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The Age of the Universe

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1 Abstract

An overview of the current controversy on the age of the universe is presented. It is shown that the age of the oldest star, globular clusters, yields an age estimate of approximately $14 \pm 2 \pm 2$ Gyr (where the first $\pm$ is statistical and the second systematic, and the two should *not* be added in quadrature), with a firm lower bound of ≥ 10 Gyr. It is shown how radioactive dating, nucleocosmochronology, also yields a firm lower bound of $\gtrsim 10$ Gyr. The currently favored values for the Hubble constant, when converted to ages using a cosmolgical model with zero cosmological constant, are shown *not* to be in conflict with statistical and systematic uncertainties at the present time when one takes both into account, even for critical density universes.

2 Introduction

The problem of estimating the age of the universe is longstanding. For example, in 1650, Bishop James Ussher(1658) determined by a technique of summing the Biblical begats and making other corrections and connections based on the then available historical and astronomical records that the universe began in 4004 BC, at the moment that would correspond to sunset in Jerusalem on the evening before October 23. This would correspond to 4 PM U.T. on October 22.

This early determination illustrates a key point which we will also apply to more modern techniques. Namely, while Bishop Ussher was able to obtain a result with reported accuracy of about 8 significant figures, his systematic errors are considerably larger. (Even his intrinsic error is larger than the accuracy of his result indicates, since the Jewish calendar, using essentially the same technique, obtains an age that is over 200 years off from Ussher's.)

Today the age of the universe can be estimated by three independent means:

1. Dynamics (Hubble age and deceleration)
2. Oldest Stars (globular clusters)

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3. Radioactive Dating (nucleocosmochronology)

We will see that despite much activity on the dynamical technique, the best age bounds are still those derived from nuclear arguments - namely #2 and #3. Each of these gives a lower bound of $t \gtrsim 10$ Gyr as plotted in Figure 1. Furthermore, the age of the disk also bounds the age of the universe ($t_{disk} \sim 10Gyr$), as does radioactive dating of the Earth-Meteorite system at $t_{ss} = 4.6 \pm 0.1Gyr$.

3 The Age from Dynamics

The use of the Hubble constant to determine an age is the most quoted and least accurate of all the age determination methods. The point is that it is not really determining an age but only a dynamic timescale. For perspective let us note that in the past decade astronomers have published values ranging from $H_o \sim 100$ km/sec/Mpc down to values near $H_o \sim 40$ km/sec/Mpc. The higher values tend to come from people using empirical techniques like Tulley-Fisher, whereas the smaller values come primarily from people using supernovae. In principle, supernovae are better understood physically, but some astronomical calibrations inevitably creep in. However, few hidden-variables should creep in since the physics is in reasonable shape, unlike the empirical technology. A critical question tends to be the accuracy of intermediate distance calibrators and the correction for infall into the Virgo cluster. Most of us can't see anything wrong at face value with the Tulley-Fisher techniques other than a possible susceptibility to the so-called Malmquist bias. However, many physicists have a certain fondness for the use of Type-I supernovae as standard candles. Type I's seem to be due to the detonation of a C-O white dwarf star converting its C-O to Fe. Such a model has a physical relationship between its luminosity and basic nuclear quantities that can be measured in the lab. Current best-fit models (c.f. Nomoto) tend to convert about $0.7M_\odot$ of C-O, which yields $H_o \sim 60$ km/sec/Mpc. However, even in the extreme where the entire $1.4M_\odot$ Chandrasekhar mass is burned, H_o is never below ~ 40 km/sec/Mpc (see also Nugent et al. (1995). Sandage and Tammann's (1995) empirical calibrations, which ignore the nuclear mechanism, now yield $H_o \sim 58 \pm 7$ km/sec/Mpc after using HST-measured cepheids to calibrate M101, which fall within the theoretically allowed range and correspond to almost complete burning of a Chandrasekhar core. Recently, Riess, Press and Kirshner (1995) have argued that there may be some variation in type IA light curves which shifts H_o up to $\sim 66 \pm 3$. Kirshner (Schmidt et al. 1992) also argues that the expanding photosphere of type II supernova implies $H_o \sim 73$. While selecting between 40 and 75 is still a matter of choice, it does seem that values less than 40 can be reliably excluded. Why these numbers tend to be systematically lower than the Tulley-Fisher numbers remains to be fully understood.

