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The Giant Branches of Open and Globular Clusters in the Infrared as Metallicity Indicators: A Comparison with Theory

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Abstract

We apply the giant branch slope–[Fe/H] relation derived by Kuchinski *et al.* [AJ, 109, 1131 (1995)] to a sample of open clusters. We find that the slope of the giant branch in K vs. $(J - K)$ color-magnitude diagrams correlates with [Fe/H] for open clusters as it does for metal-rich globular clusters but that the open cluster data are systematically shifted to less negative values of giant branch slope, at constant [Fe/H]. We use isochrone models to examine the theoretical basis for this relationship and find that for a given value of [Fe/H], the slope of the relationship remains constant with decreasing population age but the relation shifts to less negative values of giant branch slope with decreasing age. Both of these theoretical predictions agree with the trends found in the data. Finally, we derive new coefficients for the giant branch slope–[Fe/H] relation for specific members of 3 populations, metal-rich globular clusters, bulge stars and open clusters.

1. Introduction

Relatively little work on galactic open clusters has been carried out in the near-infrared (1.0 – 2.2 μm, hereafter IR), even though this wavelength region is well suited for the study of objects in the plane of our galaxy where the effects of reddening can be substantial. Furthermore, the evolved and brightest stars in these clusters emit most of their energy in this region of the electromagnetic spectrum, making the IR a natural place to study them. In this paper we present an empirical relation for the metallicity of open clusters based upon their IR giant branch (hereafter GB) slope ($\Delta(J-K)/\Delta K$). This method is an extension of the work by Kuchinski *et al.* (hereafter, KFTP) for metal-rich globular clusters.

KFTP demonstrated both empirically and theoretically that the slope of the upper giant branch in a K vs. $(J-K)$ color-magnitude diagram (CMD) is sensitive to the metallicity of the population. They investigated this correlation for metal-rich globular clusters and derived a linear relation between [Fe/H] and GB slope. This relationship was later refined by Kuchinski & Frogel (1995) to be

$$[\mathrm{Fe/H}] = -2.98(\pm 0.70) - 23.84(\pm 6.83) \times (\mathrm{GB\ slope}). \tag{1}$$

This equation reproduces independently determined globular cluster [Fe/H] values to ± 0.25 dex and so is comparable in quality to other photometric metallicity indicators. Tiede *et al.* (1995) applied this relationship to 8 fields along the galactic minor axis in the bulge. They found that Equation 1 reproduced independently determined metallicities for the bulge fields to ± 0.29 dex.

In this paper, we extend the [Fe/H] – GB slope correlation to the giant branch of galactic open clusters. In section 2, we describe how we selected our sample of open clusters and the technique for measuring the slope of the upper giant branches. In section 3, we investigate the effects of age on the correlation and derive preliminary new analytic relations for the studied populations. Section 4 contains our concluding remarks and indications for future work with open clusters.

2. Sample Selection

By examining the [Fe/H] - GB slope correlation in the context of open cluster giant branches, we attempt to extend the correlation from metal-rich globular cluster and bulge populations to the thin disk population. To date very little IR photometry of open clusters exists in the literature. Only two papers, Houdashelt *et al.* (1992) and Frogel & Elias

(1988), present J and K photometry complete enough for the purposes of this work. Table 1 lists the open clusters we analyzed along with their metallicities, reddenings, ages, distance moduli, and galactic coordinates.

We performed all of our analysis in a manner similar to that of KFTP. Using the reddenings and distance moduli from the respective papers, all of the photometry was reddening-corrected and M_K was calculated. We included only giants on the upper giant branch which have absolute K magnitudes in the range $-2 \leq M_K \leq -6.5$. This restriction excludes both clump giants and bright AGB stars. In addition, we excluded any stars designated as non-members or known variables. Finally, we included in our sample only those clusters which contained ≥ 8 giants that met all of these criteria; a total of 4 open clusters. The least-square fits to the giant stars in each of these 4 clusters are shown in Figure 1 along with the stars on each giant branch. The number of stars in each fit after a 2σ rejection, the derived slopes, and the uncertainties in each slope are given in Table 2. The uncertainty in the GB slope of NGC 2204 is larger than the other 3 clusters due to larger uncertainty in the photometry of stars at the dim end of the giant branch (see Houdashelt *et al.* 1992). Although the number of stars on each giant branch is small compared with the globular cluster or bulge studies, the values of the giant branch slopes derived from the fits are comparable to the values from the other studies.

