I. INTRODUCTION

The nearby triple system of α Centauri (G2 V + Kl V + dMe) provides an excellent opportunity for the comparison of stellar structure models against stars whose gross properties—mass, luminosity, temperature, chemical composition, rotation, etc.—can be reliably determined. These properties are (or can be) reliably established for the A and B components of the widely separated, i.e., noninteracting, double system. Unfortunately, the distant, active dMe component Proxima (see Haisch et al. 1977) cannot be included in our analysis because of its faintness and lack of a reliable orbit. The basic intent of this paper is similar to previous unsuccessful attempts to model the visual binary stars in the Hyades cluster (see Iben 1967 and references therein). Given two points on an H-R diagram plus the stellar masses, we seek to determine a consistent evolutionary history for the double star. Unlike the Hyades cluster, α Cen will be shown to be somewhat evolved.

The paper is divided as follows: in § II we discuss observational material available in the literature relevant to the evolutionary status of α Cen; in § III we describe theoretical evolutionary sequences appropriate for the A and B components for two values of metallicity $Z = 0.02$ and 0.04, and a reference solar model ($Z = 0.02$); in § IV we present a partial reanalysis of the observed abundances, based on the equivalent measurements of French and Powell (1971), which provide a consistency check on the evolutionary models; finally, in § V we discuss and apply our results in a more general context.

II. PHYSICAL PARAMETERS OF THE α CENTAURI SYSTEM

a) Astrometric Properties

In this section we discuss, and in some cases reanalyze, available data in order to derive accurate estimates for the stellar masses, luminosities, temperatures, and chemical composition of α Cen. The astrometric properties of the binary are quite reliable because they are based on a well observed visual orbit, on a large parallax, and on additional information available from measured radial velocity variations. Several orbital solutions for the visual binary exist in the literature (e.g., van de Kamp 1958; Gasteyer 1966); here we adopt the values recently derived by Kamper and Wesselink (1977), as listed in Table 1. The masses of the A and B components are 1.11 and 0.92 $M_\odot$, respectively, and the binary distance is 1.34 pc. Because the period and semimajor axis are 1.34 pc. Because the period and semimajor axis are well known, the total and individual masses should be accurate to about 3%, corresponding to the possible 1% error in parallax, while the uncertainty of the mass ratio is somewhat smaller, about 2%.

| TABLE 1

Astrometric Properties of α Centauri* |
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
</tr>
<tr>
<td>Semimajor axis</td>
</tr>
<tr>
<td>Parallax</td>
</tr>
<tr>
<td>$M_\odot/M_\odot$</td>
</tr>
<tr>
<td>$(M_a + M_b)/M_\odot$</td>
</tr>
<tr>
<td>$M_a/M_\odot, M_b/M_\odot$</td>
</tr>
</tbody>
</table>

* Kamper and Wesselink 1977.
b) Photometry, Luminosities and Colors

Alpha Centauri A and B have been measured photometrically in a variety of broad-band systems including the standard UBV (Johnson 1956; Cousins and Lagerweij 1967; Eggen [see Thomas et al. 1973]), the long-wave RIKLMN (Kron, Gascoigne, and White 1957; Thomas, Hyland, and Robinson 1973; Alexander and Branch 1973), and the six-color UViBGRI (Powell and French 1970). Narrow-band photometric indices are also available (Willstrop 1965; Rodgers [see Ayres et al. 1976]). Table 2 summarizes the photometric data to be discussed in this subsection.

The relative luminosities of the A and B components can be estimated to sufficient accuracy according to the following identity:

\[ \frac{L_A^c}{L_B^c} = L_c^A \left( \sum \frac{L_{\lambda}^B}{L_{\lambda}^A} \right)^{-1} \],

(1)

with

\[ L^c = \sum L_{\lambda}^A \].

We have chosen to work relative to the apparent visual magnitude \( V \); hence the expression in square brackets is a differential bolometric correction (B.C.). The sum is taken over the available photometry. A similar expression can be written for \( L^c_A/L^c_0 \), provided that we can convert measured solar irradiances (e.g., Labs and Neckel 1970) into stellar absolute magnitudes.

i) The Apparent and Absolute Visual Magnitudes of the Sun, α Centauri A, and α Centauri B

In order to evaluate the leading term on the right-hand side of equation (1), we must determine the absolute visual magnitudes \( M_\nu \) of the Sun, α Cen A, and α Cen B. These are obtained from apparent magnitudes \( V \) and measured distances. However, the Sun is some 27 mag brighter than standard photometric comparison standards (e.g., \( \alpha \) Lyr); therefore \( V_0 \) cannot be determined directly. On the other hand, the absolute irradiance of the solar spectrum at the Earth is known very accurately (e.g., Labs and Neckel 1970). In fact, we can estimate the apparent visual luminosity of the Sun, \( F_\nu^c \), indirectly by folding a numerical representation of the \( V \)-filter response function into the solar irradiance curve (e.g., Labs 1975). If we also know the absolute flux, in the same units, corresponding to the zero-point of the stellar magnitude scale (i.e., \( V = 0 \)), we can convert \( F_\nu^c \) into magnitudes to obtain \( V_\nu \).

