THE RELATION BETWEEN STELLAR EVOLUTION AND COSMOLOGY

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ABSTRACT

Observations of star clusters combined with the theory of stellar evolution enable us to estimate the ages of stars while cosmological observations and theories give us a value for the age of the Universe. This is the most important interaction between cosmology and stellar evolution because it is clearly necessary that stars are younger than the Universe. Stellar evolution also plays an important rôle in relating the present chemical composition of the Universe to its original composition.

1. INTRODUCTION

Although the title of my review is quite general, I shall restrict myself mainly to discussing the relation between stellar evolution and the big bang cosmological theory because there is such a good qualitative agreement between the hot big bang theory and observations. There are two principal ways in which stellar evolution and cosmology interact within the framework of the big bang theory. The first is concerned with the initial chemical composition of galaxies and the second with the ages of objects in the Galaxy. In the first case we need to understand the evolution of stars of very high mass as well as the processes which lead to their formation. In the second case we are concerned with the evolution of stars of solar mass and a little less.

The initial chemical composition of galaxies may differ from the primaeval composition of the Universe if some stars were formed before galaxies. In the hot version of the big bang theory, the primaeval composition is about three parts hydrogen to one part helium by mass with no heavy elements. In the cold version the composition is pure hydrogen. No stars have been discovered without heavy elements. Were the heavy elements in the oldest observed stars produced in Population III stars which preceded galaxy formation or in a first generation of galactic stars, which are no longer observed? In the cold big bang with

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no primaeval helium, there must be pregalactic Population III stars which produce not only the heavy elements but also the helium which we deduce to be present in the oldest stars. In either case we are interested in the process of star formation in the early Universe and we are particularly concerned with those stars which were sufficiently massive to evolve and to release processed matter in the time available before or during galaxy formation. It is possible that Population III contained a significant number of stars which were much more massive than any stars observed today.

The second main point of interaction concerns stars which were formed essentially the time of galaxy formation and which are at an interesting stage of their evolution today. Stellar evolution studies can give us an estimate of the ages of such stars, specifically the stars in globular clusters, and, if the standard cosmological theory is to be correct, the ages of these stars must be less than the age of the Universe as determined from Hubble's constant and the deceleration parameter. In particular the ages of all objects must certainly be less than the reciprocal of Hubble's constant. If that is not the case, a non-standard cosmology must be invoked, possibly involving a non-zero cosmological constant. An earlier apparent discrepancy between the age of the Universe and the age of the Sun was one factor in the development of the Steady State theory. If it were possible to make a direct observation of the helium abundance in old unevolved stars, one would be able to check whether it is comparable with that supposed to have been produced in the hot big bang. As there are no such observations, stellar evolution theory must also be used to obtain an estimate of the helium abundance. In fact the determination of age and helium abundance is part of a single process.

2. COSMOLOGICAL BACKGROUND

I shall discuss observations in terms of the big bang theory, in particular the hot big bang theory in which a primaeval composition of about three parts hydrogen to one part helium by mass is attributed to nuclear reactions in the first few minutes and in which the cosmic microwave radiation is another indicator of a hot origin. However most of my remarks will be equally applicable to the cold big bang model in which both the helium and the microwave radiation must be attributed to stars formed before galaxies.

In any version of the big bang theory in which the cosmological constant, Λ, is zero, there is a simple relation between Hubble's constant, H_o, the deceleration parameter, q_o, and the age of the Universe, t_o. Instead of q_o one can use the present mean density of the Universe, ρ_o, which for $\Lambda = 0$ is related to H_o and q_o by

$$\rho_o = 3H_o^2 q_o / 4\pi G \ . \tag{2.1}$$

At present there are not really reliable values of any of H_o, q_o, ρ_o.

q_o is difficult to measure because of the lack of reliable *standard candles* at large distances, while ρ_o must include not only visible matter and matter which is detected by its gravitational influence but also hidden matter such as low mass elementary particles. H_o is generally believed to lie in the range

$$50 \leqslant H_o/\mathrm{kms}^{-1}\ \mathrm{Mpc}^{-1} \leqslant 100\ , \qquad (2.2)$$

although more extreme values cannot be totally excluded. Whatever is the value of q_o, t_o is less than $t_H(\equiv 1/H_o)$ and, using (2.2),

$$10^{10} \leqslant t_H/\mathrm{yr} \leqslant 2 \times 10^{10}\ . \qquad (2.3)$$

The higher the value of q_o, the lower is the value of t_o/t_H. If the Universe is just closed, $q_o = 1/2$ and $t_o = 2t_H/3$.

