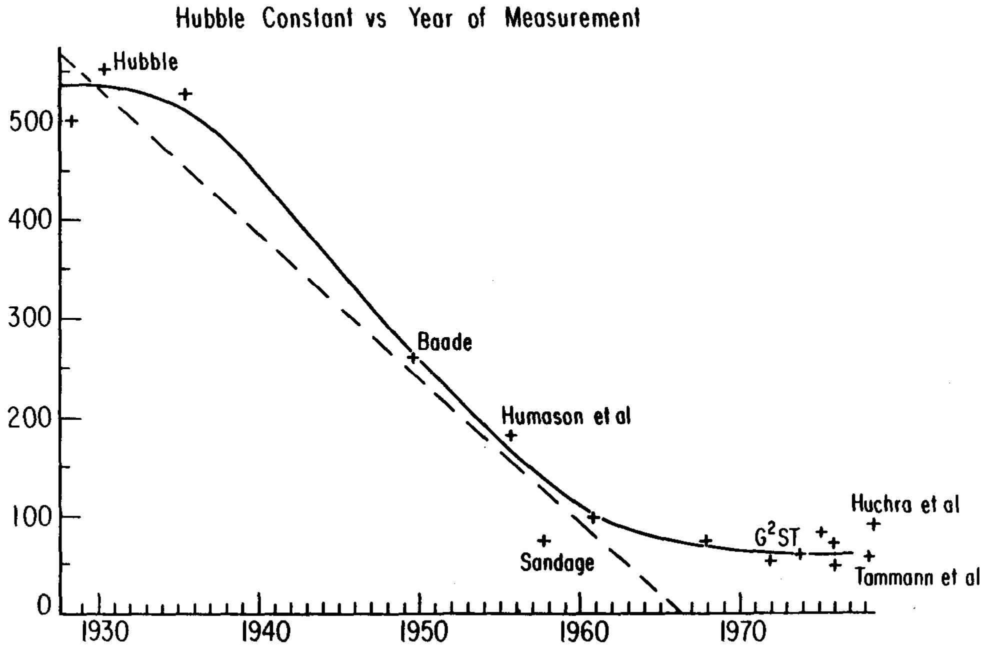

Figure 1: Hubble constant vs. year of measurement.

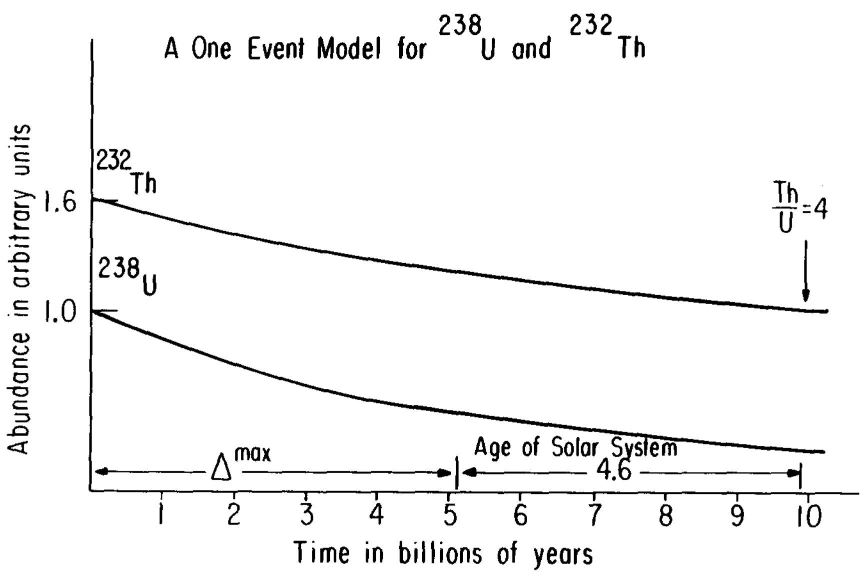

Figure 2: At time = 0 it is assumed that the ratio of the abundances is $^{232}Th/^{238}U \simeq 1.6$. It is known that $^{232}Th/U \simeq 4$ now. From the diagram it can be seen that it takes about 10 billion years for the ratio to change from 1.6 to 4. Thus, an event at time 0 occurred $\sim$ 10 billion years ago in this model. Notice that when the solar system formed 4.6 billion years ago, the ratio $^{232}Th/^{238}U \sim 2.4$ which was about 5.0 billion years after time = 0.

