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EVOLUTIONARY MODELS AND THE p-MODE OSCILLATION SPECTRUM OF α CENTAURI A AND B

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ABSTRACT

Detailed evolutionary models of the stars α Cen A and B have been constructed. The opacities were calculated specifically with the Los Alamos Opacity Library using recently determined abundances of α Cen A. Consistent with the measured masses and a common age and composition for both α Cen A and B, we have derived the initial helium abundance $Y = 0.300 \pm 0.005$ (corresponding to $Z = 0.026 \pm 0.003$) and age $= 4.6 \pm 0.4$ Gyr, where we have ignored errors intrinsic to the models. The effects of helium diffusion in the interior were also included in the evolutionary sequences. Helium diffusion lowers the inferred age of the system by 2% (from 4.7 to 4.6 Gyr) and increases the mixing length needed to reproduce the radius of α Cen A. Thus the inclusion of helium diffusion effectively decreases the need for a smaller mixing length in α Cen A than in the Sun. The predicted first-order spacing of p-modes averages to $\langle \Delta\nu \rangle = 108$ μHz for $l = 0$ for α Cen A and $\langle \Delta\nu \rangle = 179$ μHz for $l = 0$ for α Cen B. The second-order splitting averages to $\langle \delta\nu \rangle = 6.2$ μHz for $l = 0$ for α Cen A and 12.6 μHz at $l = 0$ for α Cen B. The reduction in Y at the surface of α Cen A due to diffusion has no detectable effect on the frequencies of the low-l p-modes.

Subject headings: stars: evolution — stars: individual (α Centauri) — stars: interiors — stars: oscillations

1. INTRODUCTION

Observational studies of the binary system α Cen A, B provide many opportunities to challenge theories of stellar structure and evolution. The high apparent brightness, large parallax, and binary nature of α Cen imply that the surface abundances and astrometric parameters are known better than for any star other than the Sun. In particular, the masses of each component may be estimated accurately, greatly aiding precise modeling of the system. By coincidence, the masses of α Cen A and B (1.1 $M_\odot$ and 0.9 $M_\odot$) bracket the mass of the Sun, making the α Cen system a primary target in the study of the solar-stellar connection. Furthermore, we may assume that both components have a common age and identical initial chemical compositions. The initial helium abundance and present age of the system may then be derived by using theory to evolve appropriate zero-age main-sequence (ZAMS) models to the current temperatures and luminosities of the two stars. Yet to be fully exploited are the additional constraints that become available through the fact that α Cen A, B are likely to exhibit measurable nonradial p-mode oscillations analogous to the 5 minute oscillations on the Sun. This paper presents a comprehensive theoretical study of α Cen A, B, including detailed predictions of the p-mode spectrum of the optimal models.

Several groups have previously presented models of α Cen A. Flannery & Ayres (1978) using Cox-Stewart (1970) opacities, evolved models of α Cen A, B from the ZAMS, estimating $Y - Y_\odot = -0.01$ (where Y is the helium abundance of α Cen) and claiming an age for the system of 6 Gyr. They assumed two fixed values of the metallicity, $Z = 0.02$ and $Z = 0.04$, and a solar value of the mixing length parameter α (ratio of mixing length to pressure scale height). Demarque, Guenther, & van Altena (1986) performed similar modeling of the α Cen system using Cox-Stewart (1970) opacities. They varied the helium abundance from 0.15 to 0.28, and α from 0.5 to 1.6, again assuming $Z = 0.02$ and $Z = 0.04$, and deduced that the age of α Cen lies between 4 and 4.5 Gyr with a metallicity encompassed by the adopted limits. The smaller age found in this second study can be traced primarily to the more accurate equation of state and opacity interpolation of Demarque et al. (1986). Recently, Noels et al. (1990), using opacities from the Los Alamos Opacity Library (Huebner et al. 1977, hereafter LAOL) and $Z = 0.04$, derived the relatively high value of $Y = 0.32$ for the helium abundance and an age of 5 Gyr lying between the two previous estimates. These authors assumed identical ages and chemical compositions for both stars, and determined four free parameters (age, Z, Y, and α) from the observed values of the luminosities and effective temperatures of α Cen A and B. In all of these previous studies, it was assumed that the "metal" component, characterized by Z, had element abundances in the same proportion as solar abundances. Moreover, any effects of diffusion were neglected. In the present study we construct new models of α Cen A and B using recently determined abundances for the system (Furenlid & Meylan 1990) and examining the effects of diffusion.

The aim of our study is not only to explore the influence of these modifications, but also to provide new predictions of the p-mode spectra of the models. Of the structural models described above, only that of Demarque et al. (1986) has been used to predict p-mode frequencies. This work predicted a spacing $\Delta\nu_{n,l} \equiv \nu(n, l) - \nu(n-1, l)$ for $l = 0$ to be around 100 μHz for α Cen A [$\nu(n, l)$ is the frequency of modes with order n and degree l]. Please note that this definition of $\Delta\nu$ is for the

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1992ApJ...394..313E

full spacing between adjacent modes and not the half-spacing defined in Demarque et al. (1986). In our study, theoretical oscillation frequencies are determined for both α Cen A and B. In view of the high quality of the fundamental stellar data for α Cen A, B, we have made a special effort to improve on several aspects of the oscillation predictions. In addition to using improved abundances specifically and including diffusion, a precise set of opacity tables were constructed using the program developed by one of us (D. B. G.) to calculate Rosseland mean opacities from the LAOL data, as is done for modern models of solar oscillations.