Because this is a symposium on stellar evolution rather than on cosmology, it is not my present concern to discuss the accuracy of estimated values of H_o, q_o and t_o. Instead I shall consider the age of the Galaxy and in particular of the globular star clusters and ask whether it is compatible with suggested values of these quantities. The most obvious problem arises if H_o is so large that the ages of the globular clusters are found to be greater than t_H. There is then a clear contradiction between the predictions of stellar evolution theory and the standard cosmology. However, it is also desirable that the age of the Universe should not be too much greater than the ages of the oldest objects in the Galaxy, because it is not easy to see how galaxy formation and star formation can be delayed for an arbitrarily long time. If the age of the Universe does appear to be less than that of the globular clusters, it may be necessary to consider theories with positive Λ in which it is possible for t_o to exceed t_H. There are possible objections to such theories which we shall discuss briefly below.

It should be noted that for t_o to exceed t_H, Λ must necessarily exceed $4\pi G\rho_o$. For given value of H_o the age is increased by increasing Λ or by decreasing ρ_o or by doing both simultaneously. A positive value of Λ can only give an age in excess of t_H if q_o is negative; this is a necessary but not sufficient condition. For non-zero Λ equation (2.1) is replaced by

$$q_o = (4\pi G\rho_o - \Lambda)/3H_o{}^2, \qquad (2.4)$$

so that $q_o < 0$ for $\Lambda > 4\pi G\rho_o$. Table 1 shows the present age of the Universe in terms of t_H for various values of the two parameters $\Lambda/8\pi G\rho_o$ and $8\pi G\rho_o/3H_o{}^2$. These specific results were obtained by Bukhari (1983) although similar results have been obtained by many previous authors. It should be noted that the second column is the ratio of ρ_o to the density required to close the Universe in the $\Lambda = 0$ case.

Table 1

$\Lambda/8\pi G\rho_o$	$8\pi G\rho_o/3H_o^2$	t_o/t_H	q_o
3.75	0.4	1.28	-1.3
2.86	0.7	1.36	-1.65
10.0	0.1	1.38	-0.95
20.0	0.05	1.57	-0.975
6.0	0.25	1.70	-1.375
3.64	0.55	1.89	-1.725

It can be seen from Table 1 that ages reasonably in excess of t_H can be obtained if q_o is of order -1 or -2. de Vaucouleurs (1983) has for example suggested that $\Lambda/8\pi G\rho_o = 16.4$ and $8\pi G\rho_o/3H_o^2 = 0.07$ is consistent with $H_o = 100$ kms^{-1} Mpc^{-1} and the accepted ages of globular clusters. It is necessary to ask whether the values of ρ_o and q_o listed are reasonable. The minimum acceptable value of $8\pi G\rho_o/3H_o^2$ is probably between 0.05 and 0.1 but the actual value could be considerably higher. In particular, if the inflationary model of the very early Universe (see e.g. Guth 1981) is correct, the value should probably be unity. In such a case even higher values of $-q_o$ would be required to give ages much in excess of t_H. Is it in fact reasonable to suppose that q_o is negative? Hoessel et al.(1980) by assuming that first ranked galaxies in clusters are standard candles obtained the formal result $q_o \approx -0.55 \pm 0.45$. They pointed out that corrections are needed both because isolated galaxies would have been more luminous in the past and because the galaxies which they studied might have increased their luminosity by merger with smaller galaxies. Two corrections in the opposite direction, which they estimate to be $1 \leqslant \Delta q_o \leqslant 1.7$, are required to the observed q_o. It does not therefore seem possible to rule out values of q_o comparable to those in Table 1. In contrast, a similar investigation by Kristian et al.(1978) gave $q_o = 1.6 \pm 0.4$ so that the position is far from clear.