3. Discussion

Using the derived GB slopes from Table 2 and the relation given in Equation 1, we calculated the [Fe/H] for each of the four open clusters and compared the derived values with those from the literature. Table 3 lists the values from the literature and the values calculated from Equation 1. The literature values are from various sources (see Houdashelt *et al.* 1992, Table 1) and were determined using various photometric techniques. Errors given for the literature values are the standard deviation in the spread in the values from the various sources. Although the correlation of [Fe/H] and GB slope holds qualitatively for open clusters (i.e. steeper slopes mean lower [Fe/H]), the [Fe/H] of the open clusters is underestimated by Equation 1. Figure 2a is a plot of the literature values of [Fe/H] versus GB slope for globular clusters (solid circles), bulge fields (stars), and open clusters (open circles). The solid line is Equation 1. From this figure, it is apparent that the slope of the relationship is similar for the three populations, but that there is a systematic shift to more positive GB slope at constant [Fe/H] for the open clusters, and to a lesser extent for all but one of the bulge fields.[1]

Though the number of data points from each population is statistically small, this change in absolute positioning is suggestive of a second effect. KFTP examined the possibility of an age effect among the globular clusters and concluded that for ages typical of globular clusters, $10 \leq t(\mathrm{Gyr}) \leq 16$, any change due to the age spread would be much smaller than changes due to expected metallicity variations and ultimately too small to detect. However, open clusters have ages typically much less than 10 Gyr so in the context of this work we consider ages spanning the range, $1 \leq t(\mathrm{Gyr}) \leq 16$ when making comparison with theoretical models. The upper limit is chosen to be in accordance with KFTP and the lower limit is chosen as the youngest age for which the GB slope – [Fe/H] correlation is likely to hold. For clusters younger than ~ 1 Gyr the upper giant branch does not terminate in a helium flash and tends to curve toward hotter temperatures at higher luminosities. Therefore, the upper giant branch is not even approximately linear and the curvature will overwhelm any metallicity effect.

To examine the relationship between upper giant branch slope and age, we construct M_K vs. $(J-K)$ CMDs using the latest edition of the Yale Isochrones (hereafter referred to as the Y96 isochrones) from Demarque *et al.* (1997). We construct the CMDs for ages $= 1, 2, 3, 5, 10, 16$ Gyr and $[\mathrm{Fe/H}] = 0.0, -0.3, -0.7, -1.3$. The Y96 isochrones do not contain JK magnitudes; therefore it was necessary to derive relationships between J and K and theoretical parameters. We calculated $(J-K)$ from effective temperature (T_e) using the relationship:

$$(J-K) = 259.44 - 137.72\log(T_e) + 18.31(\log(T_e))^2 \qquad (1\sigma_{fit} = 0.02) \tag{2}$$

which we derived from the model atmospheres presented in Table 3 of Cohen *et al.* (1978). These models are only defined in the range $3.58 \leq \log(T_e) \leq 3.72$ therefore we had to extrapolate Equation 2 for the coolest stars in the isochrones ($\log(T_e) \sim 3.52$). This extrapolation was only necessary for isochrones with $[\mathrm{Fe/H}] \geq -0.3$ and ages greater than 5 Gyr. Even for these isochrones only stars within $\lessapprox 1.0$ magnitude of the giant branch tip had effective temperatures cool enough to necessitate the extrapolation. We calculated bolometric K corrections (BC_K) and hence absolute K magnitude (M_K) from total luminosity and effective temperature using the relationship:

$$M_K = -21.89 - 2.5\log(L/L_\odot) + 6.70\log(T_e) \qquad (1\sigma_{fit} = 0.03) \tag{3}$$

[1] The one bulge field which falls to the *left* of the globular cluster relation is the minor-axis -12° field which is likely to be composed of more halo/thick disk stars than bulge stars.

which we derived from the metal-rich globular cluster data presented in Table 28 of Frogel *et al.* (1983). From these data, we found a linear relation between BC_K and T_e and combined this relation with the standard transformation from total luminosity to bolometric magnitude to arrive at Equation 3. The range of T_e in the metal-rich globular cluster data spanned from $3.5 \leq T_e \leq 3.7$ so Equation 3 did not require any extrapolation when applied to the isochrone giant branches. Once we used these relationships to calculate M_K and $(J-K)$ for the isochrones, we constructed CMDs and fit lines to the upper giant branches, in the same absolute K magnitude range as we did for the data. The resulting giant branch slopes are plotted versus [Fe/H] in Figure 3.