On the observational side, attempts have been made to detect p-mode oscillations in α Cen A by Fossat et al. (1984), Brown & Gilliland (1990), and Butcher, Christensen-Dalsgaard, & Frandsen (1990). Fossat et al. (1984) reported a detection but the claimed separation between the oscillation frequencies $\Delta\nu$ is inconsistent with the theoretical value predicted by the work of Christensen-Dalsgaard (1984) and subsequently improved by Demarque et al. (1986). Brown & Gilliland (1990) failed to detect oscillations on α Cen A despite using techniques more sensitive than Fossat et al. (1984). Butcher et al. (1990), using six nights of observing on the 3.6 m ESO telescope, have made the first detection of oscillations on α Cen that are consistent with the known properties of this star. They have found a set of regularly spaced peaks in their power spectrum, with a separation corresponding to a $\langle\Delta\nu\rangle = 110\ \mu$Hz.

The evolutionary models used in our study are described in § 2. The results of the calculation of the p-mode oscillation spectrum of α Cen A and B are given in § 3. Section 4 discusses the age and helium abundance derived for α Cen followed by a summary of the results of this work.

2. EVOLUTIONARY MODELS

The Yale Rotating Evolution Code (YREC; Pinsonneault et al. 1989) has been used to construct models of α Cen A and B at ZAMS, and then to evolve these models from the ZAMS to a point beyond the present age of the stars. The predicted evolutionary tracks in the $T_{\rm eff}$–log L plane are compared with the current positions of the two stars (see Table 1), and the initial conditions and other modeling assumptions are adjusted to achieve satisfactory coincidence. This process provides insight into the sensitivity of the outcomes to uncertainties in the parameters. In particular, the present calculations involve a detailed exploration of the influence of changes in abundance and of diffusion.

Because a star's luminosity is relatively insensitive to variations in the mixing length parameter, we are able to constrain the stellar models of α Cen A and B in two distinct steps. In the first step we vary the helium abundance of the binary system until each star reaches their observed luminosity at the same age. With the age and helium abundance determined, we then construct a sequence of tracks with different mixing length parameters (with and without diffusion) and use the observed surface temperatures of the stars to select the best mixing length parameter for each model. We adopt, without variation, the masses 1.09 $M_\odot$ and 0.90 $M_\odot$ for α Cen A and B, respectively. Both the astrometry used to obtain these masses and the sensitivity of the calculations to errors in the masses are discussed in Demarque et al. (1986) and will not be repeated here other than to note that the combined effect of the uncertainties in the mass and metallicity determinations introduces an uncertainty of 0.5 Gyr in the age determination.

TABLE 1

MASS, LUMINOSITY, AND EFFECTIVE TEMPERATURE OF α CENTAURI

Component	Mass ($M_\odot$)	Luminosity[a] log ($L/L_\odot$)	Temperature[b] $T_{\rm eff}$(K)
α Cen A........	1.09 ± 0.01	0.16 ± 0.01	5770 ± 20
α Cen B........	0.90 ± 0.01	−0.33 ± 0.01	5350 ± 50

[a] Values from Demarque et al. 1986.

[b] Values from Soderblom 1986.

2.1. *Abundances and Opacities*

The Rosseland mean opacities used in YREC were calculated from the LAOL of extinction coefficients for the 20 most abundant elements in the Sun. These extinction coefficients were combined in proportions based on the α Cen abundance measurements by Furenlid & Meylan (1990) where available, the solar abundances of Ross & Aller (1976) being adopted otherwise. Below 10,000 K the Cox-Stewart tables (Cox & Stewart 1970; hereafter CS) were used because the LAOL tables do not extend below this temperature. The CS tables are based on a different mixture and include fewer elements.

To assist in calibrating the α Cen models a standard solar model was constructed. The values of the helium abundance Y and the mixing length parameter α (the ratio of the mixing length to the pressure scale height) of this model were adjusted so that a ZAMS solar model had the correct luminosity and radius when evolved to the present age of the Sun. It was found that $Y = 0.282$ and $\alpha = 1.25$ for accurate solar models constructed with LAOL opacities and the physical system defined by the YREC equations (Guenther, Jaffe, & Demarque 1989; Kim, Demarque, & Guenther 1991).

2.2. *Effects of Helium Diffusion*

Heavy elements will tend to flow with respect to hydrogen in stellar interiors because of gravitational forces, diffusion along thermal and density gradients, and selective radiation pressure (we call these processes, collectively, diffusion). Although it has in the past been generally ignored in calculations of stellar evolution, diffusion can be important in stars with long evolutionary lifetimes. Helium in particular diffuses relatively rapidly, and because it is so abundant its downward diffusion may significantly modify the internal structure. The effects of helium diffusion on solar structure have been studied recently by Bahcall & Pinsonneault (1992), and also by Cox, Guzik, & Kidman (1989) and Proffitt & Michaud (1991). M. H. Pinsonneault has incorporated helium diffusion in the YREC stellar evolution code using the diffusion coefficients of Bahcall and Loeb (1990). These authors have shown that the evolution of the mass fractions of each element at a given point in a model obey diffusion equations to an accuracy of several tens of percent, neglecting nuclear reactions. This accuracy is adequate for examining the effect of diffusion in solar-type stars.

