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HEAVY-ELEMENT DIFFUSION IN METAL-POOR STARS

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ABSTRACT

Stellar evolution models that include the effect of helium and heavy-element diffusion have been calculated for initial iron abundances of [Fe/H] = −2.3, −2.1, −1.9, and −1.7. These models were calculated for a large variety of masses and three separate mixing lengths, $\alpha = 1.50$, 1.75, and 2.00 (with $\alpha = 1.75$ being the solar calibrated mixing length). The change in the surface iron abundance for stars of different masses was determined for the ages of 11, 13, and 15 Gyr. Iron settles out of the surface convection zone on the main sequence; this iron is dredged back up when the convection zone deepens on the giant branch. In all cases, the surface [Fe/H] abundance in the turnoff stars was at least 0.28 dex lower than the surface [Fe/H] abundance in giant branch stars of the same age. However, Gratton et al. recently found, based on high-dispersion spectra of stars in the globular cluster NGC 6397, that the turnoff and giant branch stars had identical (within a few percent) iron abundances of [Fe/H] = −2.03. These observations prove that heavy-element diffusion must be inhibited in the surface layers of metal-poor stars. When diffusion is inhibited in the outer layers of a stellar model, the predicted temperatures of the models are similar to those of models evolved without diffusion, while the predicted lifetimes are similar to those of stars in which diffusion is not inhibited. Isochrones constructed from the models in which diffusion is inhibited fall halfway between isochrones without diffusion and isochrones with full diffusion. As a result, absolute globular cluster ages based upon the absolute magnitude of the turnoff are 4% larger than ages inferred from full-diffusion isochrones and 4% smaller than ages inferred from non-diffusion isochrones.

Subject headings: diffusion — globular clusters: individual (NGC 6397) — stars: abundances — stars: evolution — subdwarfs

1. INTRODUCTION

Atomic diffusion, whereby heavier elements settle relative to hydrogen in a star, is a physical process that occurs in stars. Helioseismology provides clear evidence that diffusion is occurring in the Sun (see, e.g., Christensen-Dalsgaard, Proffitt, & Thompson 1993; Basu, Pinsonneault, & Bahcall 2000). As a result, a large number of studies have been made of the effect of diffusion on the evolution of the Sun and other stars (see, e.g., Noerdlinger & Arigo 1980; Michaud, Fontaine, & Beaudet 1984; Michaud 1986; Deliyannis & Demarque 1991; Chaboyer & Demarque 1994; Vauclair & Charbonnel 1995; Salaris, Groenewegen, & Weiss 2000; Salaris & Weiss 2001). Models and isochrones appropriate for globular cluster stars have shown that the inclusion of diffusion reduces the main-sequence lifetime and effective temperatures of the stars. The absolute age inferred for the oldest globular clusters is reduced by $\sim 7\%$ when diffusion is included in the stellar models (Chaboyer 1995).

Diffusion leads to changes in the surface abundances of elements. In particular, the abundances of elements heavier than hydrogen will decrease over time. The characteristic timescale for the depletion of an element out of the surface of a star is given by

$$\tau \simeq K \frac{M_{CZ}}{M T_{CZ}^{3/2}} \qquad (1)$$

(Michaud et al. 1984), where M is the total mass of the star, M_{CZ} is the mass of the surface convection zone, T_{CZ} is the temperature at the base of the convection zone, and K is a constant, which can vary for different elements. Because M_{CZ} can be a strong function of the total mass of the star, the diffusion models predict that the surface abundances vary for stars of different masses.

Observations of Li in metal-poor stars have shown the existence of a plateau where the abundance is constant over a wide range of effective temperatures and metallicities (see, e.g., Spite & Spite 1982; Thorburn 1994; Ryan, Norris, & Beers 1999). These observations suggest that diffusion is inhibited near the surface of metal-poor stars (see, e.g., Michaud et al. 1984; Deliyannis & Demarque 1991; Chaboyer & Demarque 1994). However, Salaris & Weiss (2001) have shown that the Li abundance observations can be reproduced by models that include fully efficient diffusion. This follows from their analysis, which includes the effects of observational errors, uncertainties in the Li abundance determinations and in the effective temperature scale, and the size of the observed samples of stars. Li is one of three elements produced during the big bang, and so its primordial abundance is of considerable importance in constraining big bang nucleosynthesis. Salaris & Weiss (2001) found that, because of diffusion, their predicted primordial Li abundance was a factor of 2 higher than that observed in the metal-poor plateau stars.

The inclusion of diffusion in stellar models has important consequences for the estimated age of the oldest globular clusters and the inferred primordial Li abundance. Thus, it is important to determine if diffusion is actually occurring in metal-poor stars. The recent observations of iron abundances in turnoff and giant branch stars in the metal-poor globular cluster NGC 6397 by Gratton et al. (2001) provide an excellent test for the occurrence of diffusion in metal-poor stars. Gratton et al. (2001) found that the turnoff and giant branch stars had identical iron abundances (within a few percent). Stars near the turnoff can have convective masses orders of magnitude smaller than those on the giant branch. Thus, one would expect that if diffusion does occur near the surface of metal-poor stars, it would lead to a marked difference in the surface abundance of iron between the main-sequence turnoff stars and those in the giant branch. These effects should be particularly noticeable in NGC 6397 because it is a relatively metal-poor cluster, with [Fe/H] $= -2.02 \pm 0.04$ (Gratton et al. 2001; Thévenin et al. 2001). The convective envelope masses on the main sequence become smaller as one goes to more metal-poor stars; as a result, the diffusion timescale (eq. [1]) is shorter for metal-poor stars.

