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PRIMORDIAL HELIUM AND THE LUMINOSITY OF HORIZONTAL-BRANCH STARS

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I. INTRODUCTION

The discovery of the 3°K cosmic blackbody radiation (Penzias and Wilson, 1965) has provided compelling evidence for element synthesis in a primordial fireball. In particular, the primordial helium abundance by mass, $Y = 0.27$, as deduced by Peebles (1966), should therefore be found in present-day population II stars. We are concerned in this paper with the confirmation of the existence of the primordial helium.

It is well known that the direct determination of helium abundances is difficult, especially in the population II stars. The indirect approach of comparing theoretical stellar models with observation also leads to difficulties, since in many cases the stellar evolution depends upon the stellar mass, which is often observationally uncertain. Our approach involves the latter method, but considers only certain types of stars whose absolute magnitudes are insensitive to the stellar mass, viz., horizontal-branch stars in globular clusters and field RR Lyrae stars.

II. OBSERVATIONAL DATA AND THEORY

Following the work of Melbourne (1960), an extensive study was made by Wildey, Burbidge, Sandage, and Burbidge (1962) concerning the ultraviolet excess and the line-blanketing corrections for metal-deficient stars. Absolute magnitudes of the horizontal-branch stars were considered to be observationally determined rather precisely by fitting the observed cluster H-R diagrams to the

Hyades main sequence after correction for line blanketing. However, it is to be noticed that this method has come into question, as will be discussed in Section IV.

We now summarize the observational data. In Figure 1, the absolute magnitudes of the horizontal branches of several clusters (near their RR Lyrae stars) are shown by horizontal bars (Arp 1962; Sandage 1962; Eggen and Sandage 1964), together with data for the field RR Lyrae stars, whose absolute magnitudes have been determined by applying the semi-empirical period-luminosity-color relation given by Fernie (1965a, b) to the data of Sturch (1966). It is to be noticed that these stars are dispersed in a range of absolute magnitude, $+0.5 \lesssim M_v \lesssim +1.5$. In Figure 2, the absolute magnitudes are plotted against the ultraviolet deficiency, defined by Sturch (1966) as

$$\delta(U - B) = (U - B) - [-0.35 + 0.72\,(B - V)]\,, \tag{1}$$

which is an indicator of metal abundance.

Theoretically, the horizontal-branch stars are interpreted as stars of low mass in the helium-burning phase (see Hayashi, Hōshi, and Sugimoto 1962 ["HHS"]) in which energy production due to central helium-burning, L_{He}, and to shell hydrogen-burning contribute to the luminosity. The former is determined essentially by the mass of the helium core, M_{He}:

$$\frac{L_{He}}{L_\odot} = 56\left(\frac{M_{He}}{0.53\,M_\odot}\right)^3 . \tag{2}$$

This relation, which is normalized for the star of 0.7 $M_\odot$ computed by HHS (stage 1, Table 7-4), holds (in our mass range) as long as electron-scattering opacity dominates. The hydrogen shell-burning depends essentially upon the mass fraction, Q, of the hydrogen-rich envelope. It is negligible for small values of Q; for example, $Q \lesssim 0.4$ for $Y = 0.1$. In any case, the theoretical luminosity should not be less than the value of L_{He} given in equation (2).

The mass of the helium core is determined at the time of the helium flash preceding the stable helium-burning phase. Since mixing at the time of the flash has been shown not to occur (Härm and Schwarzschild 1964, 1966; Sugimoto 1964), the critical core mass for the helium flash is equal to the core mass in the stable helium-burning phase. As discussed by HHS (Section 6E), this critical core mass is quite independent of the stellar mass because of the highly condensed structure at the time of the flash; thus it depends only upon the abundance of helium in the hydrogen-rich envelope and upon the abundances of heavy elements, especially nitrogen. If we fix the helium abundance at the primordial value, then the absolute magnitudes of the horizontal-branch stars are determined solely by the heavy-element abundances.