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(Schramm 1982) presented at the AAAS meeting on the Age of the Universe. Before going into the nuclear techniques let us glance at Figure 1, where we see the Hubble constant plotted versus the year of measurement. This reminds us that the direct determination of the distance scale has been plagued with systematic errors. In contrast we might note that the nucleochronologic ages first determined by Fowler and Hoyle (1960) are still in good agreement with the current determination which will be presented here.

2. AGE BY NUCLEOCOSMOCHRONOLOGY - RADIOACTIVE DATING OF THE UNIVERSE

Nucleocosmochronology was reviewed in detail by Symbalisty and Schramm (1981). The method is similar to the Carbon-14 dating method used by archaeologists and paleontologists to pinpoint the time that living tissues died. In effect, nucleocosmochronology is a way of dating the creation of the heavy elements.

Nearly all elements heavier than iron are formed by neutron captures. The S-process or slow neutron capture process takes place in the envelope of red giants. The r-process or rapid neutron capture process apparently takes place in supernovae. However, the detailed astrophysical site of the r-process is still not determined. (See discussions by Norman and Schramm (1979) and references therein.) From meteorites we in fact know that the actinide producing r-process is probably not the same as the r(n)-process which produces the lighter r-process nuclei. (See arguments presented by Olive and Schramm (1981) and references therein.) However, to get the high neutron flux needed to yield actinides requires a catastrophic event which is probably in some way associated with the death of massive stars. Thus, in this paper I will use the term supernova to refer to the r-process site but remember we may actually be referring to some other catastrophic astrophysical site.

The best nucleochronometers (this is those with sufficiently long lives to be cosmologically interesting) are the radioactive elements formed by the r-process. By dating the origin of certain r-process elements, we can derive a date for the supernovae (or whatever) that generated them. By dating the oldest supernovae, we come to a date not too much after the Big Bang itself. Stars that become supernovae take $\lesssim 10^7$ yr to evolve. Then adding this to the time it takes to make a star ($\sim 10^7$ yr) yields the first supernovae blowing up and making heavy elements much much less than a billion years after recombination, and recombination is $\sim 10^5$ yr after the Big Bang. Thus the age of the first supernovae is a good estimate of the age of the universe. The question is, then, how do we go around finding the oldest supernova.

Happily enough, to make the calculations it is not necessary to know the actual, absolute abundances of the elements today or at any time in the past. All we need do is compare the ratio in which a suitable pair of chronometers were formed (their <u>production ratio</u>) and the ratio in which they are found today (their <u>abundance ratio</u>) and

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TABLE 1

	Half-lives	
Rhenium-187	(^{187}Re)	43 billion years
Osmium-187	(^{187}Os)	stable
Thorium-232	(^{232}Th)	14 billion years
Uranium-238	(^{238}U)	4.5 billion years
Uranium-235	(^{235}U)	713 million years
Plutonium-244	(^{244}Pu)	82 million years
Iodine-129	(^{129}I)	16 million years
Iodine-127	(^{127}I)	stable
Aluminum-26	(^{26}Al)	700,000 years