The use of iron abundances in globular clusters to study diffusion has several advantages over using Li observations in field halo stars. First, all the stars in NGC 6397 were born with the same initial composition and at the same time.[1] Li abundances are usually determined for field halo stars, which have different compositions and may have different ages. Second, the interpretation of the Li observations is complicated by the fact that Li is destroyed at temperatures $T \gtrsim 2.5 \times 10^6$ K, implying that mixing or turbulence within a star can lead to a change in the surface abundance of Li. In contrast, mixing or turbulence can only change the surface abundance of iron if diffusion is already operating; otherwise the abundance of iron is the same everywhere in the star, and mixing cannot change the surface abundance of iron. Finally, iron abundance measurements are typically determined from a large number of lines, minimizing the observational errors. Li abundances are determined from a single line, and the Li abundance measurements are quite sensitive to the adopted effective temperature scale.

Section 2 of this paper discusses the stellar models and isochrones used in this study. This includes fits of the isochrones to the observed color-magnitude diagram of NGC 6397. The effects of metal diffusion on the surface abundance of iron are presented in § 3, where it is concluded that diffusion must be inhibited in the surface layers of metal-poor stars. The effect of inhibiting the diffusion on the derived ages of globular clusters is explored in § 4. Finally, § 5 contains a summary of the principal results in this paper.

2. STELLAR MODELS AND ISOCHRONES

The stellar evolution models were calculated using Chaboyer's stellar evolution code. The basic input physics used in the code is described in Chaboyer, Green, & Liebert (1999), with the exception of the atomic diffusion coefficients. These calculations use the Thoul, Bahcall, & Loeb (1994) diffusion coefficients for helium and heavy elements. The variations of the abundances of H, He, and Fe are followed; all other heavy elements are assumed to diffuse at the same speed as fully ionized iron. The differences in the diffusion velocities among the heavy elements are small for the low-mass stars ($M \leq 0.9\ M_\odot$) considered here (Turcotte, Richer, & Michaud 1998), and our procedure does not introduce any significant error into the calculations. The local changes in the metal abundance are taken into account in the opacity computation by interpolating among tables with different heavy-element mass fractions (Z).

Note that the Thoul et al. (1994) diffusion coefficients do not include the effects of radiative acceleration. Studies of the effects of radiative acceleration on solar-metallicity F stars have been performed by Richer et al. (1998) and Turcotte et al. (1998). These studies have shown that radiative acceleration is predicted to be important for solar-metallicity stars with masses greater than approximately 1.2 $M_\odot$. The importance of radiative acceleration depends on the opacity (which is a function of temperature and density) and the radiative flux. In general, the physical conditions near the base of the surface convection zone in an $M = 0.80\ M_\odot$ metal-poor star are similar to those in an $M = 1.2\ M_\odot$ solar-metallicity star. As a result, it is unlikely that radiative acceleration is important in the stars we will model in this paper. Furthermore, if radiative acceleration was important, the surface abundances of the elements would be affected, leading to large abundance anomalies (Turcotte et al. 1998). Such abundance anomalies are not observed.

A calibrated solar model was calculated by adjusting the initial mixing length, Z, and the helium abundance in the model until a 1.0 $M_\odot$ model yielded the correct solar radius, luminosity, and a surface Z/X of 0.0245 (Grevesse & Noels 1993) at the solar age (assumed to be 4.6 Gyr). The calibrated solar model had a mixing length of $\alpha = 1.75$, an initial heavy-element mass fraction of $Z = 0.02$, and an initial helium abundance of $Y = 0.275$. At 4.6 Gyr, the model had a surface $Z = 0.0179$ and $Y = 0.249$. This value for the present-day value of Y is in good agreement with helioseismic helium abundance determinations, which find $Y = 0.24$–0.25 (Basu 1998; Richard et al. 1998). The base of the convection zone is located at $R = 0.716\ R_\odot$ in the model, which is a similar to the depth inferred from helioseismology of $R = 0.713\ R_\odot$ (Basu 1998).

The metal-poor stellar models were calculated for four different initial Fe abundances: [Fe/H] $= -2.3$, -2.1, -1.9, and -1.7. The α-capture elements were assumed to be uniformly enhanced by 0.2 dex, similar to the observed value in NGC 6397. Gratton et al. (2001) found [O/Fe] $= +0.21 \pm 0.05$ in their high-dispersion study of NGC 6397. As α-element–enhanced low-temperature opacities were not available to us, a scaled solar composition was used in the calculations. The effect of α-element enhancement was taken into account by changing the relationship between Z and [Fe/H] (Salaris, Chieffi, & Straniero 1993). Salaris et al. (1993) showed that most of the evolutionary properties of metal-poor stars with enhanced α-capture elements could be reproduced by models with scaled solar compositions if the total heavy-element mass fraction Z was identical in the two sets of models. By calculating models over a relatively large range in [Fe/H], we can explore what effect possible mismatches between the observed abundances and those used in our models has on predictions.