Figure 3 is a plot of [Fe/H] versus GB slope for our constructed theoretical M_K vs. $(J-K)$ CMDs. Each line is for a particular age (see the figure caption). Since the J and K values were calculated from simple and incomplete (in parameter coverage) models, we do not expect, nor do we find, good absolute agreement with the data in Figure 2. What we are interested in is the *relative* change in GB slope at a constant [Fe/H] as a function of population age. The two left-most lines are for 16 Gyr and 10 Gyr populations. Since all globular clusters are likely to fall in this range of ages, little change in GB slope as a function of age (at any metallicity) is likely to be apparent. This agrees with the conclusion of KFTP, where they find that age is not likely to add any scatter to their relationship. This conclusion is not true for open clusters however. Old open clusters have ages that place them between the 10 Gyr line and the 1 Gyr line (the right most). In this regime isochrones predict that the contribution of age to determining the GB slope is comparable to the contribution from [Fe/H].

This age effect is a possible explanation of the trend we found in Figure 2. Assuming that the metal-rich globular clusters are older than the mean age of the bulge stars, which are older that the open clusters, then the systematic shift to more positive GB slope at constant [Fe/H] of the bulge field data and the open cluster data are in the same sense as that expected for their age differences. This systematic shift would also explain why Equation 1 systematically underestimates the [Fe/H] of the open clusters – the equation requires an age term. We cannot, however, derive an empirical relation between these three parameters – age, [Fe/H], and GB slope – because there are too little data presently available. Additionally, a theoretical relation cannot be derived because the current isochrones cannot even reproduce one of the empirical relations precisely. For example, if the globular cluster points from Figure 2 are placed on the isochrone models in Figure 3, the globular clusters fall between the 3 Gyr line and the 1 Gyr line. Further, the open clusters span an age range of 5.3 Gyr (Table 1), yet the observed spread in GB slope shift is only a fraction of that predicted by the isochrones.

Finally, we examine Equation 1 taking into account these new data. Figure 2b displays the same data points from Figure 2a with their associated 1σ errors. The error estimates for the globular cluster data and the bulge field data are discussed in KFTP and Tiede *et al.* (1995) respectively. The errors for the open clusters are from Tables 2 and 3 and were discussed previously. The lines are error weighted least squares fits to each population; globular clusters (solid line), bulge fields (dotted line), and open clusters (dashed line). The coefficients for these lines are given in Table 4 which also contains the slope of the [Fe/H]–GB slope relation for each of the theoretical isochrones. The error associated with each of these slopes is due to the nonlinearity of the theoretical upper giant branches. Note that the average slope from the isochrones statistically agrees with the open cluster and bulge slopes, both of which are statistically identical to each other. The globular cluster fit, though steeper than the other relations, is heavily weighted by the lowest point. This lowest point is NGC 6712 which due to its rather low [Fe/H] and its combination of galactic position–velocity, may not be part of the metal-rich disk globular cluster system (Cudworth 1988). Excluding this point, the slope of the globular cluster relation becomes statistically identical to those of the other empirical relations and to the theoretical ones. This concordance suggests that the slope of the original calibration, Equation 1, is likely too large.

4. Conclusions

In this work we have examined the [Fe/H] - GB slope correlation, derived by KFTP for metal-rich globular clusters, in the context of open cluster giant branches. We found that though the correlation is in the same sense for open clusters as for globular clusters, for the open clusters there is a systematic shift to more positive GB slopes at constant metallicity. This shift is also apparent to a lesser degree for the minor-axis bulge fields studied by Tiede *et al.* (1995).