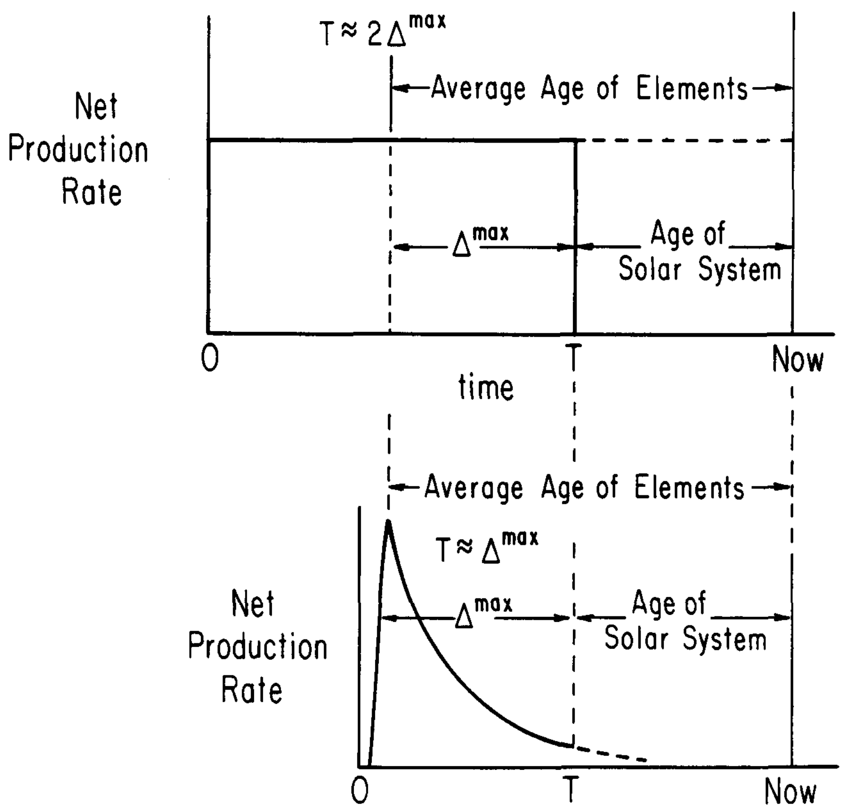

Figure 3: Average ages and total ages.

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couple these together through the known radioactive decay time.

Production ratios of the various r-process elements can be calculated theoretically. For example, we can calculate that ^{232}Th is made in a supernova 1.6 times as much as ^{238}U. This calculation basically involves estimating how many r-process produced nuclei will eventually decay to ^{232}Th [5 = (232) + (236) + (240) + (244) + (248)] compared to how many will decay to ^{238}U [3.1 = (238) + (242) + (246) + 0.1(250)] (see Schramm, 1974). ^{232}Th has a half-life of 14 billion years. ^{238}U has a half-life of 4.5 billion years. A sample of lunar rock today reveals an abundance ratio today for ^{232}Th and ^{238}U of approximately 4 to 1. In order for the production ratio of 1.6 to have changed to the present abundance ratio of 4, almost 10^{10} years must have elapsed (Figure 2). In other words, the event which created our lunar sample went on 10^{10} years ago, if it was only one event. (Note that our solar system is known to be $4.6 \pm 0.1 \times 10^9$ yr old.)

This tells us the age of the elements if there was just one supernova that created all the Th and U in our sample. There have been about a billion supernovae in our galaxy's history, and it is unlikely that they all went off at the same time. In fact, because ^{129}I, ^{244}Pu and ^{26}Al were present when the solar system formed and they could survive much less than a billion years it is apparent that supernovae went off not just 5 billion years before the solar system formed but also only millions of years. (One needs to be a little careful here since the ^{26}Al producing event probably did not make actinides like Pu nor Th and U but the basic argument is valid.)

Let us see how to convert our single event age for a more realistic age. Any distribution of supernovae has an average rate and an average age. Obviously the oldest nuclei must be older than the average age of the elements. We can also use statistical analysis to compare the supernova rate at certain times with the overall average rate.

We get our overall average rate from the very long-lived nucleochronometers. Table 1 shows that ^{232}Th and ^{187}Re have half-lives far longer than the entire duration of the period of their nucleosynthesis. ^{238}U has a half-life very near the duration of nucleosynthesis. These long-lived nuclei will still have some fraction of the abundance produced by the very first supernova that has not completely decayed away. Thus, the average rate of supernovae contributing ^{232}Th, ^{187}Re and ^{238}U nuclei is the average rate of supernova detonation for the galaxy's entire history. And the average age of these nuclei is the average of all the elements above carbon, because nearly all the heavy elements (with the exception of the s-process) are formed in supernovae. The shorter lived chronometers are not able to give us good total age information but they do tell us about events just prior to the formation of the solar system. These short-lived nuclei tell us that some nucleosynthesis took place in events that were the order of 5 billion years after the average event. Thus, to put the average where it is there may have been events 5 billion years before the average or else many, many more events near the average than after it.