The helium abundance in the models was determined assuming a primordial helium abundance of $Y_p = 0.245$ and $\Delta Y/\Delta Z = 1.5$. The primordial helium abundance was chosen to be in agreement with Burles et al. (1999), who base their determinations upon big bang nucleosynthesis and deuterium abundance measurements in quasars. The value of $\Delta Y/\Delta Z$ was determined using Y_p and the solar values of initial Y and Z from the models.

In order to investigate how uncertainties in the treatment

[1] The spectroscopic observations of Gratton et al. (2001) and Castilho et al. (2000) have found no star-to-star abundance variations among the giant branch stars. Photometric studies (Alcaino et al. 1997) show a single turnoff, which indicates that all the stars in NGC 6397 have the same age.

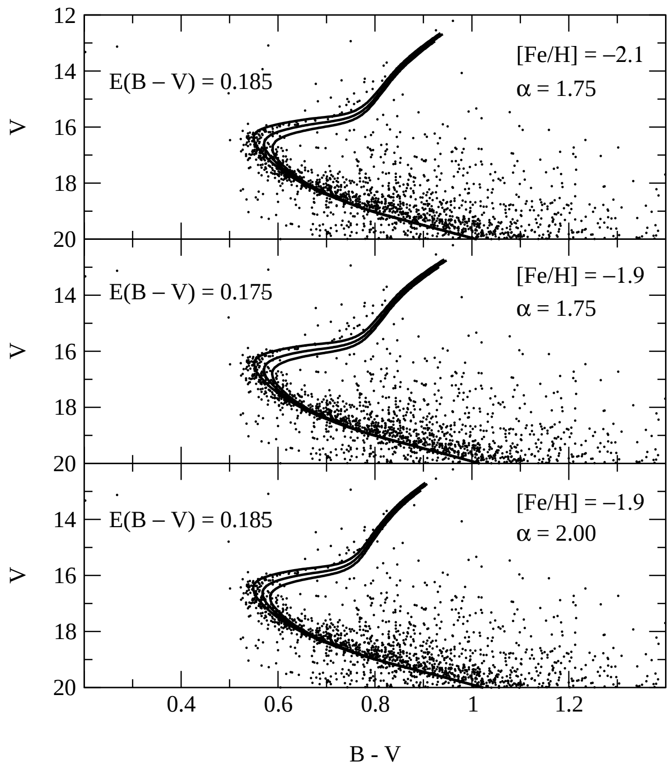

FIG. 1.—Isochrone fits to the NGC 6397 photometry of Alcaino et al. (1997) for different values of [Fe/H] and the mixing length α. All panels show 11 (*bluest turnoff*), 13, and 15 Gyr isochrones. Distance modulus $(m-M)_V = 12.60$ was used in all fits.

of convection affect the results, models were calculated for three different values of the mixing length, $\alpha = 1.50$, 1.75, and 2.00 (recall that $\alpha = 1.75$ is the solar calibrated mixing length). Models with masses in the range $M = 0.5$–$0.9\ M_\odot$ were evolved to ages of 11, 13, and 15 Gyr. The mass spacing ranged from 0.01 to 0.001 $M_\odot$. In total, over 4000 stellar evolution runs were calculated. The age range of 11–15 Gyr was chosen because it encompasses the most recent estimate for the absolute age of old, metal-poor globular clusters, 13.2 ± 1.5 Gyr (Chaboyer 2001).

As a test of the models, isochrones were calculated using stellar models that included the effects of diffusion and fitted to the NGC 6397 color-magnitude observations of Alcaino et al. (1997). The isochrones were constructed in manner described by Chaboyer et al. (1999). In performing the isochrone fits, the distance modulus and reddening were varied until the best fit to the unevolved main sequence was obtained. The reddening was constrained by the study of Anthony-Twarog & Twarog (2000), who obtained *uvby* Hβ photometry of NGC 6397 and found $E(B-V) = 0.179 \pm 0.003$ mag. In fitting the theoretical isochrones to the observed data, the reddening was allowed to vary by $\pm 2\ \sigma$ from the value determined by Anthony-Twarog & Twarog (2000). The distance scale to globular clusters is still a matter of considerable debate (see, e.g., Chaboyer 2001), and as a result the distance modulus was allowed to vary by ±0.15 mag. Some samples of the isochrone fits are shown in Figure 1. In general, an age of 11 Gyr was found for NGC 6397. The best-fitting isochrones had temperatures at the turnoff in the range $T_{\rm eff} = 6460$–6630 K. Based upon the H_α profiles in their high-dispersion spectra, Gratton et al. (2001) estimated the temperature of the turnoff stars to be $T_{\rm eff} = 6576 \pm 90$ K, which is in good agreement with the models.