Diffusion of helium is the envelope tends to change the stellar radius because it changes the opacity as a function of depth. The time scale for helium diffusion is shortest near the base of the surface convection zone and is shorter for stars with thin surface convection zones than for stars with thick ones. This follows because the diffusion coefficients are relatively weak functions of the local physical conditions (see tables in Proffitt & Michaud 1991), while the density decreases dramatically in the outer layers of stars. In the context of the α Cen

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1992ApJ...394..313E

system, this implies that diffusion will affect the envelope of α Cen A more than that of the Sun, while it has virtually no effect on α Cen B. The resulting change in the radius of the α Cen A model requires a different mixing length parameter from that of the standard model.

Because the time scale for diffusion in the core is very long, it has a relatively small impact on dwarf stars in general. Diffusion in the core raises the central mean molecular weight and increases the luminosity; this implies a younger age when comparing the model to observation. Because the time scale for diffusion is similar in the cores of α Cen A and B, its net effect will be a change in the absolute age rather than in the relative luminosities.

2.3. *Results*

Since α Cen is a binary system, we assume that its two components have a common age and the same initial chemical composition. Using the heavy-element abundances measured by Furenlid & Meylan (1990), the helium abundance was varied until both components reached their present measured luminosities at the same age. This approach yields the initial helium abundance $Y = 0.30$ and an age of 4.7 Gyr for the α Cen system. These parameters are consistent with $Y = 0.32$ and the age of 5.0 Gyr derived by Noels et al. (1990), when the higher metallicity ($Z = 0.04$) adopted by Noels et al. (1990) is taken into account.

To provide the best fit to the effective temperature of α Cen A, the mixing length used in the model was lowered from the solar value of 1.251 to 1.06. This change fixes the radius of the model at the measured radius of α Cen A, enabling accurate calculation of the *p*-mode frequencies. A smaller mixing length value corresponds to a smaller temperature gradient in the outer layers of the convection zone, implying less efficient energy transport in this region. Other workers (Lattanzio 1984; Demarque et al. 1986) have also found that models for α Cen A require a smaller mixing length than standard solar models.

Following the same procedure, evolutionary sequences were also calculated including the effects of helium diffusion. Figures 1, 2, and 3 show the sensitivity of the results to changes in Y, Z, and the mixing length (keeping all other parameters constant), compared with the current positions of α Cen A and B in the H-R diagram. The inclusion of diffusion slightly lowers the estimate of the age of α Cen to (4.6 ± 0.4) Gyr, due to more rapid helium exhaustion in the core. This accounts in part for the lower age (by 0.4 Gyr) inferred by us, compared to the estimate of Noels et al. (1990).

An age of (4.6 ± 0.4) Gyr for the α Cen system is consistent with most other age constraints on α Cen A obtained by comparing this star with the Sun and other solar-like stars. For example, the strength of Ca II chromospheric activity of α Cen A indicates that its age is close to solar. The estimate of the rotation rate of α Cen A by Dravins (1987) lies close to the solar value, further indicating the probable similarity in age between the two stars, in accord with the Skumanich relationship (Skumanich 1972).

Figure 4 compares the stellar evolutionary tracks for α Cen A with and without diffusion and shows that diffusion makes only a small difference to the evolution of the star. This result is consistent with previous work by Vauclair, Vauclair, & Pamjatnikh (1974), Montmerle & Michaud (1976), and Fontaine & Michaud (1979). All other parameters being kept unchanged, the effective temperature of the evolved α Cen A model with diffusion is lowered by 57° compared with a model with no diffusion. This decrease in effective temperature (due to a larger radius) is the result of the uniformly lower helium abundance in the surface convection zone. The effect of diffusion may be compensated by increasing α to 1.15 to achieve a match to the