Most recently there has been much publicity about the Hubble Space Telescope (HST) seeing individual cepheid variable stars in Virgo Cluster (Freedman et al. 1994) galaxies as well as other potential calibrator galaxies out to about 20 Mpc. Over the next few years, HST will find many more cepheids in other galaxies in Virgo so that part of the uncertainty will decrease. Freedman et al. (1996, Sandage and Tamman 1995 - Kluwer) have been very conscientious in listing both statistical and systematic errors in their recently quoted value of $H_o = 73 \pm 7 \pm 8$ km/sec/Mpc. Although most astronomers add the errors in the quadrature, it is probably more realistic not to add systematic errors in quadrature since the second derivatives of these systematic errors are probably not well behaved. In fact, in some cases, the distributions may even be bi-modal. Hence, a better estimate is 73 ± 15. Even this large error does not include the possibility that cepheids themselves may have a systematic shift in luminosity between the LMC (where the calibration is done) and other galaxies. Historically, Hubble got $H_o \sim 500$ due to using cepheids calibrated from Pop II objects and applied to Pop I in other galaxies. While much of the metalicity effect is now taken into account, the observed trends of cepheids in M31 may hint that there is still some residual effect. Thus, while some systematic errors will be reduced with more HST detections of cepheids in other galaxies, some systematic errors will remain (including potential differential reddening between the southern LMC direction and the northern Virgo direction).

With all of these systematics, it is clear at the present time that the SN technique and the Tulley-Fisher techniques are not really in conflict and values in the range of $40 \leq H_0 \leq 100$ cannot be categorically ruled out (yields 10 Gyr $\lesssim 1/H_o \lesssim 25$ Gyr) with $50 \leq H_0 \leq 80$ km/s/Mpc being the current preferred range.

Age, t_u, is related to H_o by:

$$t_u = \frac{f(\Omega)}{H_o} \tag{1}$$

where for standard matter-dominated models with cosmological constant $\Lambda = 0$,

$$f(\Omega) = \begin{cases} 1 & \Omega = 0 \\ 2/3 & \Omega = 1 \\ \sim 0.5 & \Omega = 4 \end{cases} .$$

From dynamics alone we can put an upper limit on Ω by limiting the deceleration parameter q_o. From limits on the deviations of the redshift-magnitude diagrams at high redshift, we know that $q_o \lesssim 2$ (for zero cosmological constant $\Omega = 2q_o$). Thus, we can argue that $\Omega \lesssim 4$ or that $f(\Omega) \gtrsim 0.5$. Therefore, from dynamics alone, with no further input, we can conclude only that

$$5 \lesssim t_u \ (Gyr) \ \lesssim 25 \tag{2}$$

Since the lower bound here could also be obtained from the age of the earth, it is clear that the dynamical technique is not overly restrictive unless one could somehow decide between the supernova approach and Tulley-Fisher.

Even high values of H_o can be consistent with high ages by invoking the cosmological constant. Figures 2a and 2b are the equivalent of Figure 1, but with effective $\lambda = \Lambda/3H_o^2$ of 0.8 and 0.4, respectively. Note that even $\lambda \sim 0.4$ allows high H_o to be consistent with a flat universe. It is interesting to speculate that $\Lambda \neq 0$ can be produced by a late-time vaccum phase transition of the type proposed by Hill, Schramm and Fry (1989). However, such models do require a fair degree of tuning.

4 The Age from the Oldest Stars

Globular cluster dating is an ancient and honorable profession. The basic age comes from determining how long it takes for low mass stars to burn their core hydrogen and thereby move off the main sequence. The central temperature of such stars is determined by their composition and the degree of mixing. While there has certainly been some static as to what is the dispersion between the age of the youngest versus the oldest globular cluster in a given calculation, there is a surprising convergence on the age of the oldest clusters. Since the age of the very oldest cluster is the critical cosmological question, it is really somewhat of a red herring as to how much less the youngest cluster may be. The convergence on the age of the oldest does require a consistency of assumptions about primordial helium and metalicity (including O/Fe). Difference between different groups can be explained away once agreement is made on these assumptions. For example, Sandage's (1995) oldest ages of $\sim$ 18 Gyr and Iben and Renzini's (1984) (see also Bolt in these proceedings, 1996) of $\sim$ 16 Gyr are consistent if the same helium is used. (Lower helium yields lower ages. Iben assumed the Pagel (1989) value of y = 0.23.) Another decrease of a billion years occurs if O/Fe is assumed high as current observations show for extreme Pop II.