3. METAL DIFFUSION RESULTS

The principal results of this paper are shown in Figures 2 and 3, which show the change in the surface iron abundance as a function of log *g* (Fig. 2) and of effective temperature (Fig. 3). Since stars on the giant branch and on the main sequence can have the same effective temperatures, it is easiest to illustrate the effects of heavy-element diffusion on the surface iron abundance when the surface [Fe/H]-value is plotted as a function of log *g* (Fig. 2). The lowest-mass stars (which are on the main sequence) have the highest surface gravities. As one goes to lower surface gravities (to the right in the figure), the stars are more and more massive. Low-mass main-sequence stars have fairly large convection zones. As a result, the timescale for the diffusion of metals out of the surface convection zone is very long, resulting in little change in the surface abundance of iron. The higher mass stars on the main sequence have less massive surface convection zones, leading to shorter diffusion timescales and a larger depletion of iron at the surface. The maximum depletion in the surface [Fe/H] abundance occurs around the main-sequence turnoff, where the depth of the convection zone is at a minimum. As stars evolve past the turnoff point, their convection zone rapidly deepens, dredging up the iron, which had diffused out of the surface convection zone on the main sequence. As a result, the surface iron abundance returns to its initial value on the giant branch ($\log g \lesssim 3.6$).

The top panel in Figure 2 illustrates how the depletion of [Fe/H] varies as a function of the assumed age of NGC 6397. If NGC 6397 is 11 Gyr old (as suggested by the iso-

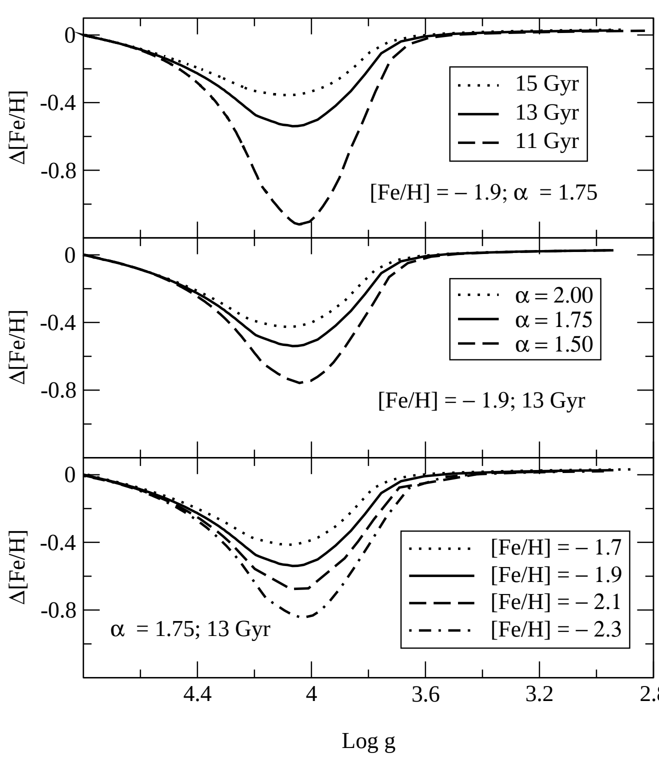

FIG. 2.—Change in the surface [Fe/H] as a function of log *g* for different ages (*top*), mixing lengths (*middle*), and values of initial [Fe/H] (*bottom*). The solid line is the same in all panels (initial [Fe/H] = −1.9, α = 1.75, and 13 Gyr). Main-sequence stars are on the left of this diagram, while red giant branch stars are on the right.

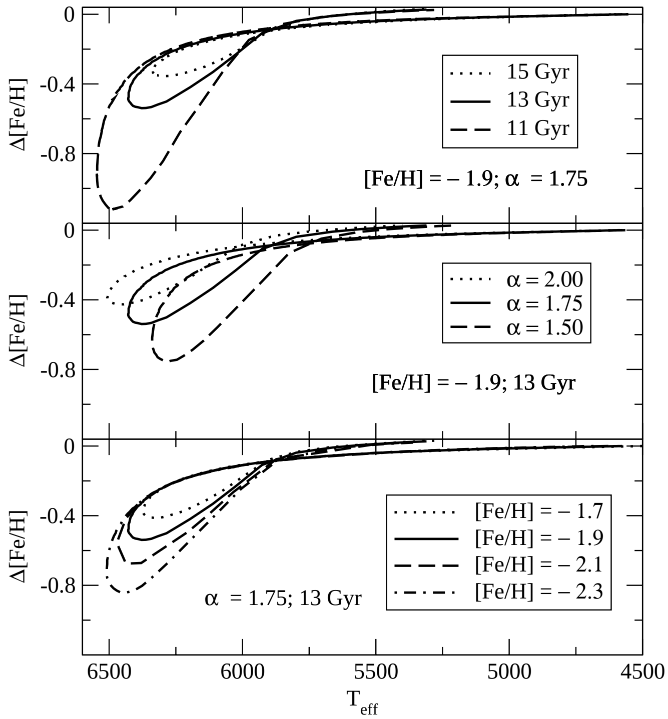

FIG. 3.—Same as Fig. 2, but for change in the surface [Fe/H] as a function of effective temperature. Cool main-sequence stars are on the extreme right of this diagram, while red giant branch stars are located slightly above the main-sequence stars for $T_{\rm eff} \lesssim 5800$ K.

chrone fits), then the turnoff stars have a mass of $M \simeq 0.80$ $M_\odot$ and during their main-sequence lifetime have an average convective envelope mass of around $M_{\rm CZ} \sim 1 \times 10^{-3}$ $M_\odot$, leading to large depletions in [Fe/H] in the turnoff stars. In contrast, 13 Gyr turnoff stars have a mass of $M \simeq 0.76$ $M_\odot$ and during their main-sequence lifetime have a convective envelope mass about 3 times as massive as an $M \simeq 0.80$ $M_\odot$ star. As a consequence, if NGC 6397 is really 13 Gyr old, then the predicted [Fe/H] depletion at the surface is substantially smaller than if it is 11 Gyr old. In general, older ages for globular clusters imply that the effects of atomic diffusion are smaller.