It is next necessary to ask whether there are any other possible objections to a finite value of Λ. There are first some observational constraints. When Λ is zero, the cosmological scale factor R(t) increases smoothly from zero to infinity if the Universe is open or increases smoothly from zero to some R_{max} and then decreases to zero again if the Universe is closed. If $\Lambda \gtrsim 4\pi G\rho_o$, there is a point of inflexion in the R(t) curve at some past time and there may have been a considerable period in which R changed only slightly. This means that there is a plateau in the relation between redshift and time since, for radiation received now which was emitted at time t,

$$R_o/R(t) = 1 + z, \qquad (2.5)$$

where z is the redshift. There might therefore be expected to be a bunching of objects observed at the plateau redshift (see e.g. Tytler 1981). The observations might be capable of ruling out the model or making it implausible if the plateau redshift has a value for which observations are easy. In addition, if the Universe is closed and if Λ

is so large that the age of the Universe is significantly greater than t_H, it might be possible for light to travel more than once round the Universe during its present lifetime so that long-lived objects could be observed at different stages of their evolution and a bunching at one redshift could be repeated at another. This could place additional constraints on $\Lambda > 0$ models.

There are also theoretical reasons for being concerned about non-zero values of Λ. For example, the inflationary model of the very early Universe which has been mentioned earlier does not appear to provide an explanation for a value of Λ of the size required. In addition the interesting values of $\Lambda/8\pi G\rho_o$ being close to unity provides us with another cosmological coincidence between small numbers which must be explained since Λ is a constant while ρ_o varies as the Universe evolves.

The above considerations apply equally to the hot and cold versions of the theory. These theories differ in how the initial chemical composition of galaxies is determined. The hot big bang theory predicts that there was a primaeval composition of about three parts hydrogen to one part helium by mass after the first few minutes of the expansion of the Universe. It is well-known (see e.g. Tayler 1982) that the precise value of the helium abundance, Y, depends on the present mean baryon density of the Universe and on the total number of species of low mass neutrinos or other weakly interacting particles. The theoretical predictions are compared with the primaeval helium abundance deduced from observations. This abundance is usually obtained from a study of gas clouds in our own and other galaxies. There appears to be a correlation between helium and heavy element abundances and extrapolation to zero heavy element abundance then gives the original value of Y. A value of 0.23 ± 0.01 has been obtained (Pagel 1982) and this is in reasonable agreement with theory provided that the baryon density is significantly less than closure density and that there are no more than three species of light neutrino.

One problem with this discussion is that we cannot definitely assert that we are determining the primaeval abundance. At best we are determining the original disk composition of our own and nearby galaxies. Unfortunately it is not possible to obtain an observational value for the helium content of unevolved halo stars although, as will be mentioned below, indirect discussions do suggest $Y \sim 0.25$ and no obvious difference between the original helium abundance of the disk and halo. Some evolved halo stars have been reported with very much lower values of Y, which looks like a serious contradiction with cosmology, but it seems that these surface abundances can be explained in terms of a settling of helium similar to that discussed by Cox for δ Scuti stars in this Symposium. Halo stars contain some heavy elements whereas the predicted primaeval composition contains no heavy elements. Their origin must be placed before that of the observed globular cluster stars and a possible site is pregalactic Population III stars, which might also produce some helium. Kunth and Sargent (1983) have recently deduced $Y = 0.245$ for dwarf metal-poor galaxies and this is perhaps comparable with a halo abundance but even this is not obviously a primordial abundance; it may be noted that Kunth and Sargent do not find the correlation between helium and heavy element abundance claimed by previous authors.

There are reasons for believing that the formation of galaxies might have been preceded by a generation of pregalactic stars. Such stars could then evolve and produce the heavy elements in the oldest stars presently observed. In the hot big bang theory, that is all that is required. There have, however, also been suggestions of a cold origin for the Universe with not only the heavy elements but also the helium and the microwave radiation being produced by pregalactic stars and we shall have more to say about this possibility below.

3. GLOBULAR CLUSTERS

Globular clusters play a key role in the comparison between stellar evolution and cosmology because they are the oldest known objects in the Galaxy. Of importance are estimates of their ages and of their chemical compositions. Their metal abundance can be observed directly and, although there have been recent significant changes in estimated metallicities as a result of high-resolution spectroscopy reducing the spread in metallicity from cluster-to-cluster, two things are clear; the globular clusters are very significantly metal-deficient when compared with the Sun and other younger galactic stars and the metal abundance is clearly non-zero with a minimum value of at least 10^{-5} by mass. In addition there is a variation of metal content with position in the Galaxy with those clusters nearer to the centre tending to have more metals. The existence and size of the metal abundance lies at the boundary between cosmology and galactic evolution. At what stage in the history of the Universe were these metals produced?