We determine the \( V = 0 \) absolute flux using Vega as a transfer standard. To calibrate \( F_\nu^c_{\alpha Lyr} \) in absolute flux units, we adopt the Hayes and Latham (1975) monochromatic calibration of Vega at 5556 Å, and apply the synthetic \( V \)-filter response described by Labs (1975) to the Schild, Peterson, and Oke (1971) energy distribution. Finally, we convert \( F_\nu^c_{\alpha Lyr} \) to \( F_\nu^c = 3.63 \times 10^{-9} \pm 3\% \) ergs cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\) (at the Earth).

The uncertainty in the zero-point absolute flux arises equally from the Hayes and Latham monochromatic calibration and \( F_\nu^c_{\alpha Lyr} \).

Applying the \( V \)-filter response to the solar irradiances tabulated by Beckers, Bridges, and Gilliam (1976; Labs and Neckel calibration), and converting \( F_\nu^c \) to the stellar magnitude scale, we obtain,

\[ V_\nu = -26.76 \pm 0.03 \text{ mag} \],

which implies

\[ M_\nu^0 = +4.81 \pm 0.03 \text{ mag} \],


Combining the solar estimate with the values of \( M_\nu \) for α Cen A and B in Table 2, gives,

\[ \frac{L_A^c}{L_B^c} \sim 1.53 \pm 4\% \],

\[ \frac{L_B^c}{L_\nu^0} \sim 0.44 \pm 4\% \].

### Table 2

<table>
<thead>
<tr>
<th>Star</th>
<th>( V )</th>
<th>( B - V ) [( T_{eff}, \delta(\text{B.C.}) )]</th>
<th>( V - I ) [( T_{eff}, \delta(\text{B.C.}) )]</th>
<th>( M_\nu ) [( \delta(\text{B.C.}) )]</th>
<th>( L/L_\nu^0 ) [( \delta(\text{B.C.}) )]</th>
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</thead>
<tbody>
<tr>
<td>Sun</td>
<td>-26.76(^a)</td>
<td>0.65(^a) 0.87(^b)</td>
<td>4.81 (\pm 0.03)</td>
<td>1.00 (\pm 0.00)</td>
<td></td>
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<tr>
<td>α Cen B</td>
<td></td>
<td>0.88(^a), 0.91(^d)</td>
<td>0.72(^a)</td>
<td>0.91 (\pm 0.02)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.33(^a,e)</td>
<td>0.02 (\pm 0.02)</td>
<td>1.03(^e) (\pm 0.02)</td>
<td>5.69 (\pm 0.02)</td>
<td>0.47 (\pm 4%)</td>
</tr>
<tr>
<td>α Cen A</td>
<td>-0.01(^a), +0.01(^b)</td>
<td>0.68(^a), 0.69(^d)</td>
<td>0.69(^e) (\pm 0.02)</td>
<td>4.35 (\pm 0.02)</td>
<td>1.51 (\pm 4%)</td>
</tr>
</tbody>
</table>

\(^a\) Using unrounded values for \( L_A, L_\nu \).

**Notes.**—\(^a\) Adopted for this work. \(^b\) Thomas et al. 1973. \(^c\) Cousins and Lagerweij 1967. \(^d\) This work, based on Rodgers (see Ayres et al. 1976) photometry. \(^e\) This work, based on Willstrop 1965 photometry. \(^f\) From Johnson 1966, as scaled to \( (B - V)_0, (V - I)_0 \). \(^g\) Alexander and Branch 1973 (uncorrected).
We estimate differential bolometric corrections for α Cen A and B using (B.C.)-(color) relationships as well as by applying the information available in broad-band photometry via equation (1). We normalized the Johnson (1966) B.C.-(B-V) and B.C.-(V-I) relationships to the solar colors listed in Table 2, and obtained the \( T_{\text{eff}} \), \( \delta \) (B.C.) pairs for α Cen A and B listed in Table 2. The corresponding values of \( L^*/L^0 \) are plotted versus log \( T_{\text{eff}} \) in Figure 1. Notice that the results based on \( (V-I) \) (open squares) and \( (B-V) \) (open triangles) differ significantly. This would be expected if α Cen A and B were ultraviolet-deficient relative to standard color-color diagrams (French and Powell 1971; Alexander and Branch 1973).

Finally we have applied the differential B.C. scheme represented by the brackets of equation (1) using the available broad- and narrow-band photometric indices. We estimated \( \delta \) (B.C.) corresponding to \( L^*/L^0 \) using the narrow-band observations of α Cen A by Rodgers, and analogous measurements for the solar energy distribution simulated by integrating the appropriate bands in the Beckers, Bridges, and Gilliam (1976) high-resolution irradiance Atlas. Following Thomas et al. (1973), we assumed that the α Cen A and solar energy distributions longward of 0.6 μm are identical, as the \( V-R \) and \( V-I \) colors cited by Thomas et al. would seem to suggest. \( L^*/L^0 \) was determined solely from the available broad-band filter measurements. These approaches should be entirely adequate for our purposes here, especially given the uncertainty in \( M_0 \) and the lack of higher-resolution, more-homogeneous sets of irradiance data for the α Cen system. The inferred stellar luminosities (relative to the Sun) are listed in Table 2 and plotted as shaded rectangles in Figure 1. We point out the relatively good agreement between the differential bolometric corrections obtained from the B.C.-\( (V-I) \) relationship and those based on the entire body of available broad-band photometry.

c) Chemical Composition

French and Powell (1971) have studied abundance distributions in α Cen A and B using differential curve-of-growth techniques applied to moderately high dispersion spectrograms (2.4 Å mm\(^{-1}\)). Their results suggest that both components have similar compositions, and that the system is slightly metal-rich compared with the Sun, perhaps by as much as a factor of 2 (see, e.g., Ayres et al. 1976).