Another effect is the fact that these old stable stars will have some gravitational settling of their helium which will also shorten the ages about 1 Gyr relative to calculations where core helium enrichment is purely due to nuclear burning. All of these assumptions give a standard model (Pagel and Jimenez 1996, Chaboyer and Krauss 1996, Sandage 1993, Mazzitelli and d'Antonna 1995) for the oldest globulars of $\sim 14 \pm 1$ Gyr where the ± 1 is only the difference between different groups using the same standard assumptions. However, in addition to the calculational errors, there are also uncertainties in composition/opacity, uncertainties in distance/turnoff luminosity, and uncertainties in reddening/surface temperature at turnoff which increase the statistical error from ± 1 to ± 2 Gyr. Then, there are systematic uncertainties due to model assumptions: the helium abundance, settling, O/Fe, etc. For example, helium abundances might even be enhanced from the Big Bang (BBN) value due to helium production accompanying the extreme Pop II metal production and perhaps preferential helium in cluster formation (Shi et al. 1995). Also note that the current best fit BBN helium is actually closer to 0.25 than 0.23. Shi et al. (1995) showed that assumptions about He could lower the best fit age by as much as 2 Gyr without violating any other constraint (e.g. Y must be ≤ 0.28 to fit RR Lyrae blue edge). Furthermore, there are recent suggestions from the first Keck spectroscopic temperature determinations of globular cluster stars that the true temperatures are as much as 200 K hotter than the photometric determinations. This could also shift the age downward by as much as 2 Gyr. Furthermore, Shi et al. (1995) (see also Shi, 1995) have shown that mass loss due to the variable strip crossing the main sequence near the cluster turnoff could also shift the age down by 1 to 2 Gyr. However, these combined effects do not add linearly. No matter what, low mass stars can burn their hydrogen only so fast. We estimate that systematics add an additional ± 2 Gyr which should not be added in quadrature with the ± 2 Gyr statistical uncertainty, since most of the systematic effects are binary assumptions rather than selections from smooth, well behaved distributions. Thus, we conclude that $t_{GC} = 14 \pm 2 \pm 2$ Gyr.

One can use the standard solar model to get a quick estimate of an extreme globular age. The main line pp-chain is the main energy generation mechanism for the Sun and the globular clusters. The basic pp part of the solar model is now well confirmed by the calibrated GALLEX and SAGE solar neutrino experiments. Since the Sun has a much higher metalicity than the oldest globular clusters, and presumably has higher helium content and is at least as massive, if not more massive, it is paramount that the calculated main sequence lifetime of 10 Gyr for our Sun will always be a lower bound on the oldest globular cluster lifetimes. This 10 Gyr is also consistent with Shi et al. (1995) and with an independant study by Chaboyer (1995). Thus, it is reasonable to conclude that shifting the "best" fit age for the oldest globulars down to 12 Gyr cannot be excluded. But an extreme lower bound at 10 Gyr is not able to be broken.

Note that the time delay for cluster formation does not change this limit, since it is certainly possible to hypothesize an isocurvature model where globular clusters are the first objects (Lee et al. 1995) to form after recombination (their Jeans mass at that time is the globular cluster mass). Their Kelvin-Helmholtz time is only $\sim 10^7$ yr, so in principle, they could be present as early as 10^8 yr after the Big Bang. (Of course, standard CDM models extend this to several Gyr.)