The middle panel in Figure 2 illustrates how the depletion of [Fe/H] varies as a function of the mixing length assumed in the models. Lower values of the mixing length lead to less massive convection zones on the main sequence. As a result, the timescale for diffusion is shorter in models with lower mixing lengths, leading to larger depletions of the surface iron abundance. Finally, the bottom panel in Figure 2 illustrates the effect that changing the initial [Fe/H] abundance has on the predicted [Fe/H] depletions. As is well known, the higher the heavy-element abundance, the higher the opacities are (see, e.g., Rogers & Iglesias 1992), leading to more massive convection zones and less depletion in the surface iron abundance.

The effective temperature of a star can be determined from observations much more accurately than its surface gravity. As a result, our model calculations are best compared with observations using temperature as the independent variable. This is shown in Figure 3, which plots the change in the surface [Fe/H] abundance as a function of $T_{\rm eff}$. Of course, stars on the giant branch and on the main sequence may have the same temperatures, and so the depletion lines are double-value functions. The lowest-mass models on the main sequence are located at the lowest effective temperatures (extreme right in Fig. 3). It turns out that even the lowest-mass models we evolved had less massive convection zones than the models on the giant branch. As a consequence, the surface iron abundance is somewhat higher ($\sim$0.04 dex) in the cool giant branch models ($T_{\rm eff} \lesssim 5800$ K) than in the main-sequence models. Note that the difference in surface [Fe/H] between turnoff stars and giant branch stars in the models plotted in Figure 3 is always greater than 0.3 dex.

Gratton et al. (2001) determined the temperature of the main-sequence turnoff stars to be $T_{\rm eff} = 6476 \pm 90$ K, while the giant branch stars they observed had $T_{\rm eff} = 5478 \pm 60$ K. For the iron abundances, Gratton et al. (2001) found that the turnoff stars had $[{\rm Fe/H}] = -2.02 \pm 0.01$, while the giant branch stars had $[{\rm Fe/H}] = -2.05 \pm 0.03$. The quoted errors are internal, given by the standard deviation in the mean for each group of stars. Possible systematic errors between the two [Fe/H] measurements are likely to be dominated by uncertainties in the adopted temperatures. Gratton et al. (2001) show that for the turnoff stars, their error of ± 90 K in the temperature translates into an error of ± 0.09 dex. For the giant branch stars, their error of ± 60 K in temperature translates into an error of ± 0.06 dex. Adding these errors in quadrature, one can conclude that the difference in the iron abundance between the giant branch and turnoff stars is $\Delta[{\rm Fe/H}] = 0.03 \pm 0.11$ dex.

In order to obtain a best estimate for the predicted Δ[Fe/H] between the giant branch and turnoff stars, the models with initial iron abundances of $[{\rm Fe/H}] = -1.9$ and -2.1 were searched to determine which cases had turnoff stars in the ± 1 σ range given by Gratton et al. (2001): $T_{\rm eff} = 6386$–6556 K. For each set of models, Δ[Fe/H] was determined by taking the difference in [Fe/H] between the turnoff stars and those stars on the giant branch that were 1000 K cooler than the turnoff stars. The results are shown in Table 1. The predicted Δ[Fe/H]-values ranged from 0.31 to 2.56 dex, with an average of 0.77 dex. The minimum predicted change in [Fe/H] between the giant branch and the turnoff stars is 2.5 σ larger than the observed difference. The lowest Δ[Fe/H]-values occur for the 15 Gyr models; however, as discussed in § 2, the 15 Gyr isochrones do not fit the observed color-magnitude diagram. For models 13 Gyr or younger, the minimum predicted $\Delta[{\rm Fe/H}] = 0.41$ dex, which is 3.5 σ larger than observed. The difficulty in matching the observed [Fe/H]-values is shown in Figure 4, which compares models that had an initial [Fe/H] of -1.9,

TABLE 1

DIFFERENCE IN [FE/H] BETWEEN TURNOFF AND GIANT BRANCH MODELS

Initial [Fe/H]	Age (Gyr)	α	Δ[Fe/H]
−1.9	11	1.50	1.58
		1.75	0.92
	13	1.75	0.50
		2.00	0.41
	15	2.00	0.31
−2.1	11	1.50	2.56
	13	1.50	0.79
		1.75	0.57
		2.00	0.45
	15	2.00	0.33