III. COMPUTATIONS

We have computed the values of the critical core mass corresponding to the time of helium flash for different abundances of helium and of heavy elements. The method of computation is essentially the same as that of HHS: Hydrogen-rich envelope was replaced by suitable boundary conditions at the outer edge of the core, the temperature distribution has been computed as a perturbation of the isothermal condition in the helium core, and subsequently the core mass has been corrected by means of the temperature distribution obtained. In addition to the existing computation of the helium flash, we have taken into account the following two factors.

First, the flash is triggered by the α-capture of nitrogen, i.e., $^{14}N(\alpha, \gamma)$ $^{18}F(\beta^{+}\nu)^{18}O$ (Cameron 1959), whose rate has been taken from Reeves (1965):

$$\epsilon_N = 7 \times 10^{13} f X_N Y_{core} \rho T_8^{-2/3} \exp(-28.7/T_8) \text{ ergs/gm-sec}, \tag{3}$$

where f is a screening factor, X_N is the abundance of nitrogen by weight, and other symbols have their usual meanings. Second, two cases have been computed, viz., with and without neutrino loss, in view of the fact that the universal Fermi interaction between electrons and neutrinos has not yet been established by laboratory experiment. In our problem, the plasma neutrino process is important, the rate of which has been taken as one-fourth (see Zaidi 1965) of the value given by Adams, Ruderman, and Woo (1963). For the equation of state, both nonrelativistic partial degeneracy and radiaton pressure have been taken into account. Opacity is due to electron scattering, free-free transitions, and electron conduction, for all of which the effect of electron degeneracy was taken into account. (The Gaunt factor in equation [3A-40] of HHS should be divided by 2.)

Our results for the critical core mass and the absolute visual magnitude of the horizontal-branch stars are summarized in Tables 1 and 2, respectively. For the determination of the absolute visual magnitude, a bolometric correction of $-0^{m}.06$ was adopted. Though the neutrino luminosity is of the order of 10^{33} ergs/sec, it is large enough to produce a temperature distribution decreasing inward near the central region, since the heat capacity therein is small because of degeneracy. This effect makes the critical core mass larger, and the flash commences not at the center, but in an outlying shell. The increases in temperature due to nitrogen-burning are illustrated in Figure 3 for various abundances of nitrogen in the case of $Y = 0.27$ without neutrinos. It was found that the effect of nitrogen-burning is appreciable for $X_N = 0.001$ and that the nitrogen flash goes over into a helium flash for $X_N \gtrsim 0.01$.

IV. UNCERTAINTIES AND CONCLUSION

We shall estimate the uncertainties of the above results first from the theoretical side. For the critical core mass, we have $0.513\ M_{\odot}$ for $Y = 0.1$ and $Z = 0.001$, as determined in a detailed computation by Härm and Schwarzschild (1966). If radiation pressure, which was neglected by Härm and Schwarzschild, is included, the stellar luminosity for a given core mass decreases in the giant branch prior to the helium flash; we have estimated that this effect increases the critical core mass by 5 per cent. Furthermore, in the Härm-Schwarzschild computation the effect of electron degeneracy on the radiative opacities was neglected and the

Gaunt factor for the free-free opacity was put equal to unity. If these effects are properly included, another 4 percent should be added to the critical core mass. The revised critical core mass becomes 0.56 $M_{\odot}$, in good agreement with our result for Y = 0.1 and negligible nitrogen abundance. Thus, uncertainty in the core mass may be less than 2 per cent, which results in an uncertainty of $0^{m}.06$, according to equation (2).

The normalization in equation (2) is also subject to uncertainty. It has been checked by using the results of numerical computations by Suda and Virgopia (1966) and found to hold within +10 and -1 per cent, i.e., $-0^{m}.1$ and $+0^{m}.01$. Horizontal-branch stars for which the free-free opacity is included with a proper Gaunt factor will be fainter by $0^{m}.09$. Thus the uncertainty of $0^{m}.2$ (from the theory) will represent a reasonable estimate. The effects due to the hydrogen shell-burning and to depletion of helium in the core make the model star brighter than is shown by the results in Table 2. However, it is to be noticed that more helium and/or more metals would be necessary to interpret the observed magnitudes if the model star were brighter.