As a simple check, we compared the equivalent widths of about 150 weak lines from iron-peak elements in French and Powell’s lists with the corresponding features in the Beckers et al. integrated sunlight Atlas. We estimated the solar equivalent widths by fitting Gaussians to isolated, clean lines in regions of well-defined continuum level. All features measured were less than 40 mÅ in equivalent width, and hence should be relatively insensitive to uncertainties in the non-thermal broadening. We found that the α Cen A equivalent widths were consistent with solar abundances to within ±0.1 dex, if α Cen A is nearly the same temperature as the Sun. This result is difficult to reconcile with the evolutionary models of § III, which suggest that the α Cen system must be metal-rich compared with the Sun by a factor of ~2. However, our result is somewhat suspect since we have not measured the solar equivalent widths at the lower dispersion of the α Cen measurements, nor by a similar technique. In addition, French and Powell include relatively little information on the important CNO abundances. The latter are, of course, substantial contributors to the stellar metallicity Z. Because of the uncertainty in the effective temperature and metallicity in α Cen in § IV we will present an alternative analysis.
of metallicity, based on the equivalent-width measurements of French and Powell and the evolutionary tracks described below, which does support the conclusion that metals are enhanced in the system.

III. STELLAR EVOLUTIONARY MODELS

Evolutionary models for \( \alpha \) Cen A, \( \alpha \) Cen B, and the Sun were constructed using a modified version of the code originally developed by Eggleton (1971) with the equation of state as described by Eggleton, Faulkner, and Flannery (1973). The standard Eggleton code treats convective mixing in a diffusion approximation, evaluates hydrogen burning with most nuclear species assumed to be present in equilibrium abundance with respect to \( ^1\text{H} \) and \( ^4\text{He} \), and follows the time variation of only one dominant nuclear species. Here we evaluate hydrogen burning from a network of nuclear reactions among \( ^1\text{H}, ^3\text{He}, ^4\text{He}, ^{12}\text{C}, ^{14}\text{N}, \) and \( ^{16}\text{O} \) based on the recently published reactions rates of Fowler, Caughlan, and Zimmerman (1975), and we treat convective mixing by standard techniques. The initial composition was specified by the standard parameters \( X, Y, Z \), and the ratios \( Z_{\text{CNO}}/Z = 0.75, ^{12}\text{C}/^{14}\text{N}, ^{16}\text{O} = 0.16:0.11:0.73, \) and \( ^3\text{He}/^{4}\text{He} = 3 \times 10^{-5} \), where all ratios are by weight (see Cameron 1973). Radiative opacities are evaluated by linear interpolation in \( \log \rho, \log T, \) and \( X \) from the values tabulated by Cox and Stewart (1969) for \( Z = 0.02, 0.04 \). Although our knowledge of the detailed abundances of metals in the Sun and the theoretical representation of radiative opacities have changed since 1969, the Cox and Stewart tables should be entirely adequate for assessing the effects of relative variations in metallicity (Cox 1976).

Even more so than for members of star clusters, it is reasonable to assume that stars in a binary formed simultaneously and with the same chemical composition. Our goal is to construct models for both components of \( \alpha \) Cen such that they satisfy the observed luminosities and temperatures at the same age. In the initial model we must specify the mass, mixing length \( \alpha \), and two of the three composition parameters \( X, Y, Z \) (as well as the distribution of the reacting constituents as described above).

Rather than attempt to determine the age, mixing length, and two composition parameters by fitting the two luminosities and temperatures of \( \alpha \) Cen (see Saio and Shibata 1974), our initial approach is to construct models assuming that both the helium abundance and mixing length for \( \alpha \) Cen A, B are similar to those for the Sun. Calibration of \( \alpha, Y \) for the Sun is achieved in the standard fashion by evolving the solar model for \( 4.7 \times 10^9 \) years to match the actual luminosity and radius, \( L_\odot \) and \( R_\odot \), which are sensitive primarily to the helium abundance and mixing length, respectively. Although the true solar metallicity is apparently somewhat lower, we used \( Z = 0.02 \) for our solar model (primarily because opacity tables were available). Having calibrated the Sun for \( Z = 0.02 \), we regard
our models with \( Z = 0.04 \) as representing stars of twice solar metallicity. For the Sun, we find \((\alpha, Y) = (1.33, 0.256)\). By comparison, recent models of the Sun with \( Z = 0.02 \) by Christensen-Dalsgaard and Gough (1976) and Iben and Mahaffy (1976) find \((\alpha, Y) = (1.10, 0.245), (1.01, 0.236)\), respectively. Christensen-Dalsgaard and Gough used the usual Eggleton code with conversion of one nuclear species, hydrogen, and reaction rates evaluated in equilibrium from published rates of an older vintage than those used here. The Iben code is considerably different, especially in the treatment of the atmosphere, and in evaluating opacities from a polynomial fit to published tables. Our model is somewhat different from other models, but its intent is only to serve as a calibration against which variations can be measured.