5 Nucleocosmochronology

Nucleocosmochronology is the use of abundance and production ratios of radioactive nuclides coupled with information on the chemical evolution of the Galaxy to obtain information about time scales over which the solar system elements were formed. Typical estimates for the Galaxy's (and Universe's) age as determined from cosmochronology are of the order of 9.6 Gyr (e.g. Meyer and Schramm 1986). In recent years questions about the role of β-delayed fission in estimating actinide production ratios as well as uncertainties in ^{187}Re decay due to thermal enhancement and the discussion of Th/Nd abundances in stars have obfuscated some of the limits one can obtain. In particular, we note that the formalism of Schramm and Wasserburg (1970) as modified by Meyer and Schramm (1986) continues to provide firm bounds on the mean age of the heavy elements (see also recent preprint of Wasserburg and Busso 1996). In fact, Th/U provides a firm lower limit to the age and Re/Os, a firm upper limit. These limits are based solely on nuclear physics inputs and abundance determinations. To extend these mean age limits to a total age limit requires some galactic evolution input. However, as Reeves and Johns (1976) first showed, and as Meyer and Schramm (1986) developed further, one can use chronometers to constrain Galactic evolution models and thereby further restrict the age from the simple mean age limits of Schramm and Wasserburg. To try to push further on such ranges and give ages to ± 1 Gyr accuracy, as some authors have done, always necessitates making some very explicit assumptions about Galactic evolution beyond the pure chronometric arguments. At the present time such model-dependent ages are not fully justified and should probably not be used as arguments to question (or support) cosmological models, but pure, nuclear derived lower bounds are very useful. In particular, the Meyer & Schramm lower bound of $t_{NC} > 9.6$ Gyr which involves the mean age and the nuclear constrains on maximal evolutionary effects is a very firm bound.

6 Age Summary

Table 1

Age of Old Things in Universe

(Age of Universe is Greater Than Age of Oldest Things)

Globular Clusters

$t_{GC} = 14 \pm 2 \pm 2 Gyr$

≥ 10 Gyr

Long Lived Radioactive Isotopes (Nucleocosmochronology)

$t_{NC} \gtrsim 10$ Gyr

Solar System

$t_{SS} = 4.6 \pm 0.1$ Gyr

Princeton University

$t = 250 \pm ?$ yr

The age situation at the present time can be summarized by Figures 1 and 2 and by Table 1. We see there that an $\Omega = 1$ universe is consistent with $t > 10$ Gyr as long as $H_o \lesssim 66$ km/sec/Mpc. If uncertainties on H_o (including bounds on systematics) ever exclude 66, then one would require $\Lambda_o \neq 0$ to achieve the flat universe favored by inflation models.

Naively, we expect gravitational microphysics on the Planck scale, M_p to determine the scale of Λ_o. An effective $\lambda_o \sim 1$ requires $\rho_\Lambda \sim 10^{-121} M_p^4$. This seems like remarkable tuning. Of course, some late-time transition on the fraction of an eV scale could substitute for M_p if the early $\rho_\Lambda \sim M_p^4$ effects could be surpressed to more than 121 orders of magnitude. Because these problems seem awkward to avoid, most physicists think $\Lambda = 0$.

As an anthropic aside, if it were ever shown that $\Lambda_o \neq 0$, then we may have to appeal to the following anthropic argument (ugh!). While particle physics prefers a large value for $\Lambda_o \sim M_p^4$, the only values consistent with an old universe have to have $\Lambda_o < 10^{-121} M_p^4$. Thus, our existence plus particle theory would make the maximum value consistent with our existence the most likely value. (Hopefully, a better motivated physics explanation for Λ_o will eventually be found.)

To repeat the main conclusion: at present there is no age problem, even for $\Omega = 1, \Lambda = 0$ models, since the real uncertainties including systematics allow completely consistent age values.