Next we shall discuss the observational determination of the absolute magnitudes. Demarque (1967) has found that for a fixed helium abundance the zero-age main sequence of metal-deficient stars should lie below the metal-rich main sequence in the H-R diagram. If the observed stars are fitted to Demarque's main sequence, the observed horizontal branch becomes fainter than before. However, several questions are raised (Faulkner 1967; Dennis 1968) concerning the line-blanketing correction itself. If the correction of the data used in the present study is too large, the observed horizontal-branch will be brighter. To the authors' knowledge, quantitative investigations of these questions are, at present, not well established. The absolute magnitudes of the field RR Lyrae stars are also subject to the abovementioned uncertainties, since the period-luminosity-color relation derived from field RR Lyrae stars by Fernie (1965a, b) has been tested with the stars in M3. It will not be unreasonable to take the observational uncertainty to be as much as $0^m.5$.

The over-all uncertainty from both the theoretical and observational sides amounts to $0^m.7$. The observed absolute magnitude extrapolated to negligible metal content (see Figure 2) is $+0^m.5$. Even if the abovementioned uncertainties are fully taken into account, the magnitude of model stars must be fainter than $M_V = -0^m.2$. Thus, the case of $Y = 0.10$ with neutrino loss will be excluded, as may be seen in Table 2. For more precise discussion, observational studies of the absolute magnitudes of horizontal-branch stars are badly needed.

The dispersion of the theoretical magnitudes due to the different nitrogen abundances, when the helium abundance remains fixed, may be large enough to permit interpretation of the observed dispersion, especially when neutrino loss is included. For example, the faint horizontal branch of the old galactic cluster, M67 (Eggen and Sandage 1964) may be interpreted in terms of the nitrogen-triggered helium flash.

Provided that the observational results of Figure 1 are not subject to major revision, the above results may be considered as providing evidence of the existence of primordial helium in population II stars.

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TABLE 1
CRITICAL HELIUM CORE MASS AT THE HELIUM FLASH
(SOLAR MASS UNITS)

	X_N	Y = 0.10	Y = 0.27	Y = 0.40
without neutrinos	0.0005*	0.564	0.532	0.519
	0.0005	0.555	0.525	0.513
	0.001	0.533	0.503	0.493
	0.010	0.464	0.443	0.438
with neutrinos	0.0005*	0.682	0.627	0.586
	0.0005	0.635	0.593	0.563
	0.001	0.585	0.553	0.532
	0.010	0.488	0.462	0.449

*α-capture of nitrogen is neglected.

TABLE 2
ABSOLUTE VISUAL MAGNITUDES OF THE MODEL STARS

	X_N	Y = 0.10	Y = 0.27	Y = 0.40
without neutrinos	0.0005*	0.11	0.30	0.38
	0.0005	0.17	0.34	0.42
	0.001	0.30	0.48	0.55
	0.010	0.75	0.90	0.93
with neutrinos	0.0005*	-0.51	-0.24	-0.02
	0.0005	-0.27	-0.05	0.12
	0.001	-0.03	0.18	0.33
	0.010	0.58	0.76	0.86