The evolutionary results are contained in a series of five sequences, one for the Sun and two for each component of \( \alpha \) Cen with \( Z = 0.02, 0.04 \). Each series begins with a model high on the Hayashi track with central temperatures so low that negligible nuclear burning occurs. The contraction phase to the zero-age main sequence (ZAMS) required about 30-40 models for each series, during which time the nuclear species begin to equilibrate. Only about 20 additional models were required to follow the evolution during core hydrogen burning to luminosities well above the observed luminosity of the star. Figure 1 plots the sequences in an H-R diagram, but for clarity the contraction phases have been omitted. Tick marks along each track represent intervals of 2 billion \((10^9)\) years. In the right-hand portion of the figure, two vectors indicate the displacement of ZAMS models appropriate to a variation in \( Y \) of 0.02, and in mass of \( \Delta M/M = 0.02 \). As discussed in the previous section, the shaded regions correspond to the "observed" positions of \( \alpha \) Cen A, B, for which the luminosities relative to the Sun are known to about \( \pm 4\% \), but the temperatures are less precisely determined. The square boxes, representing temperatures derived from \( V-I \) colors, are probably more reliable than the triangles, which are based on \( B-V \) colors, because the latter are more susceptible to line blanketing effects.

Straightforward considerations of stellar evolution during main-sequence core hydrogen burning allow one to estimate the age of \( \alpha \) Cen. The models determine both the slope \( \beta \) of the (ZAMS) mass-luminosity relation, \( L \propto M^\beta \), and the rate of change in luminosity, \( d \log L/dt \), which, as indicated in Figure 2, is nearly constant during the main-sequence phases. These quantities, together with other properties of the models on the ZAMS and at \( 6 \times 10^9 \) years, are listed in Table 3. The observational results of the previous section indicate that the ratios of mass and luminosity for \( \alpha \) Cen A relative to B are \( 1.21 \pm 0.01 \), and \( 3.18 \pm 0.1 \), respectively. Thus the observed slope of the mass-luminosity law for \( \alpha \) Cen is \( 6.1 \pm 0.3 \), so that \( \alpha \) Cen A is approximately \( 30\% \) brighter, relative to B, than would be expected on the ZAMS, \( \beta \approx 4.7 \). Evolution beyond the ZAMS readily accounts for the enhanced ratio. In terms of coefficients tabulated in Table 3 the age \( t \) can be expressed as

\[
t = \log \left( \frac{L_A}{L_B} \right) - \beta \log \left( \frac{M_A}{M_B} \right) - \left( \frac{d \log L}{dt} \right)_A - \left( \frac{d \log L}{dt} \right)_B, \tag{2}
\]

which yields estimates of \((4.1 \pm 0.9)\) and \((6.0 \pm 1.1) \times 10^9 \) years for \( Z = 0.02 \) and 0.04, respectively. Thus, for consistent theoretical models, the observed ratios of luminosity and mass lead one to predict an evolutionary age for \( \alpha \) Cen comparable with that of the Sun.

Actual specification of the detailed properties of the model requires that we compare the absolute values of stellar parameters, not just their relative variation. For a fixed mass and metallicity, the absolute luminosity of the theoretical model is a function only of age and
helium content; variations of the mixing length produce only small changes in luminosity. As indicated in Figure 1, the variation of ZAMS luminosity is approximately \( d \log L/dY = 2.2 \), independent of mass or metallicity. The luminosity as a function of age can be expressed as

\[
\log L(Y, t) = \log L(Y_0, \text{ZAMS}) + (d \log L/dY) t \Delta Y + (d \log L/dt) t,
\]

(3)

If we define the quantity \( \Delta Y = \log (L_{\text{obs}}/L_{\text{ZAMS}}) \), then we can use equation (3) to produce two equations, one for each component of α Cen, in \( \Delta Y \) and \( t \). For \( Z = 0.02 \), \( \Delta Y = 0.247 \), \( \Delta Y = -0.003 \), which implies \( t = 4.4 \) billion years, and \( \Delta Y = -0.05 \), i.e., \( Y = 0.206 \). The near coincidence in luminosity of α Cen B and the ZAMS models for \( Z = 0.02 \), coupled with the necessity that some evolution must occur to produce the non-ZAMS luminosity ratio, requires that \( Y \) must be lowered relative to its solar value in order that both model luminosities can be below the observed values before evolutionary brightening occurs. To accommodate models of solar metallicity requires a helium abundance which is even slightly below the minimum predicted primordial helium abundance. (See, for example, the discussion in Trimble 1975 which gives \( Y = 0.229 + 0.094 \alpha/\rho_\odot \).) The initially lower luminosity of the more metal rich models (at the solar \( Y \)) can accommodate the necessary evolution without an appreciable variation of helium abundance. For \( Z = 0.04 \), \( \Delta Y = 0.230 \), \( \Delta Y = 0.098 \), which results in \( t = 6.3 \times 10^9 \) years and \( \Delta Y = -0.01 \). As is apparent from Figure 1, the models with higher metallicity are also in better accord with the "observed" (but see § II) temperatures of the stars. This is not necessarily a compelling argument, since a variation in the mixing-length parameter can also readily produce the temperature shift. For example, the model of component B with \( M/M_\odot = 0.92 \), \( Z = 0.02 \), can be shifted from its ZAMS location \( \log T_e = 3.73 \) with \( \alpha = 1.33 \), to a temperature \( \log T_e = 3.70 \) by reducing \( \alpha \) to 0.65. This 360 K shift in temperature occurs while the luminosity of the model decreases only 2% (from 0.47 to 0.46 \( L_\odot \)). However, to the extent that the mixing length can be regarded as being the same in α Cen and the Sun, the agreement of the metal rich model with the observed location of the system in the H-R diagram is quite good, and is consistent with the enhancement of metals for α Cen found by French and Powell.