Of even greater importance than the metal abundance is the helium abundance but this cannot be observed directly in old unevolved stars and it must therefore be deduced from theory. To a first approximation we can say that we must use a comparison between theory and observation to deduce values of cluster ages and cluster helium abundances and then compare these both with the age of the Universe and the primaeval helium abundance from the hot big bang theory and with the deduced original helium abundance of the galactic disk. Relative cluster ages are almost as important as absolute ages. If the globular cluster system was formed in the initial collapse phase of the Galaxy, it is difficult to see how there can be a spread in cluster ages greater than a few x 10^8 years. This leads to a related point. Most of the recent concern about the ages of globular clusters has concentrated on the possibility that they might be greater than the age of the Universe as deduced from Hubble's constant and the conventional big bang. It would, however, be almost equally worrying if the ages of the globular clusters were substantially less than the age of the Universe because it is difficult to see how galaxy formation can have been delayed long enough; only almost as bad because this might be a failure of understanding rather than a sharp disagreement.

The comparison between theory and observation for globular cluster stars involves the use of theoretical and observational HR diagrams. The theoretical diagram is an isochrone constructed by assuming that all stars in the cluster have the same initial chemical composition and age, or rather that the spread in age is negligible compared with the present age of the cluster. There are three factors in the comparison of theoretical and observed diagrams. These are:

(a) absolute position of diagram;
(b) shape of diagram;
(c) relative populations of different parts of diagram including the observed widths.

There is no way of determining the distances to globular clusters which does not involve assuming something about the absolute magnitudes of stars in the cluster, for example either the RR Lyrae variables or main sequence stars. This means that (a) is mainly used to determine cluster distance. Because there is no independent method of obtaining distances to clusters there is some trade-off between Y and distance in main sequence fitting. The age and helium content are mainly determined from (b) with the age usually being deduced from the position of the turnoff point from the main sequence. (c) is a much stricter test of the comparison between theory and observation because, unless the initial mass function of the cluster has very peculiar properties, the population of different parts of the diagram above the main sequence should be directly proportional to the time spent in any particular evolutionary phase. Comparisons of population with theory tend to lead to problems such as the at present unexplained gaps in the observational diagram near the foot of the giant branch in some clusters, which have been mentioned by Cannon earlier in this Symposium.

In any very precise comparison between theory and observation, the theoretical models should ideally be transformed to the observational diagram rather than *vice versa*; i.e. observed colours and bolometric corrections should be calculated from the theoretical spectrum of the stars rather than use being made of standard transformations, although these will certainly be good enough for rough estimates of ages. There are of course dangers in this approach because it implies that the entire theory including its weakest points is being compared with observation. There are certainly many remaining uncertainties in theoretical models which include:

(a) the continuing solar neutrino problem;
(b) the theory of convection;
(c) opacity at low temperatures;
(d) mixing processes;
(e) treatment of stellar atmospheres.

Most of these effects have been mentioned earlier in this Symposium. An ultimate resolution of the solar neutrino problem may affect Population II stars as well as Population I stars unless it is concerned with the properties of the neutrinos themselves. There is no *a priori* reason to believe that the mixing lengths used in a crude convection theory should be the same for stars of different masses and compositions, for the same star at different stages of its evolution or at different depths in a star, although Vandenberg (at this Symposium) has made some reassuring comments about the use of a constant ratio of mixing length to scale height on the giant branch. Changes in gross stellar properties produced by a change in the value of the mixing length may also be produced by changes in, for example, chemical composition which is not completely known. Several speakers at the Symposium have stressed the need to determine the correct value of the opacity at $T \sim 10^6$K. We have also been introduced by Schatzman to possible mixing processes inside stars. Stringfellow et al. (1983) have suggested that gravitational and thermal diffusion of helium can reduce the estimated ages of clusters by 25 per cent. This would be a very important effect if true, but it is not clear what effect such settling would have on other stars such as the Sun. Although the treatment of stellar atmospheres is not going to have an important effect on the bolometric luminosity of a star, it could be important in specific wavelength ranges affecting the conversion to observed magnitudes and colours.