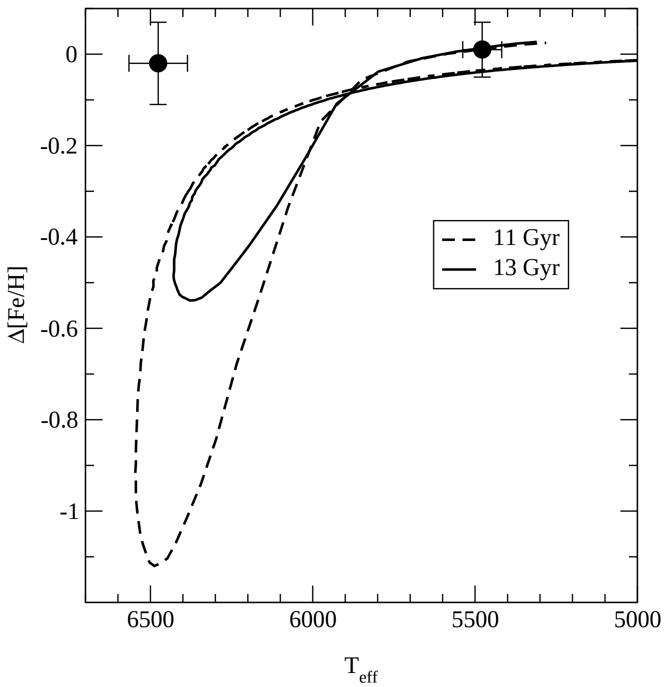

FIG. 4.—Change in the surface [Fe/H] in the models (*solid line*) with initial [Fe/H] = −1.9, mixing length $\alpha = 1.75$, and age of 13 Gyr, compared with observations of turnoff and subgiant branch stars in the globular cluster NGC 6397 (Gratton et al. 2001). Models clearly do not match the observed data.

an age of 13 Gyr, and a mixing length of $\alpha = -1.75$ with the data from Gratton et al. (2001).

An examination of Figure 2 shows that the minimum possible depletion will occur in the 15 Gyr, $\alpha = 2.00$ models that had an initial iron abundance of [Fe/H] = −1.7. These models have a turnoff temperature of $T_{\rm eff} = 6361$ K, which differs by 1.3 σ from the observed value, and a giant branch [Fe/H] that differs from the observed value by 3 σ. In this extreme case, the predicted change in [Fe/H] between the turnoff and giant branch is Δ[Fe/H] = 0.28 dex, which is 2.3 σ different from the observed value. Since all the models differ by more than 2 σ from the observations, we conclude that heavy-element diffusion does not occur near the surface of metal-poor stars.

4. DISCUSSION

Observations of Li in metal-poor field stars have suggested for some time that diffusion is inhibited near the surface of metal-poor stars (see, e.g., Michaud et al. 1984; Deliyannis & Demarque 1991; Chaboyer & Demarque 1994). However, Salaris & Weiss (2001) have pointed out that, when one takes into account the observational errors, uncertainties in the Li abundance determinations and in the effective temperature scale, and the size of the observed samples of stars, the Li abundance observations can be reproduced by models that include fully efficient diffusion. In contrast, observations of iron abundances in turnoff and giant branch stars in the metal-poor globular cluster NGC 6397 clearly show that heavy-element diffusion does not occur near the surface of metal-poor stars.

A key difference between the Li observations analyzed by Salaris & Weiss (2001) and the Fe observations analyzed here is that the Li observations are primarily obtained for field stars, while the Fe abundances analyzed in this paper have been obtained for a single globular cluster. Evolutionary timescales near the main-sequence turnoff are much more rapid than on the main sequence. As a result, observations of random field stars are biased against finding stars near the turnoff. It is stars at the turnoff in which diffusion causes the greatest depletion of Li. Hence, observations of field stars are biased against finding Li-depleted stars. The Monte Carlo simulations of Salaris & Weiss (2001) show that, even if Li diffusion occurs at the surface of metal-poor stars, observational selection effects imply that one is unlikely to observe stars with large Li depletions, given the size of present-day samples. Salaris & Weiss (2001) found that 3 times as many stars as are in the current data sets must be observed in order for the observational data to show clear signs of Li depletion at hot temperatures. In contrast, Gratton et al. (2001) were able to use the observed color-magnitude diagram of NGC 6397 to select turnoff stars for spectroscopic study. Hence, these observations are a much cleaner test for the presence of diffusion than the field star Li abundance measurements analyzed by Salaris & Weiss (2001).

Iron is not subject to depletion on the red giant branch, making it easy to compare the observed iron abundances between the main-sequence turnoff and giant branch in a given cluster. The deepening of the convection zone on the red giant branch leads to significant Li depletion in these stars. The globular cluster Li abundance data analyzed by Salaris & Weiss (2001) involved a comparison between giant branch stars and main-sequence turnoff stars. Because the giant branch stars undergo significant Li depletion, these observations do not serve as strong constraints on the presence of diffusion. As a result, there is no conflict between the study of Salaris & Weiss (2001) and this study. Salaris & Weiss (2001) simply claim that the available Li data do not rule out the presence of diffusion near the surface of metal-poor stars. The iron abundance measurements analyzed in this paper are much more sensitive to the presence of diffusion than the Li observations. Hence, the present observational data show that diffusion is inhibited near the surface of metal-poor giant branch stars.

Two mechanisms that inhibit diffusion in the surface layers of stars are modest amounts of mass loss (Vauclair & Charbonnel 1995) and mixing induced by rotation (see, e.g., Vauclair 1988; Pinsonneault, Deliyannis, & Demarque 1992; Pinsonneault et al. 1999). The wind-loss models require that the mass loss in low-mass metal-poor stars be an order of magnitude larger than is observed in the Sun. Observations of a correlated depletion of lithium and beryllium in Population I F stars suggest that rotationally induced mixing, and not mass loss, is operating in these stars (Deliyannis et al. 1998).

