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The Age of the Galactic Disk

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ABSTRACT

The galactic disk is a dissipative structure and must, therefore be younger than the halo if galaxy formation generally proceeds by collapse. Just how much younger the oldest stars in the galactic disk are than the oldest halo stars remains an open question. A fast collapse (on a time scale no longer than the rotation period of the extended protogalaxy) permits an age gap of the order of $\sim 10^9$ years. A slow collapse, governed by the cooling rate of the partially pressure supported falling gas that formed into what is now the thick stellar disk, permits a longer age gap, claimed by some to be as long as 6 Gyr. Early methods of age dating the oldest components of the disk contain implicit assumptions concerning the details of the age-metallicity relation for stars in the solar neighborhood. The discovery that this relation for open clusters outside the solar circle is different than in the solar neighborhood (Geisler 1987), complicates the earlier arguments.

The oldest stars in the galactic disk are at least as old as NGC 188. The new data by Janes on NGC 6791, shown first at this conference, suggest a disk age of at least 12.5 Gyr, as do data near the main sequence termination point of metal rich, high proper motion stars of low orbital eccentricity. Hence, a case can still be made that the oldest part of the galactic thick disk is similar in age to the halo globular clusters, if their ages are the same as 47 Tuc. The latter conclusion on coveability of the globular cluster system depends on whether the halo globular clusters of low metallicity possess progressive oxygen enhancement similar to that for the high velocity field subdwarfs.

I. INTRODUCTION

Disks in galaxies clearly are dissipative structures and as such, must have formed after the halo phase, if galaxy formation generally proceeds by collapse (eg. Eggen, Lynden-Bell, and Sandage 1962 hereafter ELS; Larson 1976). If the collapse to a disk is rapid (measured, for example, in units of the free-fall time, or the rotation period), the oldest parts of the disk will differ only slightly from the age of the halo: if slow, conversely.

ELS considered the halo phase of the collapse to be rapid (relative to the rotation period), otherwise, they argued, the high eccentricity of the halo stellar orbits could not be understood. (Slow collapse, by definition, is one where the collapse velocity toward the center is small compared to the rotational velocity about the center, never giving the observed plunging orbits of the lowest metallicity halo stars).

There is, of course, a hierarchy of collapse times, $t = (G\rho)^{-1/2}$, depending on the density of the part of the protogalaxy under consideration. Hence, the disk is expected to be built up over some time, even if the very first stages of disk formation occurred rapidly. Furthermore, the dynamics of the collapse requires that the disk forms at different rates as a function of distance from the center (Larson 1976). What then can be meant by the "age of the galactic disk"? There is no controversy that the mean age of the stellar content of the disk must be younger than the halo. Stars are being formed today in all disks of Sb to Im galaxies along the Hubble sequence. What we seek, rather, is the age of the oldest stars in the disk in the solar neighborhood. What is the age gap between the mean halo age and the first stars that can be identified with a galactic disk?

Although widely quoted from ELS, and as stated in their paper, a very short collapse time of a few x10^8 years would be the shortest possible age gap, essentially the free-fall time of the highest density regions of the protogalaxy. This very short time interval was the ELS estimate based on a rotation period of 2 x 10^8 years in the present equilibrium galaxy - as mentioned, it is the fast collapse rate required to give the high eccentricity orbits. The rotation period of the extended protogalaxy was, however, longer, than the present equilibrium value, permitting an extension of the ELS time scale. This circumstance would permit the ELS picture to accommodate a time gap of a few 10^9 years between the oldest star formation in the halo and in a nacent disk, with then a subsequent building up of the disk even into modern times by infall over an extended time, due to the hierarchy of collapse times.

The metallicity distribution of the thin disk, of the intermediate population (often now called the Gilmore-Wyse thick disk at heights between 300 and 1200pc), and of the halo give an additional clue to the timing of events of halo and disk formation. Thin disk stars [$\sigma(w) \sim 17$ km s^{-1}] with a scale height of ∼150 pc have a metallicity distribution peaked near solar with a very small dispersion in [Fe/H] - no stars of this component has [Fe/H] smaller than about -0.6 (cf. Sandage and Fouts 1987, Fig. 11). On the other hand, the metallicity of the thick disk component varies progressively with height (Gilmore and Wyse 1985; Sandage and Fouts 1987, Fig. 16; Norris 1987), showing that this transition region (call it whatever you wish, if you object to the term thick disk) between the thin disk and the halo was formed over a finite time interval sufficiently long for the progressive metal enrichment of the ISM with time to have occurred. To estimate the length of this interval, and therefore the size of the time gap, by using the metallicity distribution we must have knowledge of the rate of metal enrichment early in the galactic history, but this has usually been derived the other way around, by the age dating, using other means, of components of the galaxy of different metallicities to produce an age-metallicity relation (Sandage 1968, 1982 Fig. 7; Eggen and Sandage 1969, Fig. 7; Twarog 1980), begging the present question if we were to ask that the time interval itself be determined from the metallicity distributions. What, then, are the age dating methods; and can they be made independent of the age-metallicity relation?