To attempt to understand the source of this systematic shift to more positive GB slopes for the open clusters, we constructed a set of M_K vs. $(J - K)$ CMDs based on the Y96 isochrones. We find that the shift is in the same sense as that predicted for stellar populations of younger ages. Further, the Y96 isochrones predict that the slope of the [Fe/H] - GB slope relation will remain constant for population ages spanning $1 \leq t(Gyr) \leq 16$. Assuming the the age of the open clusters is less than the age of the bulge stars and that the age of the bulge stars is less than the age of the metal-rich globular clusters, both of these predictions are found in the data. Table 4 lists the isochrone and empirical relation slopes. After the one possible discrepant point from the globular clusters is excluded, the empirical and theoretical slopes are all statistically identical. Additionally, the younger populations are found shifted to less negative GB slopes relative to the older populations. Though age is likely a third parameter, we cannot derive a general relation between age, [Fe/H], and GB slope because there are too little data presently available to allow an empirical derivation and the uncertainties in the theoretical models are still to large.

The comparison of the [Fe/H] - GB slope correlation for the three empirical populations and the theoretical isochrones demonstrates that the correlation can be extended to populations other than metal-rich globular clusters. Both the theoretical models and the empirical data suggest that the slope of the relation is ~ -15.5, less negative than the value found by KFTP. The specific relation is dependent on age. The sensitivity to age is small for old populations like globular clusters but becomes increasingly more sensitive at younger ages. This explains why KFTP found no significant age effect while we find a systematic offset for the younger open clusters. Table 4 provides the coefficients of least-squares fits to the various populations which are likely more appropriate than Equation 1 for populations other than metal-rich globular clusters.

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TABLE 1

Open Cluster Parameters

Cluster	[Fe/H]	$E(B-V)$	Age	$(m-M)_0$	ℓ	b
Melotte 66[a]	-0.51	0.14	6.3	13.0	259.6	-14.3
NGC 2204[a]	-0.38	0.08	2.8	13.1	226.0	-16.1
NGC 2477[a]	-0.02	0.22	1.0	10.5	253.6	-5.8
NGC 7789[b]	-0.25	0.31	1.6	11.3	115.5	-5.4

[a] Houdashelt *et al.* (1992), Table 1

[b] Frogel & Elias (1988)

TABLE 2

Derived Cluster Parameters

Cluster	N	GB slope[a]	σ(slope)
Melotte 66	9	-0.077	0.014
NGC 2204	10	-0.096	0.024
NGC 2477	8	-0.111	0.006
NGC 7789	10	-0.099	0.004

[a] GB slope $\equiv \Delta(J-K)/\Delta K$

TABLE 3

Comparison of [Fe/H] Values.

Cluster	Literature		Derived (Eq. 1)	
	[Fe/H]	σ([Fe/H])	[Fe/H]	σ([Fe/H])
Melotte 66[a]	-0.51	0.15	-1.14	0.33
NGC 2204[a]	-0.38	0.20	-0.69	0.57
NGC 2477[a]	-0.02	0.05	-0.33	0.14
NGC 7789[b]	-0.25	0.20	-0.62	0.10

[a] Houdashelt *et al.* (1992), Table 1

[b] Twarog & Tyson (1985)

[c] [Fe/H] values have been compiled from various sources (see Houdashelt *et al.* 1992, Table 1) and are based on *uvby*, *UBV*, or DDO systems. Errors are the standard deviation in values from the various sources.

TABLE 4

Slope of the [Fe/H] – GB slope relation

Population	slope	σ(slope)	intercept	σ(intercept)
Open Clusters	-14.243	1.963	-1.639	0.211
Bulge Fields	-13.613	5.118	-1.692	0.500
Globular Clusters	-21.959	5.920	-2.777	0.612
GCs w/o lower point	-18.844	6.406	-2.442	0.669
Isochrones – 1 Gyr	-18.728	0.370	···	···
Isochrones – 2 Gyr	-14.539	1.212	···	···
Isochrones – 3 Gyr	-15.870	2.036	···	···
Isochrones – 5 Gyr	-14.545	1.247	···	···
Isochrones – 10 Gyr	-15.855	1.041	···	···
Isochrones – 16 Gyr	-15.287	0.932	···	···