Mixing induced by rotation suppresses diffusion by effectively increasing the mass of the surface mixed zone, leading to longer timescales for the depletion of elements at the surface of the star (see eq. [1]). Using equation (1) as a guide, we may estimate the mass of the surface mixed zone in metal-poor stars by requiring that the surface abundance of iron change by less than 0.1 dex in 13 Gyr. The constant K in equation (1) was calculated for our models, and from this we estimate that the mixed zone at the surface of a metal-poor star has a mass $M_{\rm mix} \gtrsim 0.005\ M_\odot$. In contrast, the convection zone masses in turnoff stars with [Fe/H] $\simeq -2.0$ are 0.002 $M_\odot$ or smaller. An upper limit to the mass of the mixed zone may be determined from solar observations. Helioseismology clearly shows that diffusion does occur in the Sun (Christensen-Dalsgaard et al. 1993; Basu et al. 2000). The mass of the convection zone in the Sun is $M_{CZ} = 0.02\ M_\odot$. The fact that diffusion is not inhibited in the Sun suggests that the mechanism that inhibits diffusion only acts in the very outermost layers of a star (i.e., for $M > 0.98\ M_\odot$). Combined with the estimate for the minimum mass of the mixed zone given above, it appears that the mass of the mixed zone at the surface of hot, metal-poor stars is in the range $M_{mix} \simeq 0.005$–$0.02\ M_\odot$.

To determine what effects inhibiting diffusion in the outer layers of a star has on the observed properties of the models, the diffusion subroutine in our code was altered so that diffusion was shut off in the outer layers of the star. This was accomplished by setting the diffusion coefficients to zero when $M > M_* - M_{mix}$, where M_* is the total mass of the star. The diffusion coefficients were ramped from zero up to their standard value in the region $M_* - M_{mix} > M > M_* - M_{ramp}$. For these test runs, we used $M_{mix} = 0.005\ M_\odot$ and $M_{ramp} = 0.01\ M_\odot$. The results of a sample calculation are shown in Figure 5, which shows the evolution in the effective temperature–luminosity plane. We see that, when diffusion is inhibited in the outer layers of the model, the predicted temperatures of the models are similar to those of models evolved without diffusion. The primary reason diffusion models are cooler than nondiffusion models is that diffusion of helium out of the envelope increases the envelope opacity, which increases the model radius and hence decreases the effective temperature. Thus, when diffusion is inhibited in the outer layers, the effective temperature of the models resembles that of the nondiffusion models.

The model in which diffusion was inhibited at the surface had a lifetime similar to that of the full-diffusion model. This is because diffusion was not inhibited in the deep interior of the model. Helium diffuses into the core, displacing the hydrogen and leading to a shorter main-sequence lifetime, compared with nondiffusion models. Such tracks by themselves, however, may provide a misleading guide to the effect of diffusion on cluster age estimates. To determine globular cluster ages, one compares isochrones to observations. Diffusion will change the shape of the isochrones in a different way than it changes the shape of individual tracks, because models with different masses undergo different degrees of diffusion.

To explore the consequences this modification of diffusion has on age determinations, isochrones were calculated based upon the non-diffusion models and the models in which diffusion was inhibited in the outer layers. These isochrones are compared to the full-diffusion isochrones in Figure 6. The isochrone in which diffusion has been inhibited falls halfway between the isochrone with full diffusion and the isochrone with no diffusion. If M_V(TO) is used as an age indicator, then ages determined using isochrones in which diffusion has been inhibited will be 4% larger than ages derived from the full-diffusion isochrones and 4% smaller than ages derived using the non-diffusion isochrones.

If diffusion is inhibited near the surface of metal-poor stars (likely by rotation-induced mixing), one naturally wonders if diffusion occurs in the deep interior of metal-poor stars. Perhaps the rotation-induced mixing suppresses the diffusion throughout the entire star. At the present time, there is no clear answer as to whether diffusion is occurring in the deep interior of metal-poor stars. A definitive answer will likely have to await observations from stellar seis-

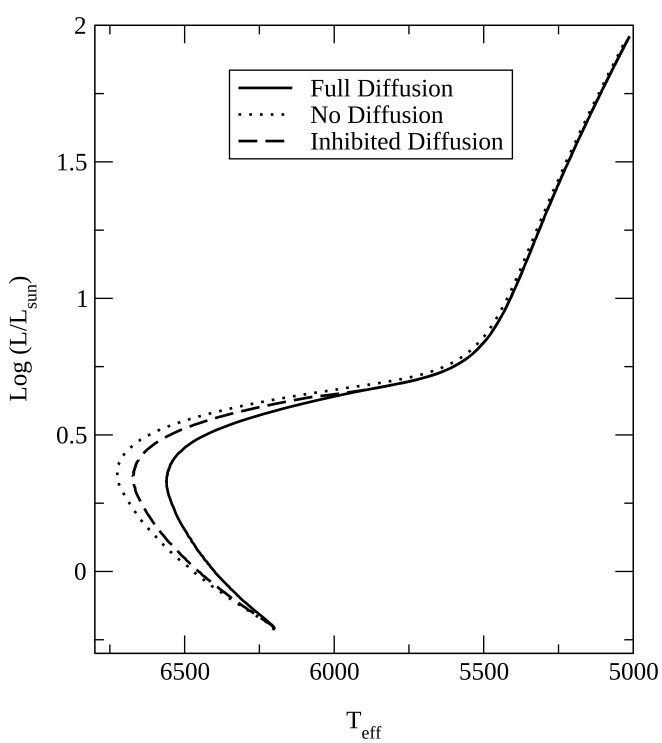

FIG. 5.—Evolution of models with full diffusion, no diffusion, and diffusion inhibited in the outer layers of the star. All models had a mass of $M = 0.80\ M_\odot$, an initial iron abundance of [Fe/H] $= -1.9$, and a mixing length of $\alpha = 1.75$.