II. EARLY MYTHS USED IN AGE DATING

a. What did Baade resolve? The earliest belief that the oldest stars in a galactic disk are the same age as globular clusters followed from Baade's description of his resolution of the disks of M31 and NGC205 into stars at the same level as the brightest stars in globular clusters in the same field. By the mid 1950's, with the identification of the globular cluster main sequence, it became evident that globular clusters in our galaxy are old. Further work on a large number of galactic globular clusters showed them to be the oldest identifiable component of the galaxy. Hence, within the most elementary two population concept (Baade 1944), the oldest stars in the disk of M31 were thought to be as old as the globular clusters. With the resolution of the red star sheet in M33, IC 1613, and NGC 6822 in the same way, the same conclusion was reached in the 1960's.

However, it is now known that the height of the giant branch of any evolving population is not a function of age but only of [Fe/H], once the Hyashi track is reached. This is true for any evolutionary track for masses less that ∼2 solar masses independent of age. Hence, the presence of the Baade background sheet in any aggregate population at any given absolute magnitude depends primarily on metallicity. This reduces its use as an age discriminate unless, again, appeal is made to an age - metallicity relation which, as we shall later emphasize, is a strong function of position in the galaxy (cf. Geisler 1987), imitating, beyond the solar circle, the age - [Fe/H] relation of LMC or SMC (Smith and Stryker 1986, their Fig. 2).

b. The presence of a horizontal branch, especially RR Lyrae stars, by analogy with its existence in globular clusters, had, in the 1950's to 1970's been taken as a sure proof of old age for any aggregate containing such stars. It is now known that HB's occur in all clusters whose ages range from NGC 2477 or NGC 2420 (2×10^8 years) to the oldest globular clusters. While it is true that the morphology of the HB does appear to depend on age (blue extensions as in M15 to red stubby as in the intermediate age open clusters), this morphology is again controlled mainly by [Fe/H], not age. Hence, arguing from the color distribution of HB stars to determine ages (Norris and Green 1988) can only be correct within the context, again, of assuming a particular age - [Fe/H] relation, valid for the particular region of the galaxy being discussed. It then also follows that the presence of $\Delta S = 0$ RR Lyrae stars with the kinematics and spatial distribution of the thin disk (Sandage 1982) does not necessarily mean that the oldest stars in this thin disk have globular cluster ages.

c. The position in color of the evolving giant sequence was early used (Wilson 1959, 1976; Sandage 1962) to show that the giant sequence of NGC 188 - then the oldest galactic cluster known - formed the envelope in the H-R diagram, redder than which no disk field giant existed. From the bluer position of giants of lower metallicity than NGC 188, using the data of Helfer (1969) and Janes (1975), I concluded (Sandage 1982, Figs. 4, 5, and 6) that disk giants as old as 47 Tuc exist, based on the variation of $(B-V)_{o,g}$ with [Fe/H] and the position of the 47 Tuc giant sequence relative to that of NGC 188.

At the time, the proof seemed strong, but it is now clear that it too relies on an assumption of an age - [Fe/H] relation for the disk stars in the solar neighborhood that were studied by Helfer and Janes. This is because the position in color of the giant branch of any aggregate is not a function of age but, again, primarily of [Fe/H], as shown in Figure 1 here. Five isochrones are shown, taken from the 1988 new Yale table of evolutionary tracks, kindly supplied before publication by Demarque. The two heavy lines are for ages of 10 and 20 Gyr. but for metal abundances of [Fe/H] = +0.37 and -2.23. (Note that the MS termination point is brighter for the 20 Gyr track of low metallicity than for the 10 Gyr track of high metallicity). As argued in the 1982 paper on disk age dating, the older more metal poor track is, as well known, bluer than the younger (but metal rich) track. However, the three dotted tracks, for very young aggregates, all with [Fe/H] = -0.23, have giant branches (the Hyashi rise) also bluer than the 10 Gyr aggregate, at a color that is almost independent of age. Hence, again, unless we can be certain that no young, low metallicity stars can exist in the solar neighborhood, the blueness of the Hyashi track for the Helfer-Janes giants is not a water-tight proof of 47 Tuc-like age, as I argued in 1982. Therefore, as before, the chemical history of the solar neighborhood (i.e., the age - [Fe/H] relation) must be known independently for the argument to be without reservation. And the work of Geisler (1987) on young clusters beyond the solar circle sends a red flag for the fundamental variation of this age-metallicity relation with galactic position, again hinted at before by the chemical gradients in the disk (Janes and McClure 1972; Searle 1972), and the difference in metallicity at a given age depending on position (Demarque and McClure 1977), but now shown explicitly by Geisler.