Figure 2 illustrates the variation in luminosity of the models with time. These tracks are based on models having a solar helium abundance. According to the discussion of the previous paragraph, a change of \( \Delta Y \) = -0.05 for the \( Z = 0.02 \) models would shift each track vertically by \( \Delta \log L = -0.11 \), and result in an intersection of the observed luminosity at \( t \approx 4.4 \times 10^9 \) years. Satisfactory agreement for \( Z = 0.04 \) requires only a small shift of \( \Delta \log L = -0.02 \) to produce an age of \( t \approx 6.3 \times 10^9 \) years. The combined agreement in both luminosity and temperature for the \( Z = 0.04 \) models, coupled with the observed enhancement of metals in α Cen, suggests that the system is 6 ± 1 \( \times 10^9 \) years in age, twice solar in metals, and essentially the same in helium content as the Sun.

### IV. MODEL ATMOSPHERES

In this section we establish additional constraints on acceptable metallicities and effective temperatures for α Cen A and B using measured equivalent widths of temperature sensitive Ca i lines.

If we make the reasonable assumption that the chemical compositions of α Cen A and B are identical, we can determine a range of atmospheric models—designated by effective temperature pairs \((T_{\text{eff}}^A, T_{\text{eff}}^B)\)—which consistently reproduce a given atomic spectrum (e.g., Fe i, Ca i) in both stars. We can then compare \((T_{\text{eff}}^A, T_{\text{eff}}^B)\) as a function of the derived abundance, say [Ca/H], with the evolutionary tracks for \((T_{\text{eff}}^A, T_{\text{eff}}^B)\). The latter depend on chemical composition \( Z \) and age \( t \). Ideally we would find only a small region in the \((T_{\text{eff}}^A, T_{\text{eff}}^B)\)-diagram which is consistent with both the model atmospheres study of the equivalent widths and the evolutionary models.

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a) A Grid of Model Atmospheres

To produce such a diagram, we first construct sets of atmospheric models appropriate to α Cen A and B. The spectrum synthesis tests here are envisioned primarily as consistency checks on the system evolution described in § III. Therefore, we adopt the simple expedient of scaled solar photosphere models. The initial solar T(Teff) model used here is that proposed recently by Allen (1976, as communicated by R. L. Kurucz; see also Avrett 1977), based on the center-limb behavior of optical and infrared continuum intensities. The solar T(τ) relation is scaled to a different effective temperature according to the ratio T_{eff}^*/T_{eff}^0. To obtain densities from T^*(τ), we assume hydrostatic equilibrium, solar abundances for helium, and the important electron donors and LTE for neutral hydrogen and H⁻. This approach should be entirely adequate over the relatively narrow range of surface gravity and effective temperature considered here (see, e.g., Carbon and Gingerich 1969).

We constructed six models for each star in steps of 100 K: T_{eff}^A = 5500–6000 K with log g^A = 4.22–4.37 cm s⁻², and T_{eff}^B = 5000–5500 K with log g^B = 4.48–4.65 cm s⁻². The surface gravities corresponding to each T_{eff}^* are based on the measured stellar masses and the bolometric luminosities cited in § II.

b) Equivalent-Width Data (Ca i)

French and Powell (1971) have published lists of weak line equivalent widths for α Cen A and B based on moderately high dispersion spectrograms. In the analysis here, we restrict our attention to the Ca i spectrum, partly for computational simplicity, but mostly because the minority species lines are particularly temperature sensitive (I.P. = 6.11 eV versus 7.87 eV for Fe).

Of course, a more complete survey of α Cen A and B would utilize the spectra of several abundant atoms and ions (e.g., § II above). However, the current lack of high-dispersion profile data and uncertainties concerning nonthermal broadening in the photospheres of α Cen A and B argue against a more comprehensive study here.

French and Powell (1971) list eight pairs of Ca i equivalent widths common to α Cen A and B. These are given in Table 4, together with estimates of the corresponding solar equivalent widths obtained from the integrated sunlight Atlas of Beckers, Bridges, and Gilliam (1976). Also listed in Table 4 are the [Ca/Fe] abundance ratios (logarithmic units) established for each line by French and Powell using differential curves of growth. The final columns of Table 4 compare the mean [Ca/Fe] ratios for the sample of eight line pairs with the values obtained by French and Powell for their entire α Cen A and B Ca i lists (34 and 30 lines, respectively). [Ca/H] ratios relative to the Sun, based on the values of [Fe/H] cited by French and Powell, are also given.

For each Ca i line pair and atmospheric model, we determined the [Ca/H] abundance ratios required to reproduce the measured equivalent widths, using the LTE spectrum synthesis approach described by Ayres (1977). In all cases, a depth-independent classical microturbulence of 2 km s⁻¹ was assumed. No account was taken of the potential effect of enhanced metallicity on the atmospheric structure of the grid models, because the optical depth scales of the Ca i lines and H⁻ background continuum both depend linearly on the electron density. Hence the computed equivalent widths should be relatively unaffected by changes in the electron donor abundances. The inferred [Ca/H] ratios were found to increase systematically with increasing model effective temperature for both α Cen A and B as would be expected according to the enhanced ionization of neutral calcium.