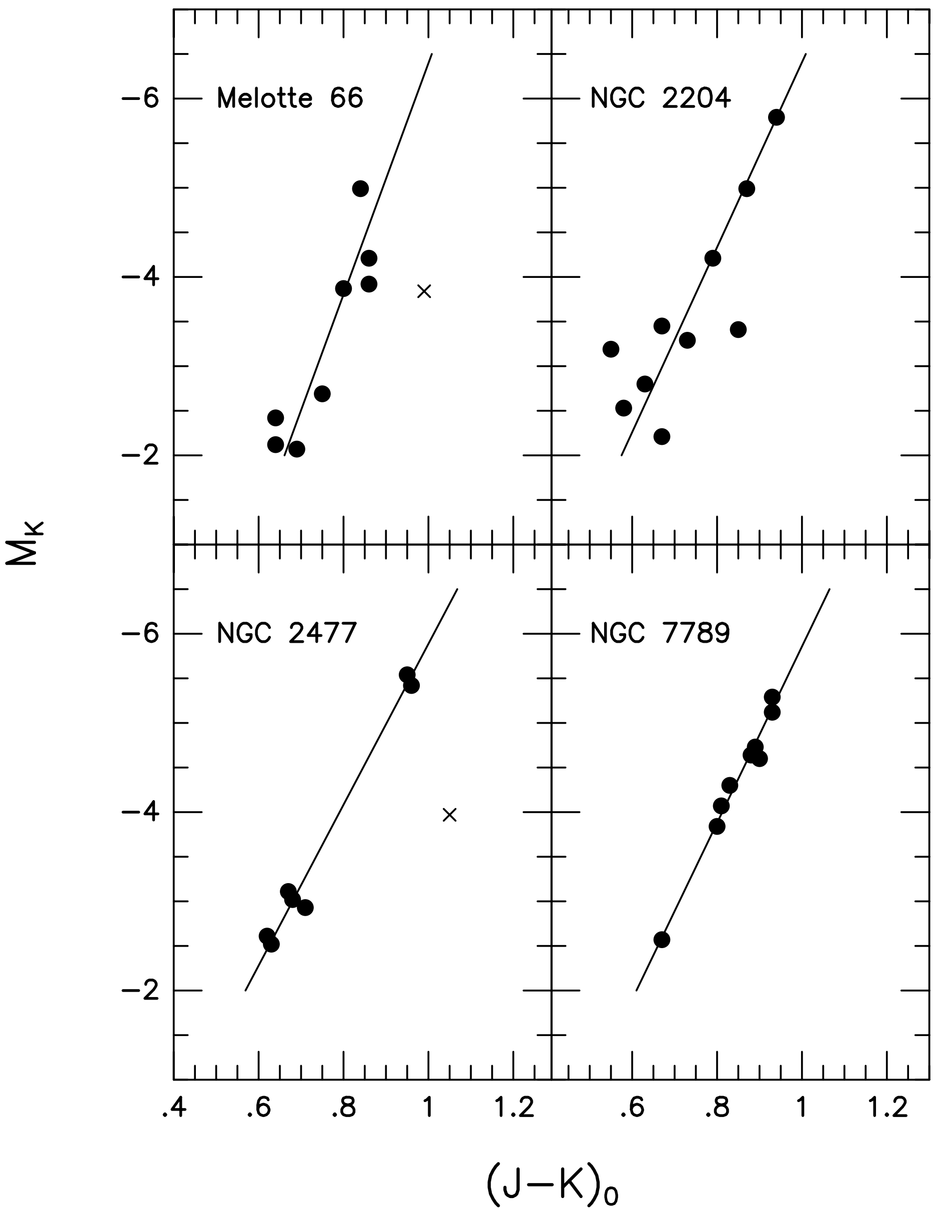

Fig. 1.— CMD of the giant branch for each cluster studied. The lines are the least-squares fits to each giant branch. Photometric errors are comparable to the size of the points with the exception of the dimmest stars in the NGC 2204 plot which have larger uncertainty. Stars denoted by X's were 2σ–rejected and not included in the fits.