7 Acknowledgements

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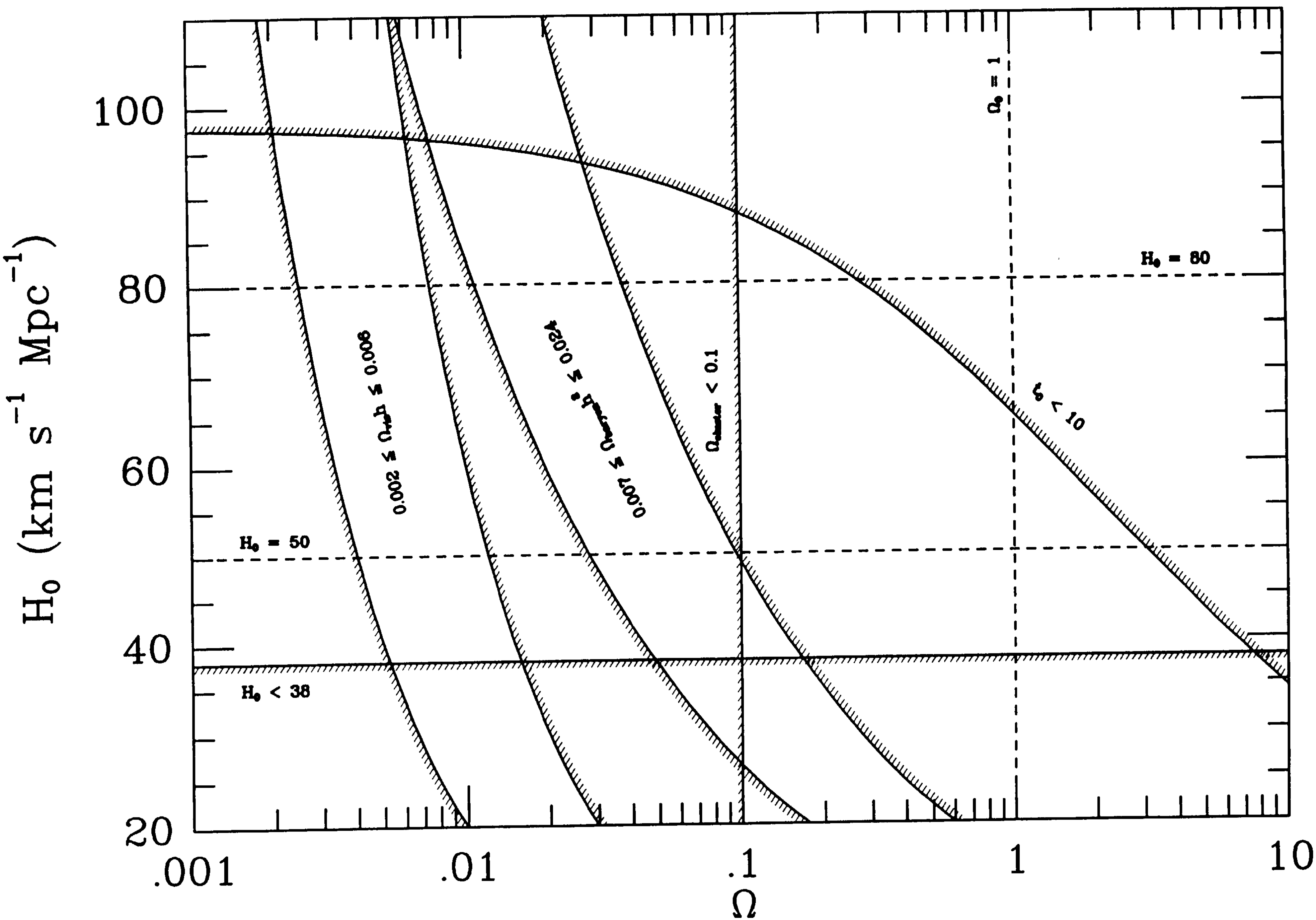
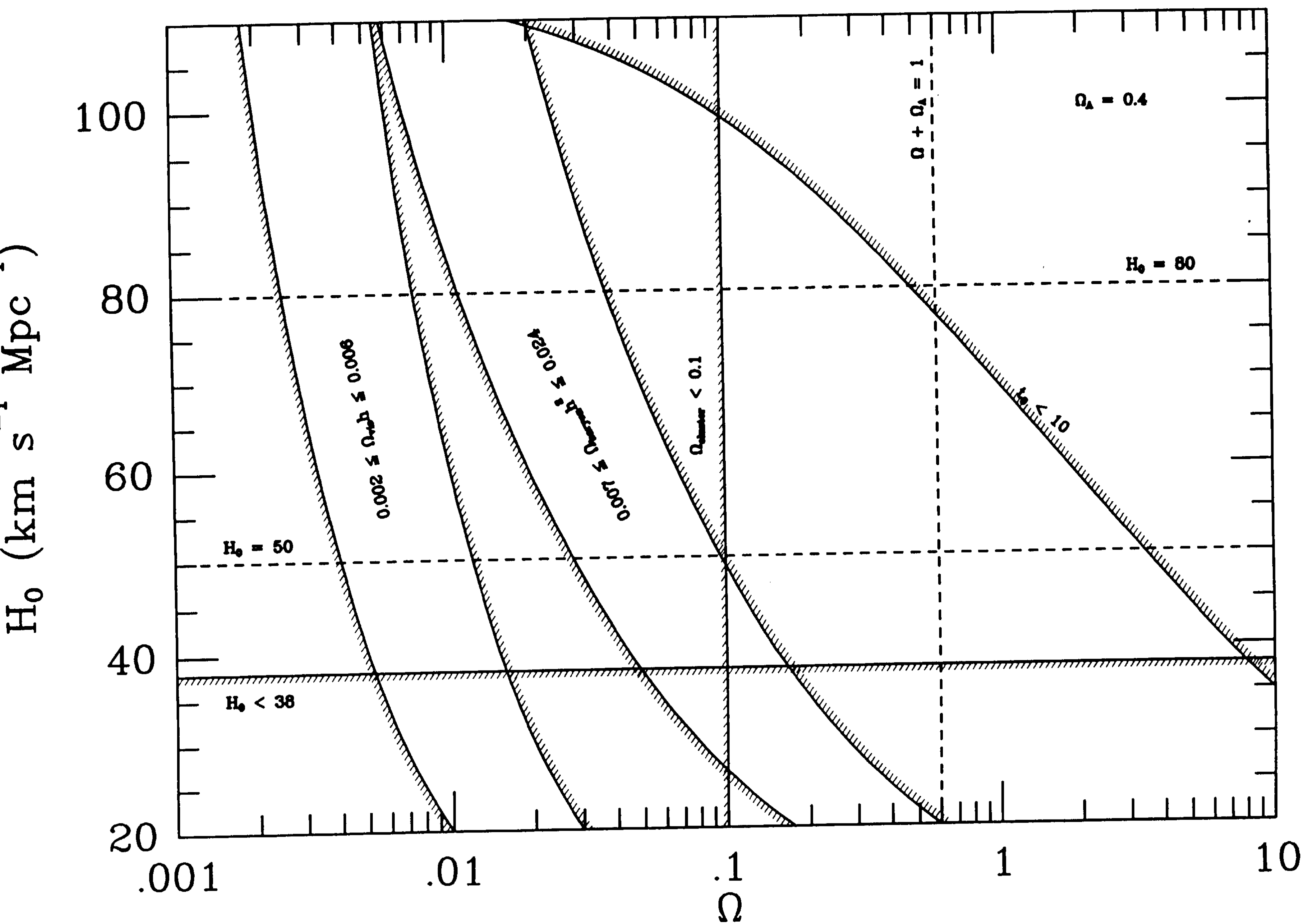
Figure Captions