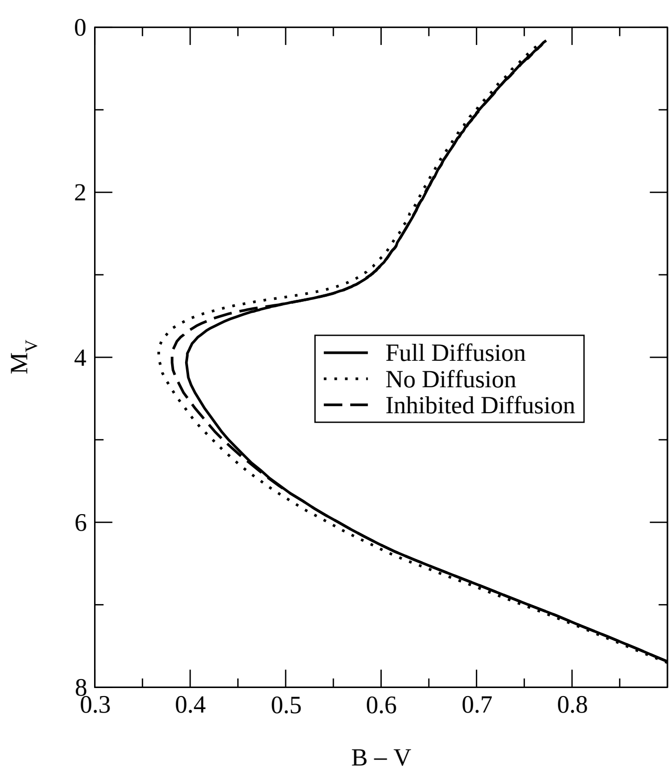

FIG. 6.—Isochrones with an age of 13 Gyr, an initial iron abundance of [Fe/H] $= -1.9$, and a mixing length of $\alpha = 1.75$.

mology, which will probe the interior structure of metal-poor stars and allow one to test the interior properties of theoretical models.

This study has shown that diffusion is inhibited in the surface layers of metal-poor stars. Stellar models and isochrones that include the full effects of diffusion are in error and should not be used for comparing with observational data. Our calculations, in which diffusion is inhibited near the surface of the star, are admittedly ad hoc. However, because helioseismology has shown that diffusion is occurring in the interior of the Sun, we believe it likely that diffusion is also occurring in the interiors of metal-poor stars. The obvious difference between the Sun and the metal-poor turnoff stars is that the surface convection zone is much larger in the Sun. Theoretical calculations of rotation-induced mixing have shown that this mixing is most effective in the outer layers of a star (see, e.g., Chaboyer, Demarque, & Pinsonneault 1995; Brun, Turck-Chièze, & Zahn 1999). The fact that diffusion is occurring in the interior of the Sun makes us believe that diffusion is only being inhibited in the outermost layers of stars. For this reason, we prefer the use of stellar models and isochrones in which diffusion operates in the interior of the model (but not in the outer layers) to models that do not include diffusion. Given that diffusion is occurring in the Sun, stellar models and isochrones that include diffusion are appropriate for solar-type stars. The model we have presented for inhibiting diffusion in the surface layers of stars allows one to use a set of isochrones calculated using the same assumptions for both metal-poor and solar-type stars.

5. SUMMARY

A large number of stellar evolution models that include the effects of helium and heavy-element diffusion were constructed. The amount of diffusion of iron out of the surface convection zone is a strong function of the mass and age of a star. As a result, the models predicted that the [Fe/H] abundance measured in the turnoff stars in the globular cluster NGC 6397 should be more than 0.28 dex lower than the [Fe/H] measured in the giant branch stars. In contrast, observations by Gratton et al. (2001) demonstrate that the turnoff and giant branch stars have identical values of [Fe/H], indicating that uninhibited metal diffusion does not occur in the surface layers of metal-poor stars. Based upon this observed fact and the physical principals underlying diffusion processes, we estimate the minimum mass of the region where diffusion is inhibited near the surface of metal-poor stars to be $M_{\rm mix} \gtrsim 0.005\ M_{\odot}$. Models and isochrones in which diffusion was inhibited in the outer layers were calculated and compared with full-diffusion isochrones and isochrones without diffusion. The isochrones in which diffusion has been inhibited have properties halfway between those of the full-diffusion isochrones and those of the non-diffusion isochrones. As a consequence, globular cluster age estimates that use M_V(TO) as their age indicator and are based upon models that include the full effects of diffusion need to be revised upward by 4%. Helioseismic observations clearly show that diffusion is occurring in the Sun, which suggests that diffusion operates in most regions of a star. Our models in which diffusion is inhibited in the outer layers of the star yield globular cluster ages 4% smaller than models that do not include diffusion, when M_V(TO) is used as an age indicator.

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