TABLE 2

$^{232}Th/^{238}U\ \Delta^{max} = 5.1 \pm {}^{1}_{2.5}$ billion years

$^{187}Re/^{187}O\ \Delta^{max} = 4.6 \pm {}^{2}_{1}$ billion years

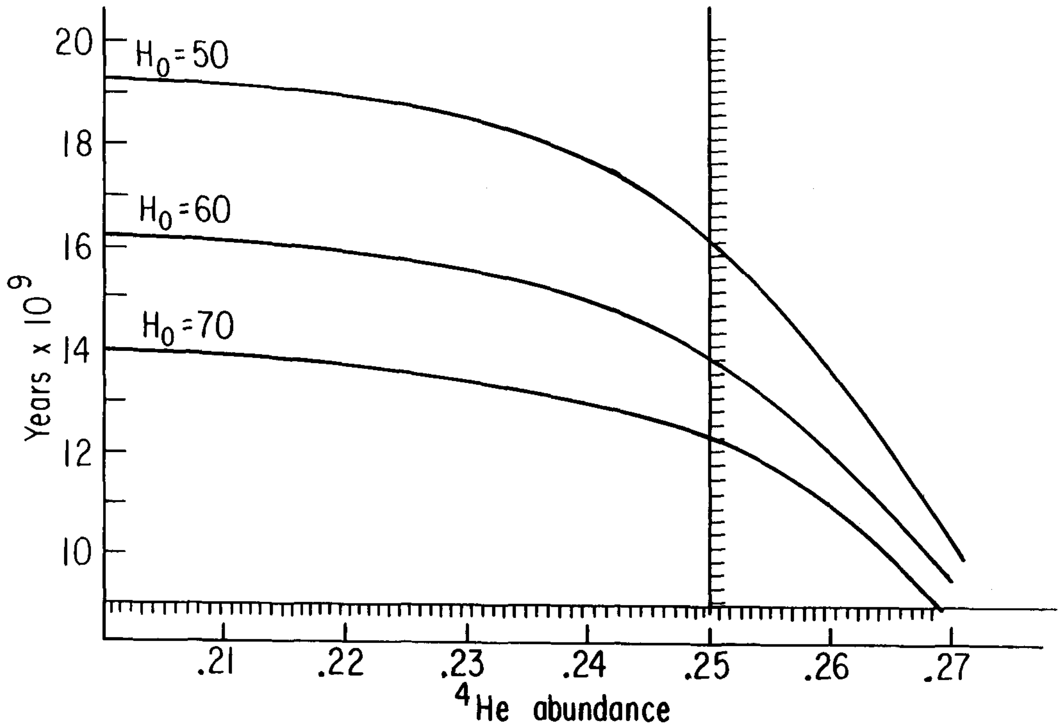

Figure 4: Age versus primoridal Helium abundance Y, for different values of H_0. Big Bang nucleosynthesis is used to obtain the density corresponding to Y, and that density is used to determine the fraction of the Hubble time that is the age. (This latter step would not hold if the bulk of the mass of the universe were not in nuclear matter.) Constraints on the lower limit age and the upper limit on Y are also shown.

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For sufficiently long lived nuclei the average age is just the equivalent of the one event age. (For a sufficiently long lived nucleus, the total duration of nucleosynthesis is negligible and can be treated as all occurring at one average time.) To get a total age we thus need to know something about the evolution of the rate of supernovae in the galaxy.

From looking at the heavy element abundances in different age stars we know that the production is not increasing now and if anything it may be decreasing. This statement comes from noting that the abundances of heavy elements in stars is not rapidly increasing with time although very early in the Galaxy's history it may have changed rapidly. Thus, production rates are at best constant and may actually be decreasing. A constant rate yields a total age which is twice the one event age and a high early production yields a total equal to the one event age (see Figure 3). Thus, the total age prior to the formation of the solar system is between the one event age and twice the one event age measured prior to the solar system formation. Current best models (Tinsley, 1975; Ostriker and Thuan, 1975; and Talbot and Arnett, 1973) for the evolution of the galaxy yield net rates that are nearly constant (see Hainebach and Schramm, 1977) and thus give total ages closer to twice the one event age)plus the 4.6 billion years for the solar system).

The two long-lived chronometer pairs are $^{232}Th/^{238}U$ and $^{187}Re/^{187}Os$. They give best estimate one event ages Δ^{max} prior to solar system formation of about 5 billion years prior to solar system formation (see Table 2) with a consistent overlapping uncertainty of ± 2 billion years. Thus, the mean age of the elements is 5±2+4.6 billion years which yields a best guess of about 10 billion years and a lower limit of 8 billion years. The best total age is twice the one event age plus 4.6. This yields about 15 billion years. However, it could go as low as 8 or as high as about 19 billion years.