The final results of the model atmospheres-equivalent widths comparison are illustrated in Figure 3. The large open parallelogram represents the envelope of (T_{eff}^A, T_{eff}^B) trajectories determined for the individual line pairs of the spectrum sample. (A particular “trajectory” represents the locus of (T_{eff}^A, T_{eff}^B) values which reproduce the measured equivalent width pair (W^A, W^B) of a given Ca i line in α Cen A and B

<table>
<thead>
<tr>
<th>λ (Å)</th>
<th>W^A (mÅ)</th>
<th>W^B (mÅ)</th>
<th>W^B (mÅ)</th>
<th>[Ca/Fe]^A</th>
<th>[Ca/Fe]^B</th>
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</thead>
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<tr>
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<td>-0.20</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

* French and Powell 1971 Appendix.
† French and Powell 1971 Table 3.
‡ French and Powell 1971 Table 2.
for the same value of [Ca/H]. The A5513 line pair was omitted from this and later comparisons because its results differed significantly from those of the other seven line pairs. The curve bisecting the open parallelogram is the \( (T_{\text{eff}}^A, T_{\text{eff}}^B) \) trajectory obtained by requiring that the average [Ca/H] abundance ratio based on the seven remaining line pairs be the same as in \( \alpha \) Cen A and B. Labels on the “average abundance” trajectory designate the particular values of the abundance ratios.

The uncertainty in these differential abundance estimates are, unfortunately, relatively large—at least \( \pm 0.15 \) dex. They arise primarily from uncertainties in the measured equivalent widths and the magnitude of nonthermal broadening in the photospheres of \( \alpha \) Cen A and B. However, the trend of increasing [Ca/H] with increasing \( T_{\text{eff}} \) is clearly a property of the model atmospheres owing to the pronounced temperature sensitivity of the LTE Ca-Ca\(^+\) ionization equilibrium.

The curves in Figure 3 labeled \( Z = 0.02 \) and \( Z = 0.04 \) represent composition-dependent system evolution tracks for \( \alpha \) Cen A and B (§ III above). The tick marks on these curves designate age in steps of \( 2 \times 10^5 \) years. Note the important result that the behavior of the system evolution tracks is opposite to that of the model atmospheres—equivalent width comparison: the \( (T_{\text{eff}}^A, T_{\text{eff}}^B) \) range occupied by the system for a solar-type age \( (t \sim 5 \) billion years) decreases with increasing metallicity. It is clear from this figure that, despite the rather large uncertainties in determining [Ca/H], the solar composition \( (Z = 0.02) \) tracks are probably too hot to be consistent with the measured equivalent widths, whereas the twice solar metallicity tracks are much more nearly consistent. In fact, the intersection of the stellar evolution and stellar atmospheres comparisons suggests \( Z \geq 0.03 \), in qualitative agreement with French and Powell’s differential curve-of-growth analysis, if the general enhancement of the other metals follows that of calcium (see, e.g., Ayres et al. 1976).

V. DISCUSSION

Using standard assumptions and techniques, we have constructed an evolutionary model for \( \alpha \) Centauri which is consistent with the observed properties of the binary. That the system is partially evolved follows directly from the observed steepness of the mass-luminosity relation: component A is 30% brighter with respect to B than would be expected for an unevolved system. The helium abundance and age can be determined by fitting the absolute luminosities of the stars. We did this for two metallicities \( Z = 0.02 \) and 0.04 with respect to a solar calibration model \( (Z = 0.02) \). Three pieces of evidence favor the higher metallicity. First, French and Powell (1971) directly measure the abundances of A and B to be up to twice solar, but, as discussed in § IV, systematic errors, particularly in the microturbulent broadening, might alter those results. Second, the evolutionary models with enhanced metallicity agree better with estimated effective temperatures for \( \alpha \) Cen A and B, but both sides of this comparison are uncertain. On the one hand, temperatures derived from color indices are suspect owing to line blanketing. In particular, we feel that the higher temperatures implied by the \( V - I \) colors are more reliable than temperatures derived from \( B - V \). On the other hand, the temperatures of the evolutionary models are sensitive to the mixing-length parameter. We have arbitrarily (but perhaps reasonably) forced the mixing length for both components of \( \alpha \) Cen to be the same as for the solar calibration model. Third, if we use models with solar metallicity, then to match the observed absolute luminosity requires that the helium abundance be substantially lower than for the solar model, \( Y_{\odot} = 0.206 \) compared to \( Y_{\odot} = 0.256 \). The low value is even less than the minimum primordial helium abundance predicted from nucleosynthesis in the big bang (see Trimble 1975). Taken together, these independent arguments all favor stellar structure models enhanced in metals with respect to the Sun. Clearly, it is desirable to resolve this issue with abundance analyses based on spectra taken with the highest possible dispersion and compared to integrated sunlight observations degraded to the same resolution. For the evolutionary sequence with twice solar metals,
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the age of α Cen is $6 \times 10^8$ years and the helium abundance, $Y = 0.246$, is essentially solar.

a) α Centauri A and B as Solar Analogs

Because so much information is available for α Cen, and because the binary is so bright, the system is well suited for the application of solar-type observational and analytical techniques. An example is the study of chromospheric and coronal properties. These are revealed typically by relatively weak emission cores in strong visible and near-ultraviolet Fraunhofer lines, or by faint (relative to the optical continuum) EUV emission features. Recent studies have suggested that the lower chromosphere of α Cen A is qualitatively similar to the solar case, at least based on the similarity of Ca II, Mg II, and Lc core emission strengths (Boesgaard and Hagen 1974; Ayres et al. 1976; Dupree 1977). However, no detection of coronal or transition-region emission lines in the EUV spectrum of α Cen has yet been reported. If α Cen A indeed possesses a corona unlike the solar example, but similar chromospheric properties, these characteristics are potentially useful in distinguishing between competing theories of chromosphere-corona heating and energy balance. This comparison is particularly useful because α Cen A and the Sun are so similar in terms of mass, age, surface gravity, and effective temperature.