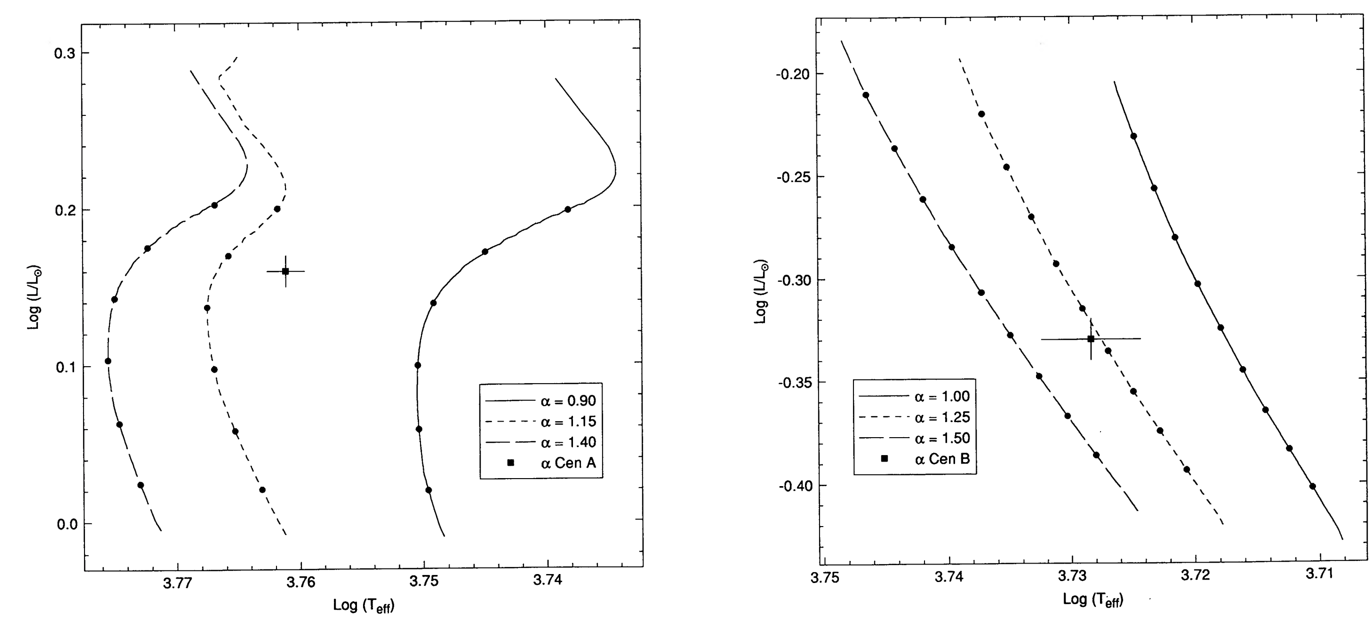

FIG. 1.—H-R diagrams for α Cen A and B, showing tracks for three different values of the mixing length parameter α, with the metallicity and helium abundance fixed at $Z = 0.0264$ and $Y = 0.30$. The measured luminosity and effective temperature of both stars is shown with error bars. The dots denote 1 Gyr intervals along the evolutionary track.

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1992ApJ...394..313E

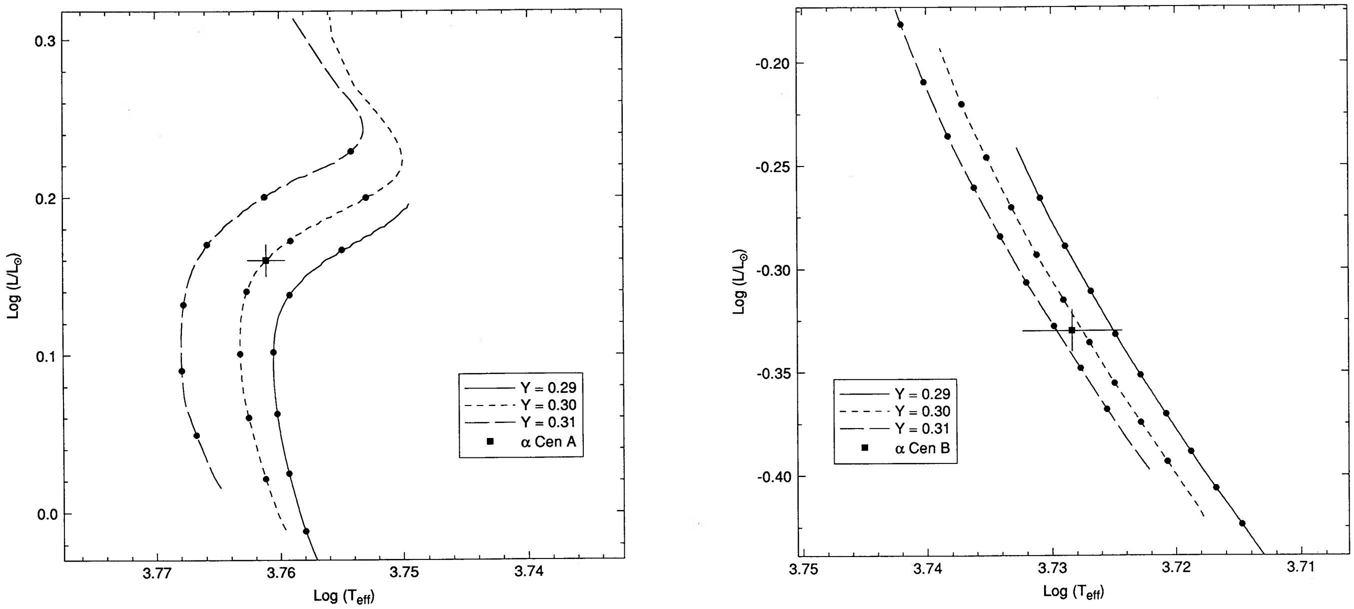

FIG. 2.—H-R diagrams for α Cen A and B, showing tracks for three different values of the helium abundance Y, with the metallicity and mixing length fixed at $Z = 0.0264$, $\alpha = 1.15$ (α Cen A with diffusion), and $\alpha = 1.25$ (α Cen B). The dots denote 1 Gyr intervals along the evolutionary track.

observed stellar radius. In α Cen A diffusion has a relatively larger effect on the radius than it does in the Sun (because the surface convection zone is less deep), so that a slightly larger adjustment in α is needed to compensate for the effects of diffusion in α Cen than in the Sun. This result helps explain why previous attempts to model α Cen without diffusion (Lattanzio 1984; Demarque et al. 1986) have required a value of α considerably smaller for α Cen A than for the Sun. This result is also consistent with α Cen B requiring a larger value of α (1.251) than α Cen A.