Soon it should be possible to diminish the vaguarities in these calculations considerably. One improvement is coming from accelerator experiments seeking to provide a much better estimate of the Os cross sections at the temperature of relevance to the s-process which enable one to estimate the fraction of the ^{187}Os abundance coming from the decay of ^{187}Re. There is also hope for developing new nucleochronometers for some non-r-process radioactive nuclei. These should allow us to see if all nucleosynthetic processes yield similar chronologies. Another hope for the future is improved understanding of Galactic evolution based on new observational constraints.

2. CONSISTENCY

What is particularly stimulating about the information conveyed by all three dating methods is that it all congregates at the same general time, the order of 10 to 20 x 10^9 yr. Certainly a 10 billion year range is not tiny, but the very fact of the numbers being that close strongly indicates that some time within or around this range

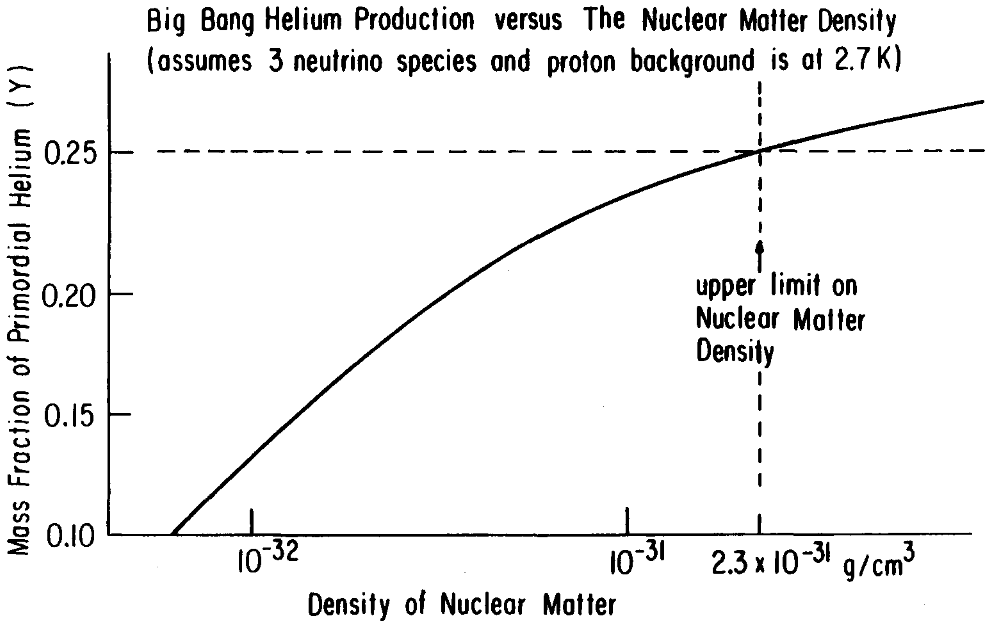

Figure 5: Big Bang Helium production versus the nuclear matter density (assumes three neutrino species and photon background is at 2.7K.)