Recent studies of the ages of globular star clusters were summarised by Cannon (1983) at the IAU General Assembly at Patras. Table 2 is a slightly modified version of the results which he presented.

Table 2

Reference	Age/10^9 year	Clusters
Demarque and McClure (1977)	14-16	Metal-poor clusters
Saio et al. (1977)	18	M92 (Metal-poor)
Carney (1980)	18	Metal-poor clusters
	10	47 Tuc, M71
van Albada et al. (1981)	11-14	Various
Sandage (1982)	17±2	All clusters
Vandenberg (1983)	15-18	All clusters

It can be seen that there are considerable differences between the results obtained by different authors, although there is a general agreement that ages exceed 10^{10} yr with most results being substantially greater. One particular source of disagreement is that most early work suggested that the metal-rich globular clusters were substantially younger than the metal-poor clusters, whereas recently several authors have concluded that there is no good evidence of an age difference between clusters. Whilst it seems reasonable that the metal-rich clusters concentrated towards the centre of the Galaxy should be slightly younger, the age spreads reported seem difficult to fit within any model of galaxy formation and what seems like a reasonable age spread (few × 10^8yr) from that point of view would be equivalent to no age difference to the accuracy to which the ages can be determined. It should be noted that all of the ages discussed by Cannon are incompatible with the standard model of the big bang if $H_o \simeq 100$ kms^{-1} Mpc^{-1} and that many of them are even incompatible with $H_o \overset{\circ}{=} 50$ kms^{-1} Mpc^{-1} if the Universe is closed. It is therefore clearly of great importance to know whether the ages are as large as those in Table 2 and whether H_o has a large or small value. We have already mentioned the reconciliation of a large H_o and the stated ages by introduction of non-zero Λ by de Vaucouleurs (1983).

The theoretical information about the globular cluster helium abundance is still somewhat unclear. In main sequence fitting there is a trade-off between helium abundance and distance and the remainder of the HR diagram is not critically dependent on the value of Y. Most results give a value of Y between 0.2 and 0.3 suggesting that there was a substantial helium abundance at the time that the globular clusters were formed and that there is no reason to worry about incompatibility with the predictions of the hot big bang theory or with the original helium abundance of the galactic disk. It has been suggested that the best way of determining Y would be to compare observed and predicted widths of the RR Lyrae instability strip but results presented by Stellingwerf (this Symposium) suggest that is unlikely to be true. Sandage (1982) has reported an anti-correlation between helium and metal abundances in his best-fit models for different clusters. This appears difficult if not impossible to understand but it certainly needs to be cleared up.

There have been several further discussions of globular cluster ages since the Patras meeting. Janes and Demarque (1983) find an age of $16.6 \pm 0.5 \times 10^9$yr for all clusters and $Y \simeq 0.2$, although they say that the actual uncertainty in the age is larger than the formal error. Sandage (1983) finds an age of $18 \pm 2 \times 10^9$yr for M92 and M15. Renzini (this Symposium) has argued that use of the main sequence turn-off alone to estimate cluster ages is unreliable and that the best method is one used by Sandage involving the difference between the bolometric luminosity of the RR Lyraes and at turn-off. This appears to be essentially independent of metallicity and is a measure of age. The helium abundance is not determined by this technique but, if $Y = 0.23 \pm 0.02$, the age of all clusters is $16 \pm 3.5 \times 10^9$yr.

All of these investigations lead to a high age for the globular cluster system, with serious discrepancy with standard cosmology with $H_o = 100$ kms^{-1} Mpc^{-1} and with a possible discrepancy if $H_o = 50$ kms^{-1} Mpc^{-1}. In one further recent paper Flannery and Johnson (1982) have also found a high value for the age but they have also argued that the theoretical uncertainties, such as I have listed earlier, are such that it is not possible to rule out an age below 10^{10}yr. However a very small age might imply a helium content which is uncomfortably small. It is clearly vital to have agreement about the uncertainties in the estimated ages as well as better agreement concerning the cosmological parameters H_o, q_o and ρ_o.

4. POPULATION III STARS

The oldest observed metal-poor stars in our Galaxy have a heavy element abundance (Z) of order or greater than 10^{-5} by mass whereas the big bang theory suggests that the primaeval composition of the Universe included no heavy elements. The simplest solution is that there was star formation earlier than the observed Population II stars and that these Population III stars produced the heavy elements. The Population III stars have to be largely or all of high mass so that no low mass zero-metal stars are observed today. It is unclear whether the Population III stars are to be associated with the time of galaxy formation or whether their formation and evolution preceded and possibly influenced galaxy formation.