3. THE p-MODE OSCILLATION SPECTRUM

The adiabatic nonradial oscillation program of D.G.B. was used to calculate all p-modes for $l = 0$ to $l = 3$ between $n = 1$ and $n = 49$, for both α Cen A and α Cen B. Input to the program are detailed models produced by YREC with 1800 shells. The absolute accuracy of frequencies predicted by the program is limited to about one part in 100 due to the sensitivity of the engenfunctions to the physical characteristics of the outer layers of the model. This accuracy is entirely suffi-

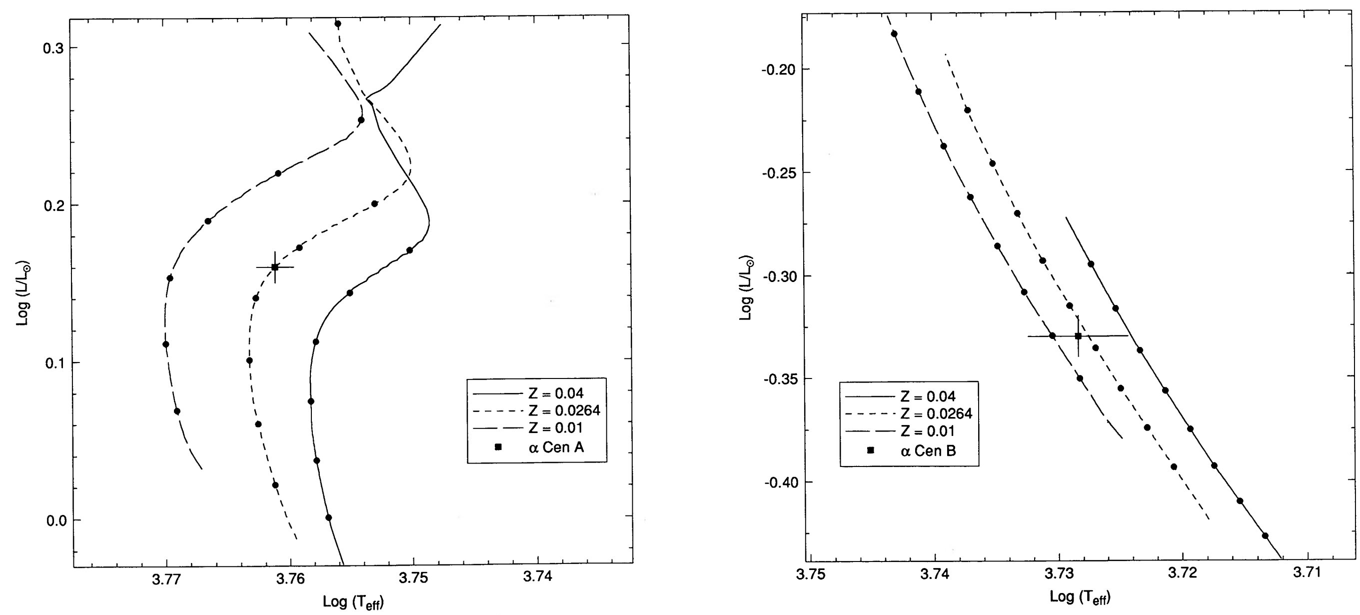

FIG. 3.—H-R diagrams for α Cen A and B, showing tracks for three different values of the metallicity Z, with the helium abundance and mixing length fixed at $Y = 0.30$, $\alpha = 1.15$ (α Cen A with diffusion), and $\alpha = 1.25$ (α Cen B). The dots denote 1 Gyr intervals along the evolutionary track.

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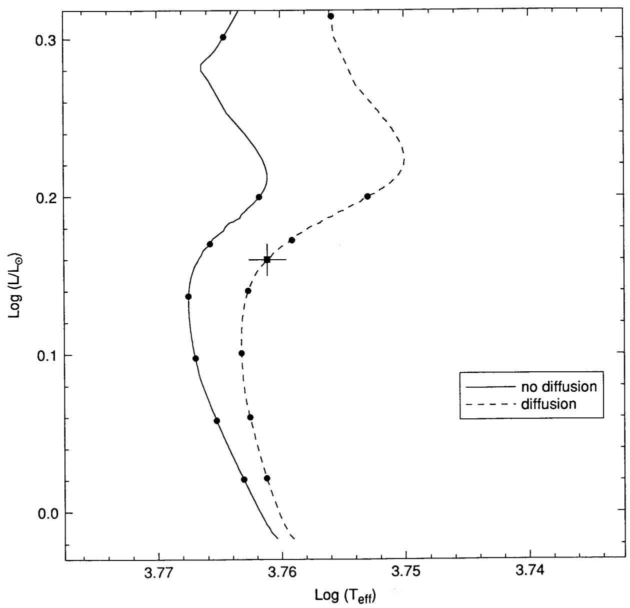

FIG. 4.—H-R diagrams for α Cen A, showing tracks with and without diffusion. The metallicity, helium abundance, and mixing length are kept fixed at $Z = 0.0264$, $Y = 0.30$, and $\alpha = 1.15$. The dots denote 1 Gyr intervals along the evolutionary track.

cient for comparing with early observations of nonradial oscillations in stars. The use of gray atmosphere routines built into YREC rather than a detailed model of the atmosphere of α Cen will mean that the higher frequency p-modes are not calculated accurately. Higher accuracy would require a detailed model atmosphere constructed specifically for α Cen A and properly applied as boundary condition to the α Cen A interior model.