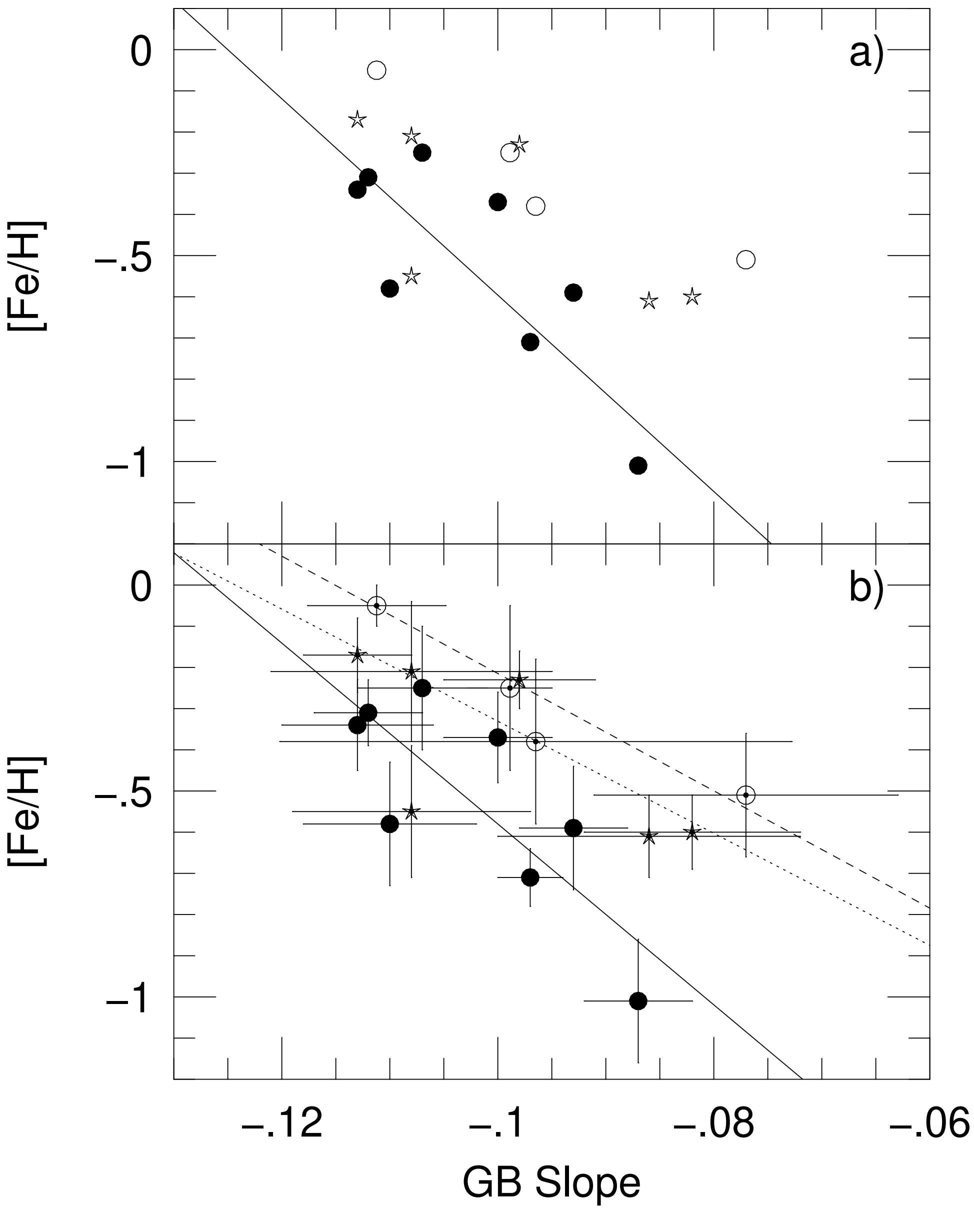

Fig. 2.— Plots of [Fe/H] vs. giant branch slope for globular clusters (solid circles), bulge fields (stars), and open clusters (open circles). a) The solid line is the relation from KFTP derived for globular clusters (Equation 1). b) Same data as in panel a) but with errors from the literature. The lines are error-weighted least squares fits for each population; globular clusters (solid line), bulge stars (dotted line), open clusters (dashed line). Coefficients of these fits are given in Table 4 and are discussed in the text.