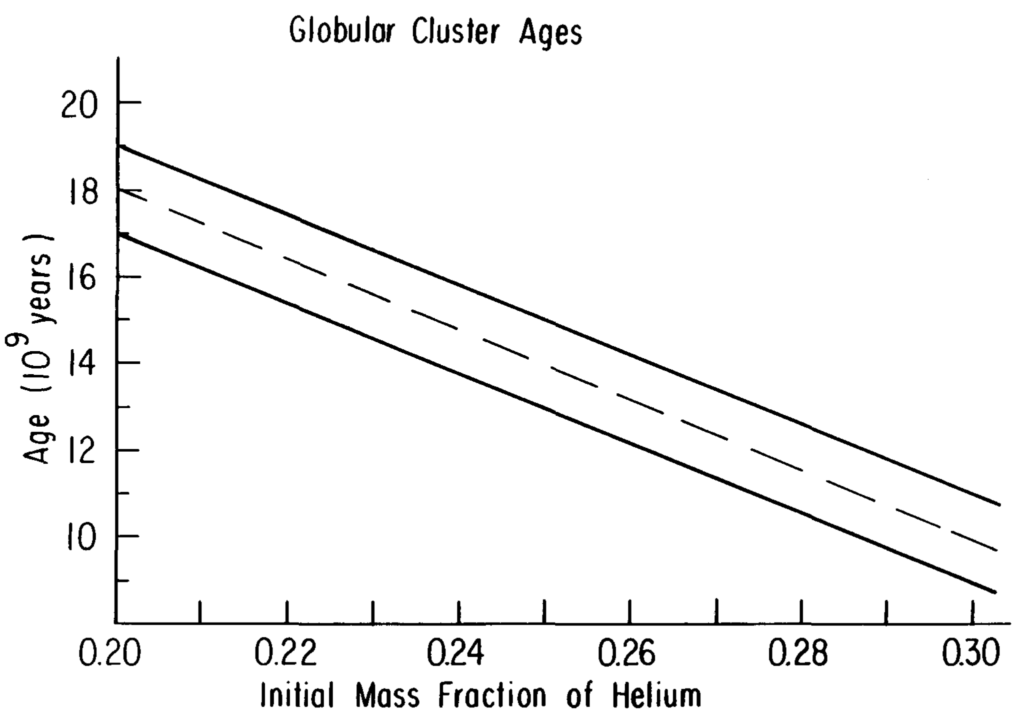

Figure 6: Globular cluster ages versus initial ^{4}He abundances from Iben (1973).

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something very profound must have happened; something which happened everywhere in this universe. It was big enough to leave its imprint on the timing of such diverse phenomena as the universe's rate of expansion and the timing of star formation and element creation. If all of these events are not somehow related in a single space-time context, then there is no reason why the numbers should not be wildly different.

Once one is convinced that these three independent techniques are really dating the same event - the Big Bang, we can argue that they must give exactly the same value for the same set of input assumptions. In particular, we can combine two of the above methods, use the third for an accuracy check and add further constraints from related observations and calculations.

Figure 4 shows the relation between age and helium abundance for three different Hubble constraints. This graph is possible because of the relationship between the age, the density and the amount of Helium made in the Big Bang. In the standard Big Bang model with $\Lambda = 0$ the age is a monotonic function of the density times the inverse Hubble constant with higher densities corresponding to smaller fractions of $1/H_o$ and the critical density yielding an age of $2/(3H_o)$. Big Bang nucleosynthesis produced He and the amount of He produced is sensitive to the density of nuclear matter in the universe (see Figure 5). If nuclear matter is the dominant form of matter in the universe like it is in the solar system then this density yields the fraction of the Hubble time that is the total age. We have superimposed on Figure 4 the upper limit on the primordial ^{4}He abundance of 0.25 (see discussion in Yang, et al. (1979) and Pagel (1982).

Calculations by Icko Iben and Robert Rood (1970) indicate that the globular clusters are between 9 and 19 billion years old for starting Helium abundances between 20% and 30% of the mass of the star. If primordial Helium is restricted to be less than 25% the lower limit moves up to 13.5 billion years. The primary uncertainty comes from the Helium abundance. Since higher primordial He requires less time to convert the rest of the core H to He and thus move off the main sequence (Figure 6). In the standard globular cluster models of Iben and Rood (1970), all other uncertainties amount to less than $\pm$ 1 billion years.

Some authors (c.f. Demarque and McClure, 1977; and Flannery, 1981) obscure the sensitivity to the Helium by fitting to some cluster observable like the relative numbers of red giants and horizontal branch stars. Since such parameters are very sensitive to the helium abundance such a fit is merely changing the name of the real physical variable and is in effect fitting to a particular helium abundance. Recently non-standard effects have been included in globular cluster calculations. These include gravitational settling of the He which decreases the age (Noerdlinger et al., 1981) and rotation induced turbulence (Maeder and Shatzman, 1981) which increases the age and also eliminates the gravitational setting. Even with various age lowering effects and large parameter shifts ages do not go under 8 or 9 billion years (Flannery, 1981). Since effects which decrease the age