We also point out the opportunity for very detailed comparisons of abundance distributions in the Sun and α Cen, owing to the suitability of the binary system for high-dispersion optical and infrared spectroscopy. Such studies might shed some light on the properties of the perhaps quite different samples of the interstellar medium from which our Sun and the α Cen system separately condensed. Studies of the rotation-vibration bands of carbon monoxide (CO) would be especially useful in this regard. Relative intensities of weak, unsaturated lines in the 2.4 μm first overtone bands should accurately reflect the atmospheric temperatures of the two stars, while the absolute line strengths should indicate unambiguously whether $Z_{\text{Cen}}^{\alpha,b}$ is enhanced relative to the solar value. Furthermore, observations of isotopic lines such as from $^{12}$C$^{16}$O and $^{12}$C$^{18}$O in the 5 μm fundamental bands might provide insight into the nuclear history of the stellar material. These measurements would complement recent studies of light element abundances in α Cen [e.g., Boesgaard and Hagen 1974 (Li); Dravins and Hutqvist 1977 (Be)].

b) The Relative Galactic Motion of α Centauri and the Sun

The components of α Cen are similar to the Sun not only in terms of mass and age, but also in terms of galactic orbits. In Table 5 we list the galactic motion of α Cen and the Sun derived from the observed space velocity of the binary, $V_r = -24$ km s$^{-1}$ (Allen 1973); $\mu_{\alpha} = -0.4904$ s yr$^{-1}$, $\mu_{\delta} = +0.712$ yr$^{-1}$ (SAO Star Catalog 1966), and the solar velocity with respect to the dynamical local standard of rest (Mihalas 1968). Following Mihalas (chap. 13), we have determined the inner, $R_1$, and outer, $R_2$, radii appropriate to epicyclic motion, and the scale height $Z$ of the motion perpendicular to the orbital plane. These are also listed in Table 5. We have used the values given by Mihalas for the solar distance from the galactic center, 10 kpc, and the Oort constants, $(A, B) = (15, -10)$ km s$^{-1}$ kpc$^{-1}$. The guiding centers about which the epicyclic motion occurs are at 10.609 and 10.635 kpc for the Sun and α Cen, respectively, and separate in angle at the slow rate of only 0.07 radians per 10$^9$ years. Unless the orbits have been fortuitously aligned by an unlikely close encounter involving one of the systems, the separation of the stars arises both from motion along the epicyclic ellipses with radial and tangential range of 2.1 by 3.3 kpc and 1.4 by 2.2 kpc for the binary and the Sun, respectively, and from a secular drift of 0.7 kpc per 10$^9$ years between the guiding centers. During this motion, the time average rms velocities, $\langle v_{\text{rms}} \rangle^{1/2}$, of the Sun and α Cen with respect to the instantaneous local standard of rest are 17 and 27 km s$^{-1}$, respectively. Finally, note that the vertical scale height for α Cen, 140 pc, and the Sun, 80 pc, are comparable with the scale height of gas and dust, 125 pc (Mihalas 1968).

c) Constraints on Accretion Hypotheses

Newman and Talbot (1976) and Auman and McCrea (1976) have proposed that accretion from the interstellar medium could have substantially enriched the metallicity of the solar surface with respect to the interior. To our knowledge the actual structure and evolution of the Sun under these circumstances has not been calculated; however, based on homogeneous models of lower metallicity, the effect is likely to lower the flux of solar neutrinos, perhaps by enough to remove the apparent conflict between theory and experiment (Bahcall and Davis 1976). Since the captured material will be mixed at least throughout the solar convection zone, it is important to know the extent of that zone in an accreting star, but, again, to our knowledge such models have not been calculated. The accretion rate varies as $M^2V^{-3}$ (Hoyle and Lyttleton 1939), and therefore is most effective for low relative velocities $V$. In the cited references on solar accretion it is estimated that accretion will be most effective for a relative velocity between the Sun and an interstellar cloud in the range 2-10 km s$^{-1}$. In addition, accretion can occur only if the infall velocity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sun</th>
<th>α Centauri</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$ (radial) (km s$^{-1}$)</td>
<td>-9.2</td>
<td>+24.0</td>
</tr>
<tr>
<td>$r_2$ (angular) (km s$^{-1}$)</td>
<td>+12.0</td>
<td>+12.5</td>
</tr>
<tr>
<td>$Z$ (perpendicular) (km s$^{-1}$)</td>
<td>+6.9</td>
<td>+12.7</td>
</tr>
<tr>
<td>$</td>
<td>\varepsilon</td>
<td>$ (km s$^{-1}$)</td>
</tr>
<tr>
<td>$R_1$ (kpc)</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
<td>$R_2$ (kpc)</td>
<td>17.4</td>
<td>26.8</td>
</tr>
<tr>
<td>$Z$ (pc)</td>
<td>0.08</td>
<td>0.14</td>
</tr>
<tr>
<td>$\langle v_{\text{rms}} \rangle^{1/2}$ (km s$^{-1}$)</td>
<td></td>
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</tbody>
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is sufficient to overwhelm the pressure of the outflowing solar wind. Application of this simple theory to α Cen provides some complications. For the entire binary of mass 2.03 M☉, the accretion radius, 2GM/V^2, appropriate to velocities between 2 and 10 km s^-1 lies in the range 900 and 36 AU, compared to a variation in the binary separation of 35 to 12 AU. The maximum velocities of the components about the center of mass are 6.8 and 8.2 km s^-1. Therefore, at low velocity, accretion is essentially into the binary; but at high velocity, capture could occur onto the individual components.