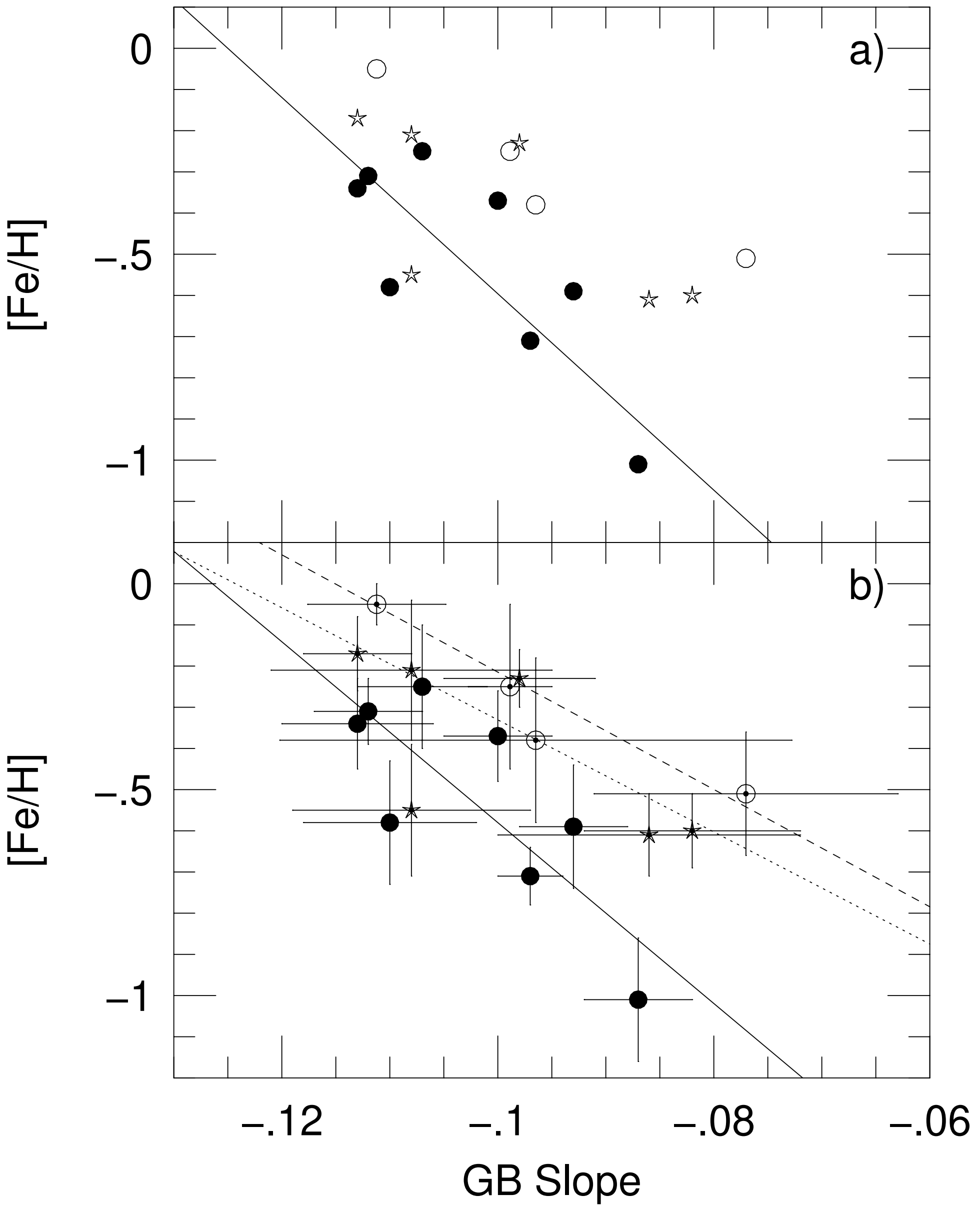

Fig. 3.— Plot of [Fe/H] vs. giant branch slope for isochrone models at various ages. Ages, left to right are 16, 10, 5, 3, 2, 1 Gyr.