There are both theoretical and observational reasons why most interest in Population III stars has concentrated on the possibility that they formed slightly after recombination, or the equivalent phase in a cold Universe. The theoretical reason is that discussions of the formation of structure in the Universe have indicated that condensations probably formed which were more massive than ordinary stars but less massive than galaxies. It is suggested that these condensations either directly or after some fragmentation formed a first generation of very massive objects. The various observational reasons are summarised in a forthcoming paper by Carr et al. (1984), which contains references to all of the earlier work. Population III stars might produce the metals in the oldest observed stars, a small distortion in microwave background radiation or even the whole of the radiation, and some or all of the original galactic helium. Their radiation might reionize the intergalactic medium or stimulate the formation of galaxies and their remnants could account for missing mass in clusters of galaxies and galactic halos.

In the simplest discussion it is assumed that the hot big bang theory is correct and that only heavy elements with possibly a small distortion in the microwave radiation and a very small amount of helium are required from Population III stars. Thus it is assumed that the helium abundance of the material after Population III stars have evolved is indistinguishable from the primaeval abundance but that there is now $Z \sim 10^{-5}$. There are, however, more radical suggestions that the Universe had a cold origin and that all of the primaeval helium and the cosmic microwave radiation were produced by Population III stars. There are obvious disadvantages of losing the natural explanation of $Y \sim 0.25$ and the black body radiation but it is argued that there may be compensations in a better understanding of the origin of structure in the Universe (see e.g. Hogan 1982). Because it is essential that $Z \sim 10^{-5}$ is produced in the cold big bang just as in the hot big bang, it is necessary either that there is a very different spectrum of masses in this case or that the predicted element production by stars of different masses is very different from what has previously been assumed.

A crucial role in this discussion is played by star formation, a topic which has not been discussed at this Symposium. Cosmological theory should predict the initial spectrum of irregularities from which the Population III stars can form but we then need to know what initial mass function is formed by fragmentation. There are several reasons why the initial mass function should be different from what is observed in the solar neighbourhood today. One is the absence of heavy elements and another, in the hot big bang, is the much greater intensity of the background radiation at a time close to recombination. Both of these are thought to encourage the formation of more massive stars. Once the stars have formed it is crucial to know at what stage in their evolution they lose mass and what is the composition of that mass. Here two things must be recognised. We do not at present have a good theoretical understanding of mass loss from stars in the mass range that can be studied observationally and we do not have any observations relevant to the evolution of objects of the supposed Population III masses, particularly, if as has been suggested earlier in this Symposium, R136a is a star cluster and not a single massive object.

It is naturally to be hoped that eventually the predicted mass spectrum of Population III stars in both the hot and cold versions of the big bang will be understood and that it will be possible to discover whether their evolution produces element abundances and microwave radiation in agreement with observations in either case. It must, however, be recognised that results other than the two extreme ones could be relevant. For example, Population III stars in the hot big bang might produce a small amount of heavy elements, a small distortion in the cosmic microwave radiation and a small but significant amount of helium. Suppose the Population III stars produce about 2 per cent helium as well as the minimum Population II metal abundance; while different authors are prepared to consider that they produce either essentially no helium or 25 per cent helium, it is not obvious that this value or any other intermediate value can be ruled out except as a result of prejudice. Carr et al. (1984) mention the possibility that Population III stars could impose fluctuations of a few per cent on the primordial helium abundance. This would imply that the original value of $Y \sim 0.23$ to 0.25 deduced by a study of gaseous nebulae in nearby spiral galaxies or of dwarf compact galaxies need not be the true helium abundance produced in the big bang and it could make the constraints on the hot big bang model that much more stringent.

While there remains the possibility that Population III stars might produce enough helium to modify the primaeval abundance, it must be premature to pass final judgement on the consistency between theory and observation of the hot big bang. It is partly for this reason that a proper understanding of the formation and evolution of Population III stars is vital and that theoretical studies must be made of a type of star which cannot be observed. Because it is necessary to understand the origin of the Population II metal abundance, they cannot simply be ignored.