The calculated oscillation frequencies of α Cen A and B are listed in Table 2. In the integrated spectrum of a star undergoing nonradial oscillations, individual modes are not readily identifiable. However, the characteristic frequency spacing is observationally accessible because modes of order and degree (n, l) very nearly overlap those of order and degree $(n + 1, l - 2)$, increasing the observed power at appropriate frequencies. Therefore, the spectra of low-degree modes appear as peaks containing several unresolved overlapping modes separated by a constant frequency interval $\delta\nu/2$. The overlap of the modes can be seen from the asymptotic theory of Tassoul (1980), which gives (for small l)

$$\nu_{nl} \approx \nu_0\left(n + \frac{l}{2} + \epsilon\right),$$

where ν_0 and ϵ are parameters that depend on the structure of the star. In particular,

$$\nu_0\left(2\int_0^R \frac{dr}{c}\right)^{-1}$$

is the inverse of the sound travel time between the center and the surface. The average frequency spacing $\langle\Delta\nu\rangle \approx \nu_0$ can easily be measured by Fourier transforming the observed spectrum and equals 135.6 μHz for the Sun.

3.1. α *Centauri A*

Previously Demarque et al. (1986) found that $\langle\Delta\nu\rangle_{l=0} = 104$ μHz for α Cen A, significantly different from the value of 162.6 μHz measured by Fossat et al. (1984). Here $\langle\Delta\nu\rangle_{l=0}$ is defined as the average $\Delta\nu_{l=0}$ over n from 10 to 35. To first order, the characteristic frequency spacing depends only on the radius of the star and is insensitive to the internal structure of the model. Demarque et al. (1986) confirmed this by varying the helium abundance and mixing length, while keeping the luminosities and effective temperatures of the models fixed. They found that

TABLE 2A

THEORETICAL p-MODE FREQUENCIES OF α CENTAURI A (μHz)

	$l = 0$			$l = 1$			$l = 2$		$l = 3$	
n	ν	$\Delta\nu$	$\delta\nu$	ν	$\Delta\nu$	$\delta\nu$	ν	$\Delta\nu$	ν	$\Delta\nu$
10........	1204.9	108.9	8.7	1253.5	107.5	15.2	1302.1	106.0	1344.2	105.9
11........	1310.7	105.8	8.6	1359.2	105.7	15.0	1408.1	106.0	1450.6	106.4
12........	1416.7	106.0	8.6	1465.4	106.2	14.8	1514.7	106.6	1558.3	107.6
13........	1523.4	106.7	8.6	1573.0	107.6	14.7	1622.2	107.5	1665.7	107.4
14........	1630.6	107.3	8.4	1680.1	107.1	14.4	1729.0	106.8	1772.5	106.8
15........	1737.2	106.5	8.2	1786.5	106.4	14.0	1834.9	105.9	1878.5	106.0
16........	1842.8	105.6	7.9	1892.3	105.8	13.8	1941.1	106.2	1985.3	106.8
17........	1948.8	106.0	7.7	1998.9	106.7	13.6	2048.1	107.0	2093.0	107.7
18........	2055.6	106.8	7.5	2106.5	107.5	13.5	2156.3	108.1	2201.5	108.5
19........	2163.5	107.9	7.2	2214.6	108.1	13.1	2264.5	108.2	2310.2	108.7
20........	2271.5	108.0	7.0	2323.0	108.4	12.8	2373.0	108.5	2418.7	108.6
21........	2379.6	108.1	6.7	2431.2	108.2	12.5	2481.4	108.4	2527.6	108.9
22........	2487.8	108.2	6.4	2539.8	108.5	12.2	2590.1	108.7	2636.7	109.1
23........	2596.3	108.5	6.1	2648.5	108.8	11.9	2699.2	109.1	2746.2	109.6
24........	2705.1	108.8	5.9	2757.8	109.2	11.5	2808.6	109.4	2855.9	109.6
25........	2814.1	109.1	5.6	2867.1	109.3	11.2	2918.2	109.6	2965.7	109.9
26........	2923.5	109.3	5.3	2976.6	109.5	10.9	3027.7	109.5	3075.6	109.9
27........	3032.7	109.3	5.0	3086.2	109.6	10.6	3137.5	109.8	3185.6	109.9
28........	3142.2	109.5	4.8	3195.8	109.6	10.3	3247.2	109.7	3295.6	110.1
29........	3251.7	109.5	4.5	3305.6	109.8	10.0	3357.1	109.9	3405.6	110.0
30........	3361.3	109.6	4.3	3415.3	109.7	9.7	3466.8	109.8	3515.6	110.0
31........	3470.9	109.5	4.0	3525.0	109.7	9.4	3576.5	109.7	3625.3	109.7
32........	3580.3	109.4	3.8	3634.4	109.4	9.0	3686.0	109.4	3734.9	109.5
33........	3689.5	109.2	3.6	3743.6	109.2	8.8	3794.9	109.0	3843.8	108.9
34........	3798.3	108.8	3.3	3852.2	108.6	8.4	3903.3	108.4	3951.8	108.0
35........	3906.4	108.1	3.1	3959.8	107.6	8.0	4010.2	106.9	4057.8	106.1

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1992ApJ...394..313E

TABLE 2B

THEORETICAL p-MODE FREQUENCIES OF α CENTAURI B (μHz)