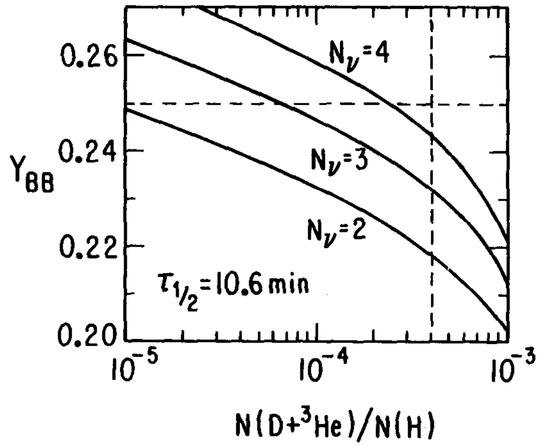

Figure 7: The primordial ^4He abundance Y_p versus the sum of ^3He+D (from the Big Bang nucleosynthesis calculations of Yang, et al., 1983). Note that for 3 or more families of neutrinos there is

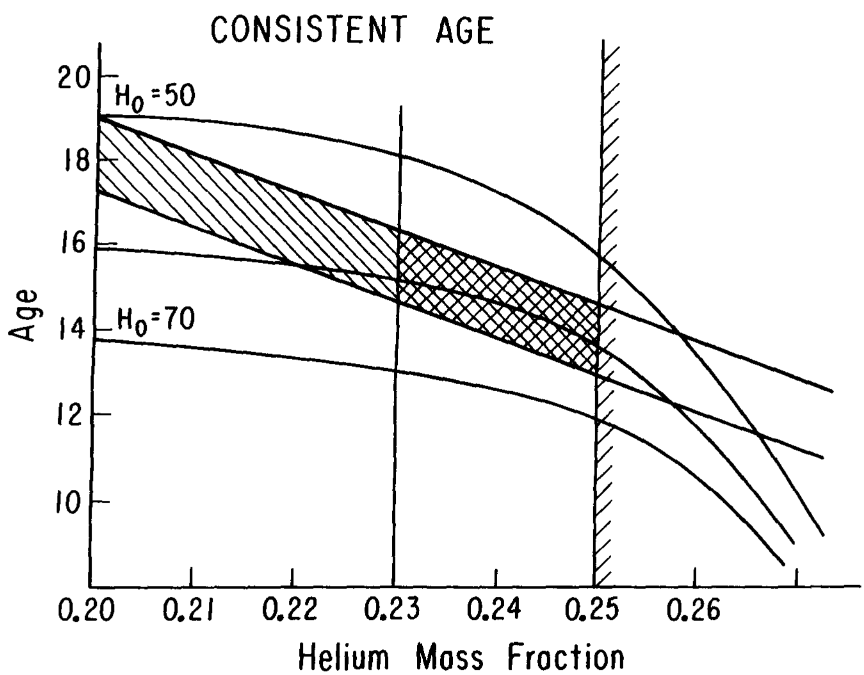

Figure 8: The combination of Figures 5, 6 and 7 showing that the only total consistent Big Bang models must have ages between 13.5 and 16.5 x 10^9 yr. and Hubble constants from 55 to 70.

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increase the solar neutrino flux and since convection and turbulent effects go in the direction of increasing the age, one can probably use Iben's (1973) calculations as reasonable estimates of the age and 13.5 billion years becomes a fairly good lower limit.

A lower bound on the primordial ^{4}He can be obtained from Figure 7. This lower bound of 0.23 comes from Big Bang nucleosynthesis and is the lowest primordial ^{4}He abundance which can be made consistent with the limits on ^{3}He + D and 3 or more neutrino families (e, μ, τ). This limit is described in detail by Yang, et al. (1983), (see also Schramm 1982). This limit is also in effect a lower bound on the density of nuclear matter. Thus meaning that even if the universe has large amounts of non-baryonic matter (e.g. massive neutrinos) the implied upper limit on the age will still be valid. This latter point tightens the constraint of Symbalisty, Schramm and Yang (1981). By using the ^{3}He + D constraint to yield $Y_p > 0.23$ we are no longer sensitive to the estimates of density, from the dynamics of galaxies as were Symbalisty et al. (1981) and Kazanas et al. (1978).

Figure 8 is a combination of the constraints of Figures 5, 6 and 7. The only age range completely consistent with all the constraints found in Figure 8 is 13.5 to 16.5 billion years. Note that this age range limits the Hubble constant to a velocity range of 55 km/sec/Mpc to 70 km/sec/Mpc, which is consistent with Tammann (1981, 1983) but not with Huchra (1981). Note that the best fit nucleocosmochronology age of 15 x 10^9 yr falls exactly in the center of the consistent Big Bang range.