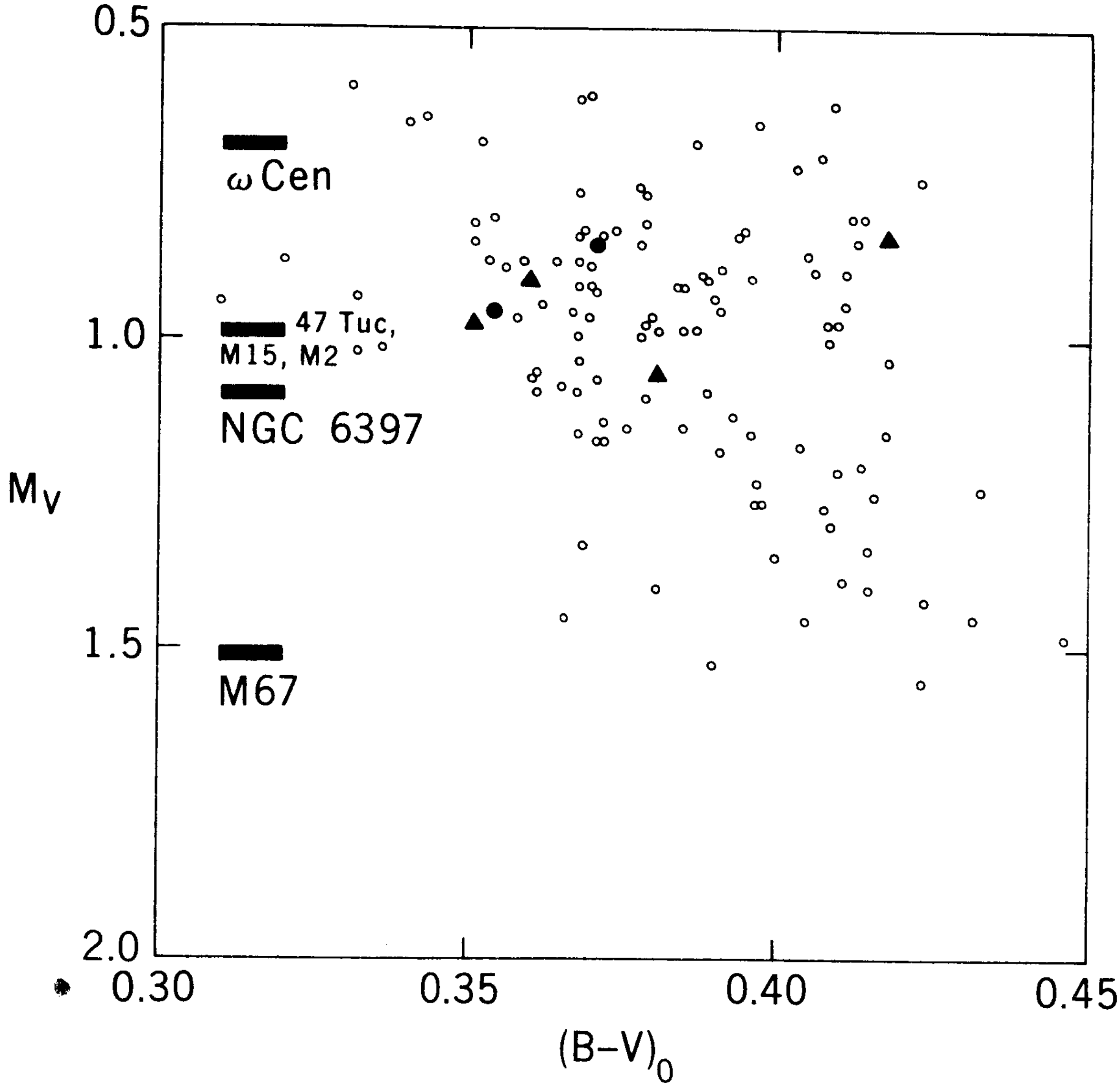
*See footnote of Table 1.

Figure Legends

FIG. 1 – Absolute magnitudes of RR Lyrae stars and horizontal-branch stars. Closed circles and triangles are RR Lyrae stars in M5 and M3, respectively. Bars at the left indicate magnitudes of horizontal branches of several clusters.

FIG. 2 – Ultraviolet excess plotted against the absolute magnitude for RR Lyrae and horizontal-branch stars. (See legend of figure 1).

FIG. 3 – Increase in temperature at the time of nitrogen-triggered helium flash. The numbers attached are the abundances of nitrogen by weight, X_N. The asterisk indicates that the α-capture of nitrogen is neglected.