	$l=0$			$l=1$			$l=2$		$l=3$	
n	ν	$\Delta\nu$	$\delta\nu$	ν	$\Delta\nu$	$\delta\nu$	ν	$\Delta\nu$	ν	$\Delta\nu$
10........	2011.9	183.8	18.7	2096.8	183.5	30.7	2175.3	182.2	2247.4	181.3
11........	2193.0	181.1	17.6	2276.9	180.1	29.5	2355.7	180.4	2428.1	180.8
12........	2372.8	179.8	17.1	2456.4	179.5	28.2	2535.0	179.3	2608.3	180.2
13........	2551.5	178.7	16.5	2635.8	179.5	27.5	2714.8	179.7	2788.0	179.7
14........	2730.6	179.0	15.8	2814.4	178.6	26.4	2893.5	178.8	2967.1	179.1
15........	2908.8	178.2	15.3	2992.4	178.0	25.2	3070.9	177.4	3144.6	177.5
16........	3085.5	176.7	14.6	3169.0	176.7	24.4	3247.8	176.9	3321.5	176.9
17........	3261.8	176.3	14.0	3344.9	175.9	23.4	3424.0	176.3	3498.6	177.1
18........	3437.6	175.9	13.6	3521.3	176.3	22.7	3600.6	176.5	3675.6	177.1
19........	3613.7	176.1	13.2	3697.7	176.4	22.1	3777.1	177.1	3853.3	177.6
20........	3790.5	176.8	12.8	3874.5	176.8	21.3	3954.8	177.1	4031.1	177.8
21........	3967.3	176.8	12.4	4051.7	177.2	20.6	4132.3	177.5	4208.9	177.8
22........	4144.3	177.1	12.0	4229.0	177.2	20.0	4310.2	177.9	4387.3	178.4
23........	4321.9	177.6	11.8	4406.7	177.8	19.4	4488.2	178.0	4566.0	178.7
24........	4499.7	177.8	11.5	4584.9	178.2	18.9	4666.8	178.6	4745.0	179.0
25........	4678.0	178.3	11.2	4763.4	178.4	18.3	4845.8	178.9	4924.5	179.5
26........	4856.7	178.7	10.9	4942.4	179.0	17.8	5024.9	179.2	5104.2	179.6
27........	5035.6	178.9	10.7	5121.6	179.2	17.4	5204.6	179.6	5284.1	179.9
28........	5215.0	179.4	10.4	5301.0	179.4	16.9	5384.3	179.8	5464.4	180.3
29........	5394.6	179.6	10.2	5480.9	179.9	16.5	5564.4	180.1	5644.8	180.4
30........	5574.5	179.9	10.0	5660.9	180.0	16.0	5744.8	180.4	5825.5	180.7
31........	5754.7	180.2	9.9	5841.1	180.3	15.6	5925.2	180.4	6006.4	180.8
32........	5934.9	180.3	9.7	6021.6	180.5	15.2	6105.9	180.7	6187.3	180.9
33........	6115.4	180.5	9.5	6202.1	180.5	14.8	6286.7	180.8	6368.3	181.1
34........	6296.1	180.6	9.4	6382.8	180.7	14.5	6467.4	180.8	6549.3	181.0
35........	6476.7	180.6	9.3	6563.5	180.7	14.1	6648.3	180.9	6730.3	181.0

large changes in the internal structure of the models led to very small changes in $\Delta\nu$.

Our estimated value of 108 μHz at $l=0$ is close to the result of Demarque et al. (1986), showing further the lack of sensitivity of $\langle\Delta\nu\rangle$ to internal structure since our models used opacities different from those of Demarque et al. (1986) and different metallicities and helium abundances and included diffusion. Varying the metallicity of the models within the estimated error bars made little difference to $\langle\Delta\nu\rangle$. This is, of course, not unexpected, since $\langle\Delta\nu\rangle$ is proportional to the inverse of the sound crossing time in the star and basically measures the stellar radius. (Note that to first order, the speed of sound depends on the adiabatic exponent γ which is independent of composition and is always close to 5/3 in most of the interior of a Sun-like star.)

The close proximity between our predicted $\langle\Delta\nu\rangle$ and the measurement of $\langle\Delta\nu\rangle = 110$ μHz by Butcher et al. (1990) provides support for the theories of stellar evolution and oscillations used in this work and is encouraging for future theoretical work on this and other Sun-like stars.

The second-order splitting

$$\delta\nu_{n,l} \equiv \nu_{nl} - \nu_{n-1,l+2}$$

is predominantly determined by conditions in the core of α Cen A. The average separation is related to D_0 (from asymptotic theory) by

$$\langle\delta\nu_{n,l}\rangle \approx (4l+6)D_0 \,.$$

The value of D_0 for the Sun is 1.5 μHz. Gelly, Grec, & Fossat (1984) claim a possible identification of $l=0$ and $l=2$ modes on α Cen A that would imply $D_0 = 2.6$ μHz, inconsistent with the trend expected from Christensen-Dalsgaard's (1984) calculations that stars more massive than the Sun should have a smaller D_0. Although the physical (rather than numerical) accuracy of their solutions to the oscillation equations was limited below the 10 μHz level, the average value of $\delta\nu_{n,l}$ between $n=11$ and $n=36$ and $l=0$ for the model of α Cen A calculated by Demarque et al. (1986) is 8.5 μHz ($D_0 = 1.42$ μHz). In our new model of α Cen A, $\langle\delta\nu\rangle_{l=0} = 6.2$ μHz ($D_0 = 1.0$ μHz), the change reflecting differences between the helium abundances of the two models. Because $\delta\nu_{n,l}$ varies by more than a factor of 2 over the observable spectrum, and because we do not know the amplitudes of each mode, it is not clear what value will come from a Fourier transform of the observed spectrum. Our model has a higher helium abundance and hence a higher mean molecular weight, higher central temperature, and central concentration. This will lead to a decrease in the speed of sound in the interior, reducing D_0.