Material accreted onto a star must be mixed at least throughout the mass contained in the surface convection zone. For the nonaccreting models of α Cen A, B, and the Sun, discussed in § III, we find masses for the convection zones of 0.01, 0.06, and 0.01 M☉, respectively (see Table 3 for the evolutionary variation). Although these values may not be appropriate for an inhomogeneous, accreting model, the difference in effective temperatures of α Cen A and B guarantees substantial differences in the fractional mass contained in their convection zones. Therefore, the agreement in metallicity of α Cen A and B as observed by French and Powell (1971) indicates that accretion onto α Cen has either been negligible, or substantial enough to saturate both convection zones (i.e., ΔM ≥ 0.06 M☉). In both cases, the metal enrichment of α Cen with respect to the Sun, coupled with the similarity in galactic orbits and age, would make it difficult to invoke accretion to explain the surface metallicity of the Sun, unless the bulk of the accretion occurs in a very small number of significant events. Since both systems have circuited the Galaxy about 20 times, and therefore have passed through spiral arms many times, severe constraints must apply for accretion to have altered the surface convection zone of the Sun without similarly affecting α Cen.

d) The Galactic Enrichment of Helium and Metals

The processes responsible for the enrichment of metals in our Galaxy are thought to produce a corresponding enhancement in helium according to the ratio ΔY = RΔZ with R in the range 3 to 5 (e.g., see Audouze and Tinsley 1976; Peimbert 1977; Perrin et al. 1977). Observational justification for this relation is subject to systematic errors since measurements of the helium abundance are difficult to obtain and interpret. For example, the ratios of helium to metals observed in planetary nebulae might not reflect the initial abundances of the parent star. In fact, the helium enrichment implied by the apparent metal enhancement of α Cen, ΔY = +0.05 to +0.10, is ruled out by the evolutionary models. For ΔY = +0.05 even the ZAMS luminosity of the model B component would exceed the observed brightness, and additional brightening would have to occur to produce the steep ratio of luminosity to mass, as discussed in § III. Perrin et al. favor R ~ 5 to account for their study of the properties of 138 stars in the solar neighborhood. However, the parameters they list for α Cen are somewhat different from those determined here—in particular ~0.1 mag higher luminosities for both α Cen A and B—and parameters for more distant stars should be correspondingly less reliable. Statistically, it may well be correct that ΔY ~ 3ΔZ, but at present we regard the observational justification for this relation as suspect and cite α Cen as a counter-example. On the other hand, the difference in Z between the Sun and α Cen is consistent with the idea that there exists a substantial dispersion in the metallicity of the interstellar medium at any one time (see Audouze and Tinsley 1976).

e) Hyades Mass-Luminosity Relation

Historically, the discrepancy between the mass-luminosity law appropriate for the visual binaries in the Hyades cluster (Eggen 1969), relative to other stars, provided one of the first indications that a relation ΔY ≈ 3ΔZ might hold (Faulkner 1967). A recent redetermination of the convergent point distance by Hanson (1975) as revised by McAlister (1977) is in agreement with other distance indicators for the Hyades, d = 44 pc (van Altena 1974). However, the masses and luminosities of the Hyades binaries still are not well known. Even though the debate concerning the distance to the cluster center is apparently resolved, and the orbital determinations of Eggen have been confirmed by Wickers's (1975) interferometric measurements, the uncertain location of the binary stars with respect to the cluster center introduces possible errors of about 30% in mass and 20% in luminosity. For example, the apparently most massive binary ADS 3475 is displaced by nearly 8° from the cluster center. Although the 10% increase in cluster distance has eliminated the discrepant zero-point in the mass-luminosity relation (formerly the Hyades stars were overluminous with respect to their mass by more than a magnitude), adjusting the distance does not change the slope of the mass-luminosity law, which is observed to be about 1.0 compared to a predicted value of about 4.7 (see § III). However, it is very likely that the shallow slope is only a reflection of the uncertainty in locating the binaries with respect to the cluster center. Therefore, the Hyades binaries do not provide as unambiguous a comparison with stellar evolution models as does the α Cen system.

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REFERENCES


Cox, A. N. 1976, private communication.


Hanson, R. B. 1975, A.J., 80, 379.


Johnson, H. L. 1956, Sky Tel., 16, 470.


van der Kamp, P. 1958, in Handbuch der Physik, ed. S. Flügge (Berlin: Springer-Verlag), Vol. 50, p. 188.


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