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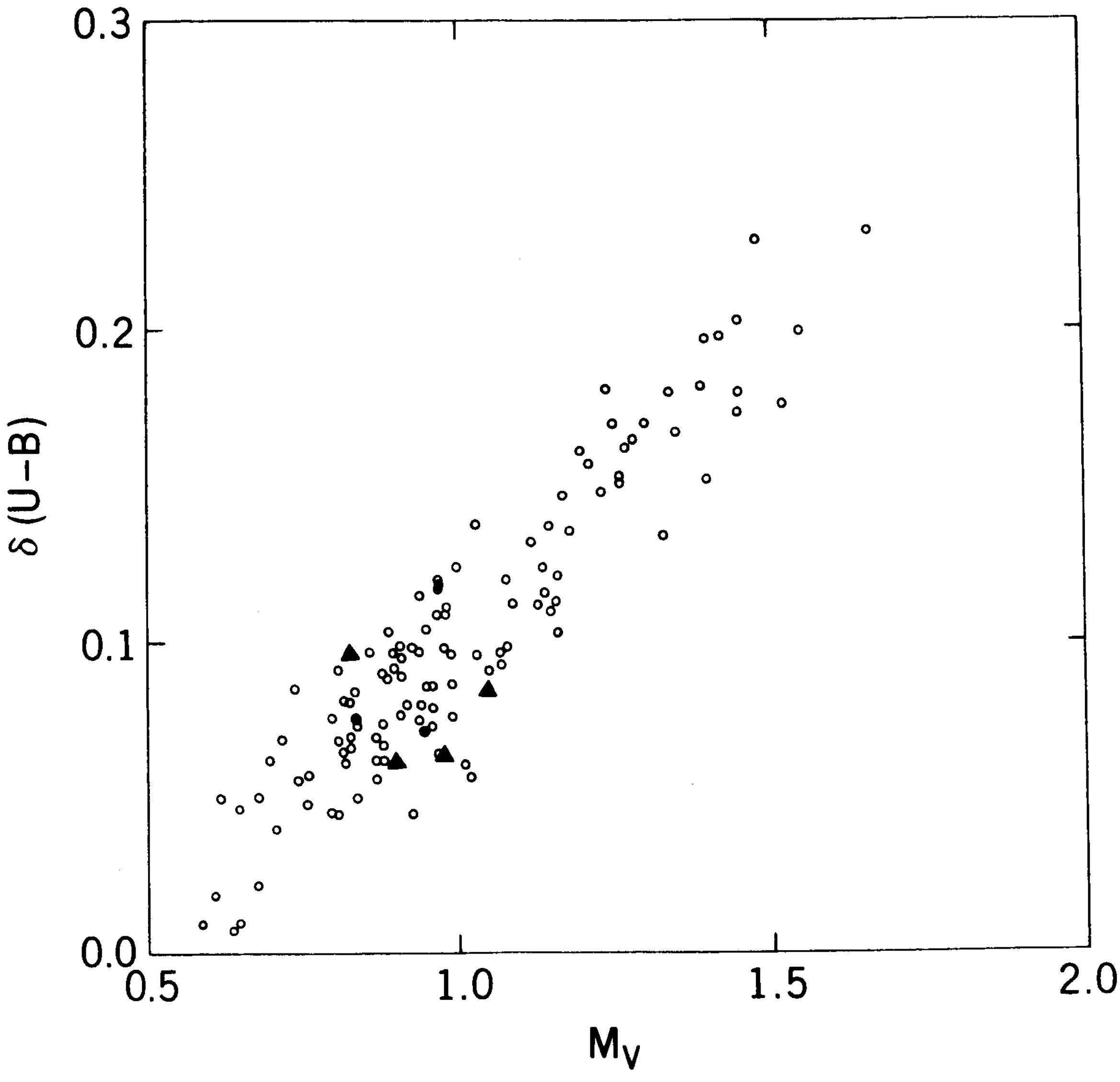