3.2. *α Centauri B*

The value of $\langle\Delta\nu\rangle$ for α Cen B was estimated in this work to be 179 μHz at $l=0$, larger than $\langle\Delta\nu\rangle$ for α Cen A because of its smaller radius. Again changes in the stellar model by varying Z within its error bars caused only small changes in $\langle\Delta\nu\rangle$. The mixing length used was $\alpha = 1.251$. For α Cen B, helium diffusion is negligible in the convective envelope and therefore does not affect the radius of the model.

Although there are no known claimed detections of nonradial oscillations on this star, it represents a good target for such observations in view of its brightness, the potential to observe it simultaneously with α Cen A, and the fact that it differs significantly from both its companion and the Sun. The larger value of $\langle\Delta\nu\rangle$ also means that less observing time would be needed to resolve the frequency spacing.

4. CONCLUSION

An important result of this work is the age estimate of α Cen. The strong evidence for the closeness between the ages of α Cen

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1992ApJ...394..313E

(4.6 ± 0.4 Gyr) and the Sun (4.5 ± 0.03 Gyr; Guenther 1989), together with their proximity in space, suggests at first sight that the two systems may have formed in similar parts of the Galaxy and have perhaps until recently been gravitationally bound. Furenlid and Meylan (1990) point out, however, that because the kinematical properties of the two systems are different with a relative drift in the epicyclic motion of 0.7 kpc Gyr^{-1} year (Flannery & Ayres 1978), and because of the differences in chemical composition, it is more likely that they formed in separate parts of the Galaxy. The fact that the age of α Cen is the same as that of the Sun even though their metallicities differ is a further indication that the two stars originated in regions with different histories of nucleosynthesis (Audouze & Tinsley 1976; Twarog 1980).

Another important result is the prediction of the initial helium abundance of α Cen. A value of $Y = 0.30$ implies that He is overabundant in this star compared to the Sun. This helium abundance is not inconsistent with other astronomical evidence. For example, Perrin et al. (1977) have studied the state of evolution of 138 stars in the solar neighborhood, finding that the helium content appears to vary in step with the metal content as $\Delta Y/\Delta Z = r$, where $r = 3$ and ΔY and ΔZ denote the differences between Y and Z in the model and in the solar value (r is known as the Galactic enrichment factor). That a relation such as this should hold has been foreseen theoretically by Reeves & Johns (1976) and observationally by Peimbert (1975), while Audouze & Tinsley (1976) propose that $r = 3$, pointing out that this result is predicted by stellar nucleosynthesis. For α Cen, keeping the heavy-element mixture unchanged but varying Z within the uncertainties (from $Z = 0.023$ to 0.030) yields the helium abundances $Y = 0.295$ and 0.305, respectively. When compared to the solar Y near 0.28 obtained with the LAOL opacities and the Grevesse (1984) solar mixture $Z = 0.0194$, we find that r is in the range 2.3–3.8.

To summarize, our main results are as follows.

1. We have constructed the most detailed models so far for α Cen A and B, using the spectroscopically observed abundances of Furenlid & Meylan (1990), and LAOL opacities specifically constructed for this mixture. In addition, models including the effects of the diffusion of helium in α Cen A's interior have been constructed.

2. Although the effect of helium diffusion is small in α Cen A, it is slightly larger than in the Sun because of the larger mass and therefore shallower convection zone of α Cen A. The effect of helium diffusion is in the right direction to explain the small value of α needed to match the observed radius of α Cen A when diffusion is ignored. However, the effect of helium diffusion on the low-l p-mode frequencies is too small to be detectable. No appreciable helium diffusion has taken place in α Cen B.

3. Keeping the heavy-element mixture unchanged but varying Z within the uncertainties (from $Z = 0.023$ to 0.030) yields limits to the helium abundance of $Y = 0.295$ and 0.305, respectively. When compared to the solar value of $Y \approx 0.28$ obtained with the LAOL opacities and the Grevesse solar mixture $Z = 0.0194$, this helium enrichment corresponds to a galactic enrichment ratio of $(\Delta Y/\Delta Z)$ in the range 2.3–3.8, which is compatible with other astronomical evidence.

4. The derived age of α Cen is 4.6 ± 0.4 Gyr, very similar to the solar age of 4.5 Gyr.

5. The first-order p-mode splitting $\langle \Delta\nu \rangle$ at $l = 0$ for α Cen A was found to be 108 μHz, in agreement with the previous study by Demarque et al. (1986). This is no surprise since $\langle \Delta\nu \rangle$ depends primarily on the stellar radius and is nearly independent of chemical composition or internal structure.

6. The value of $\langle \Delta\nu \rangle$ for α Cen B was found to be 179 μHz, also at $l = 0$.

7. Observations of the mean second-order splitting of p-modes D_0 in both α Cen A and B would probe the structure of the deep interior of the two stars. This would represent a stringent test of stellar evolution theory near the main-sequence turnoff, upon which rests many stellar age determinations.

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