In all of the above, it has been explicitly assumed that the "cosmological constant" is zero. That is, in the absence of matter space-time is assumed to be flat. If the cosmological constant were non-zero then the relationship between H_o and age can be quite different and the above mentioned constraints on H_o would be irrelevant although the age arguments would still hold since Big Bang Nucleosynthesis and globular cluster ages are unaffected by the cosmological constant.

3. CONCLUSIONS

From the above discussion, it is apparent that the age of the universe is probably between 8 and 19 billion years with the best fit age consistently determined by a combination of all techniques to be about <u>15 billion years</u>. This age also is approximately the best fit estimate of Iben (1981) and Demarque and McClure (1977) via globular cluster techniques and is in reasonable agreement with Tammann (1981, 1982) estimate from his H_o and q_o considerations.

However, if the galaxies really are closer than Tammann believes, there is one way to reconcile Huchra's (1981) "upper limit" age of 12 billion years with an actual age of 15 billion years. If there is an intrinsic curvature to space, the cosmological constant accelerates the galaxies instead of allowing gravity to decelerate them.

The cosmological constant, if we are willing to reinvoke it, could reconcile the generally accepted age of 15 billion years with the smaller separations claimed by Huchra and his collaborators (Aaronson et al., 1981). But that carries a price that most of us are not yet willing to pay, i.e., postulating something that has no other reason for existing than to tidy up the conclusions of one observation in an arena known for its past history of systematic errors. Such invocations seem ad hoc, and for now I will bet that our universe is about 15 billion years old.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

Aaronson, M., Mould, J., Huchra, J., Sullivan, W. T., Schommer, R. A., and Bothun, G. D. 1981, Ap. J. (in press).

Demarque, P., and McClure 1977, Ap. J., 213, 716.

Flannery, B. 1981, Center for Astrophysics preprint.

Fowler, W. A. and Hoyle, F. 1960, Ann. Phys., NY 10 280-302.

Hainebach, K. L., and Schramm, D. N. 1977, Ap. J., 212, 347.

Huchra, J. 1981, AAAS Symposium on the Age of the Universe, Toronto, Canada.

Iben, I. 1973, in Explosive Nucleosynthesis, ed. D. N. Schramm and W. D. Arnett (Austin: University of Texas Press).

Iben, I. 1981, AAAS Symposium on the Age of the Universe, Toronto.

Iben, I., and Rood, R. T. 1970, Ap. J., 159, 605.

Kazanas, D., Schramm, D. N. and Hainebach, K. L. 1978, Nature 274, 672-4.

Maeder, and Shatzman. 1981, in Proceedings of IAU Symposium No. 93: Fundamental Problems in the Theory of Stellar Evolution, ed. D. Sugimoto, D. Q. Lamb and D. N. Schramm (Boston: D. Reidel Publishing Company).

Noerdlinger, 1981, in preparation.

Norman, E. B. and Schramm, D. N. 1979, Astrophys. J. 228 881-92.

Olive, K. A. and Schramm, D. N. 1981, Astrophys. J. 257 276-282.

Ostriker, J. P., and Thuan, T. X. 1975 Astrophys. J. 202, 353.

Pagel, B. 1982, Proceedings of the Royal Society Meeting, London, 1982.

Schramm, D. N., 1982, Proceedings of the Royal Society Meeting, London, March 1982.

Schramm, D. N. 1981, Proceedings of the AAAS Symposium on the Age of the Universe, Toronto, Canada.

Symbalisty, E. M. D., and Schramm, D. N. 1981, Rep. Prog. Phys. 44, 293-328.

Symbalisty, E. M. D., Schramm, D. N. and Yang, J. 1980, Nature 288, 143-5.

Talbot, R. J., Jr., and Arnett, W. D. 1973, Astrophys. J. 186, 69.

Tammann, G. A., AAAS Symposium on the Age of the Universe, Toronto, Canada, 1981.

Tammann, G. A., 1983, I.A.U. General Assembly, Patras, this volume, p. 301.

Tinsley, B. M. 1975, Astrophys. J. 198, 145.

Yang, J., Schramm, D. N., Steigman, G. and Rood, R. 1979, Astrophys. J. 227, 697.

Yang, J., Turner, M. S., Steigman, G., Schramm, D. N., and Olive, K. A. 1983, University of Chicago preprint.