A further comment on this metal abundance is necessary. As is well known, all globular clusters do not have the same metallicity and there is some correlation between metallicity and place of origin in the Galaxy, with the higher metallicity clusters being concentrated closer to the galactic centre. Because of this correlation of metallicity with galactic properties, it is difficult to suppose that it has arisen because of irregularities in enrichment due to pregalactic Population III stars. Instead it must be supposed that the pregalactic metal abundance has in any case been enhanced by the evolution of early Population II stars. Assuming that these are stars which are no more massive than stars which we observe in the disk today, there is no reason to suggest any significant further enhancement of the helium abundance and we might expect all globular clusters and the oldest disk stars to have essentially the same Y. The main point is that the assumption of a significant rôle for Population III stars does not remove the need for early Population II stars to affect others that we now observe. The evolution of massive stars takes a time short compared with the period of galaxy formation so that it is possible that Population III stars have not been important and that all of the changes from original abundances have been produced inside galaxies.

5. CONCLUSIONS

In this review I have concentrated on the relation between stellar evolution and the big bang cosmological theory because at present this does seem to be in good qualitative agreement with the observations. Obviously there are also important interactions between stellar evolution and other cosmological theories one obvious case being that of theories in which the laws of physics change with time, in particular *variable G* theories. Calculations have been made of stellar evolution in some such theories and theoretical isochrones have been compared with cluster HR diagrams but I do not feel that it is really necessary to study them in detail at present. Equally I do not personally regard the cold big bang as a likely viable alternative to the hot big bang.

I have indicated that the evolution of stars in two mass ranges is of crucial importance. The first range contains stars close to and below a solar mass which can just have evolved significantly in the present life of the Galaxy. They can give information about the age and initial chemical composition of the Galaxy. The second group are stars which are sufficiently massive that they can have evolved either before galaxies were formed or during the process of galaxy formation, because they can relate the initial composition of the Galaxy determined from the oldest low mass stars to the original cosmological abundances. In the case of low mass stars we can observe the stars in whose evolution we are interested. In contrast the early high mass stars can only be studied theoretically and progress may be hampered by lack of a good understanding of the processes of star formation and stellar mass loss.

We have seen that most estimates of globular cluster ages are too high to be compatible with the big bang theory with zero cosmological constant if $H_0 \sim 100$ kms^{-1} Mpc^{-1} and that they might even be incompatible with $H_0 \sim 50$ kms^{-1} Mpc^{-1}. The origin of the metals in the lowest metallicity globular clusters may lie in pregalactic Population III stars but it is necessary to establish that the production of metals is not accompanied by a production of helium sufficient to modify the primordial abundance, unless of course the Universe had a cold origin.

Several topics have deliberately not been discussed in this review. They include the origin of the observed abundances of the light elements and isotopes such as ^{2}H, ^{3}He and ^{7}Li. In addition it should be recognised that any clear observation of a helium abundance well below Y = 0.25 in any unevolved object would cause serious problems for the cosmological theory. Also there is another source of information about the age of the Galaxy in the heavy radioactive elements.

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DISCUSSION

Audouze: I have two comments on population III stars: 1) The short one: When you speak about the formation of population III stars you refer obviously to isothermal fluctuations. 2) About the problem of cold Big Bang let me mention the work that Jo Silk and I try to pursue about this problem. In the frame of the cold Big Bang theory you have not only to worry about ^{4}He and the metals but also about D and Li. We make the hypothesis that the cold Big Bang leaves rise only to pure hydrogen. If massive stars of pure hydrogen are formed at red shifts of $Z \sim 100$, they are going to form helium and metals, some of them will be accelerated like pregalactic cosmic rays and could account for the observed D and ^{7}Li. We circumvent by this way the difficulty presented by the He + He reactio which could form too much lithium (see our abstract in the book "Primordial Helium" edited by P. Shaver and D. Kunth and published by ESO, 1983). This possibility seems to be still very ad hoc and fairly unlikely but cannot be ruled out in the present stage of our knowledge.

Demarque: You have mentioned the question of the metal-rich globular cluster ages. The main uncertainty in this regard has been due to uncertainties in the metallicity scale for globular clusters. A related problem, also important for our understanding of the evolution of the Galaxy is the apparent large difference in age between the globular cluster system and the oldest disk clusters.