Figure 1. An updated version of H_0 - Ω diagram of Gott, Gunn, Schramm and Tinsley (ref. 32) showing that Ω_b does not intersect $\Omega_{VISIBLE}$ for any value of H_0 and that $\Omega_{TOTAL} > 0.1$, so non-baryonic dark matter is also needed.

Figures 2a and 2b. Same as Figure 1 but with effective $\lambda_0 = \frac{\Lambda_0}{3H_0^2}$ 0.8(a) and 0.4 (b). Note for $\lambda_0 = 0.8$, $\Omega = 0.2$ yields a flat universe and for $\lambda_0 = 0.4$, $\Omega = 0.6$ is flat. These figures illustrate that even small λ_0 enables high H_0 to be consistent with a flat universe.



H_0 (km s^{-1} Mpc^{-1})
100
80
60
40
20
.001
.01
.1
1
10
Ω
$H_0 = 50$
$H_0 < 38$
$H_0 = 80$
$\Omega_0 = 1$
$0.002 \le \Omega_{vis} h \le 0.006$
$0.007 \le \Omega_{baryon} h^2 \le 0.024$
$\Omega_{cluster} < 0.1$
$t_0 < 10$



H_0 (km s^{-1} Mpc^{-1})
100
80
60
40
20
.001
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Ω
$H_0 = 50$
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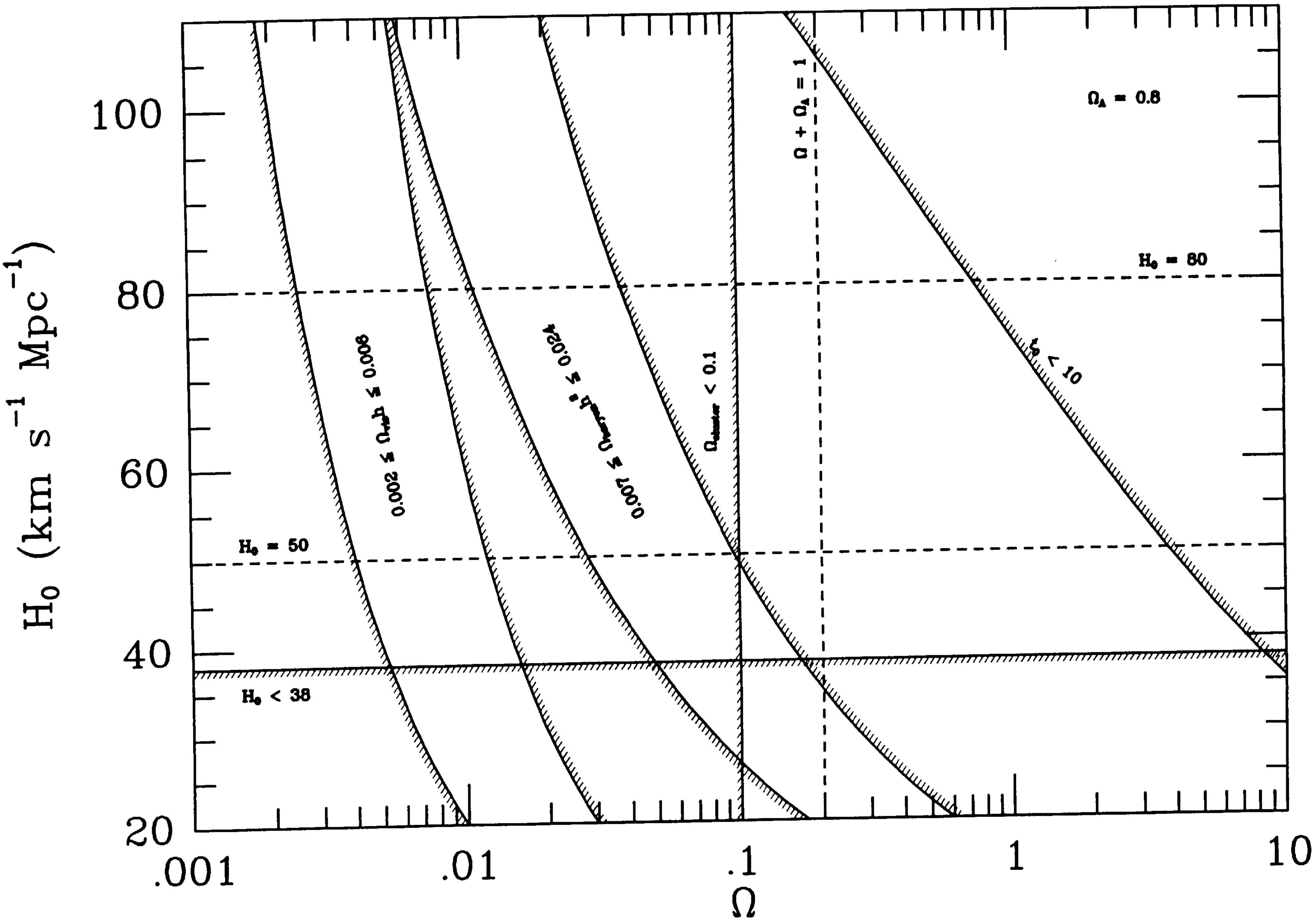
$0.002 \le \Omega_{vis}h \le 0.006$
$0.007 \le \Omega_{baryon}h^2 \le 0.024$
$\Omega_{cluster} < 0.1$
$\Omega + \Omega_\Lambda = 1$
$\Omega_\Lambda = 0.4$
$t_0 < 10$



H_0 (km s^{-1} Mpc^{-1})
100
80
60
40
20
.001
.01
.1
1
10
Ω
$H_0 = 80$
$H_0 = 50$
$H_0 < 38$
$0.002 \le \Omega_{vis} h \le 0.006$
$0.007 \le \Omega_{baryon} h^2 \le 0.024$
$\Omega_{cluster} < 0.1$
$\Omega + \Omega_\Lambda = 1$
$\Omega_\Lambda = 0.8$
$t_0 < 10$

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