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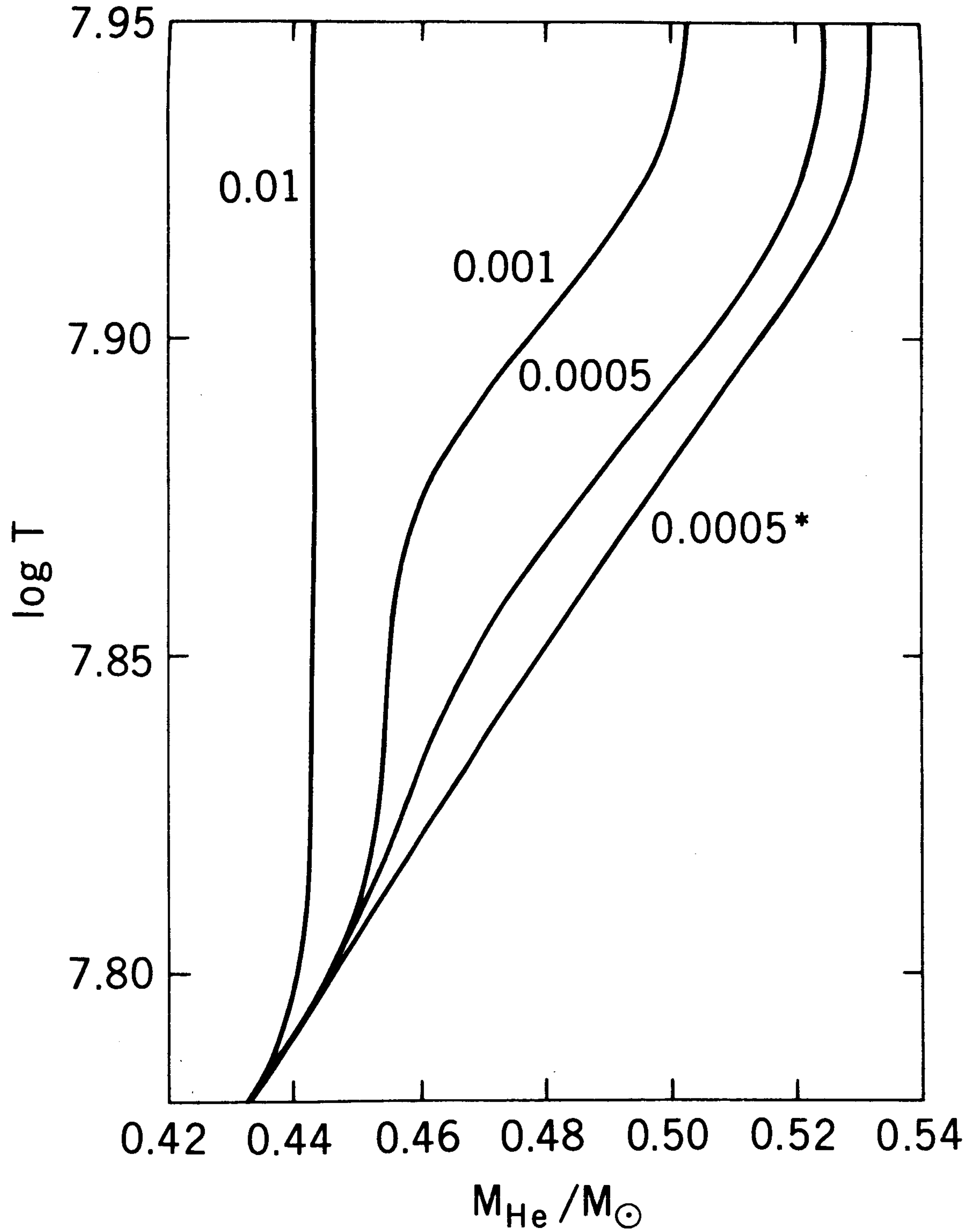

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