III. MODERN ATTEMPTS TO AGE DATE THE DISK

With, then, the failure of the methods of (1) M_v for the tip of the giant branch (Baade's method of identification of the brightest disk stars with globular clusters), (2) the presence of disk $\Delta S = 0$ RR Lyrae stars and (3) the color of intermediate metallicity disk giants, as methods to uniquely age date the disk, we are left only with the two methods of (a) main sequence turn-off points of field stars and (b) the age dating of disk clusters.

(a) In his study of colors and magnitudes of F and G stars with trigonometric parallaxes, Eggen (1964, Figs. 1 and 2; 1970, Fig. 14) called attention to disk dwarfs that lay above the zero age main sequence that are fainter than the NGC 188 turn-off. The lower envelope of the turn-off of these stars is ~0.5 mag fainter than that of NGC 188. He further showed (Eggen 1964, his Table on p. 599) that for Δ(B-V) values (due to low [Fe/H] between 0.06 and 0.10 mag, the σ(W) for such stars is 40 km s^{-1}, identical to the value of σ(W) for the thick disk of similar metallicity derived by Hartkopf and Yoss (1982, their Fig. 8) and by Sandage and Fouts (1987, their Table V for metallicities between [Fe/H] of 0 to -0.8). The argument, however, that these stars are older than NGC 188 suffers from the large errors in the trigonometric parallaxes, making the reality of a fainter turn-off than for NGC 188 possible, but not proved.

The 1988 Yale parallax catalog does contain a few bona fide subgiant stars that may be fainter that the NGC 188 subgiants (i.e. the horizontal track just before hitting the Hyashi rise), but again none of these candidates have small enough trigonometric errors to prove the case.

An indirect proof that thick disk stars (defined in terms of intermediate metallicities with <[Fe/H]>~-0.4) have turn-off colors expected for 47 Tuc-like main sequence termination colors is available from the very large photometric catalogs of proper motion stars by Sandage and Kowal (1986, their Fig. 6), and Carney and Latham (1987). As discussed by Gilmore and Wyse (1987, their Fig. 13), the bluest colors (which are, then, the colors of the main sequence termination points) as a function of metallicity move redward progressively for the disk dwarfs, as the metallicity increases, becoming identical to the turn off color of 47 Tuc (B-V = 0.55) in the 47 Tuc metallicity bin. Figure 6 of Sandage and Kowal (1986) shows the same thing in the sloping lower envelope to the bluest color distribution for different uv excesses. These stars (0>[Fe/H]>-0.8) also have thick disk kinematics (Sandage and Fouts 1987). This then is a case for a 47 Tuc age for at least one component of the thick disk in the solar neighborhood (but see the next section for a different color test - for HB clump stars - with which Norris and Green (1988) argue for a different conclusion).

(b) Janes (1988, this conference) has presented the very strongest proof for an older age than NGC 188 for the disk by showing that the thick disk open cluster NGC 6791 (ℓ = 70°, b = +11°, z = 750pc) has an age of 12.5 Gyr, about 1 Gyr less than the age derived by Hesser et. al. (1987) for 47 Tuc. An early proof of the old age of NGC 6791 was that of Kinman (1965).

IV. METALLICITY DISTRIBUTIONS OF THICK DISK GIANTS

A major kinematic and chemical survey of giants in the galactic poles by Hartkopf and Yoss (1982, HY) and by Yoss, Nesse, and Hartkopf (1987, YNH) provides important data on stars to distances from the plane of ∿5000 pc. Most of these stars are members of the thick disk, as proved by complete star counts, giving a density fall-off with height (McNeil 1986, his Fig. 10) which requires two components with different scale heights. Over the first 300 pc, the thin disk dominates the counts with a formal scale height of ∿170pc. From z between 400 to 2000pc a component with a scale height of ∿500 pc is required - obviously the Gilmore-Wyse thick disk.

Figure 2 shows the distribution of [Fe/H] for the HY plus YNH giants in two distance ranges. The well known chemical gradient (see Gilmore and Wyse 1985, their Figs 5 and 7), is evident in the shift of the distribution toward lower metallicities at the higher height. The important point to note is that, in the distance interval 1000>z>500, the distribution of [Fe/H] is similar to Zinn's (1985) disk globular clusters, whose metallicities, themselves, are generally more metal rich than [Fe/H] = -0.8 which applies for 47 Tuc, just as for the distribution in the top two panels of Figure 2 for the HY and YNH field giants.

The same conclusion that the thick disk giants have a higher metal abundance than 47 Tuc follows from an independent sample of giants isolated by Eriksson (1978) and studied by Norris and Green (1988), shown in Figure 3. Here, the metallicity distributions are compared again with the [Fe/H] distribution of the disk globular clusters. 47 Tuc is at the low metallicity end of the three illustrated distributions - the important point to bear in mind in the discussion later in Section VI.

V. COMPOSITE CM DIAGRAMS FOR INTERMEDIATE AGE OPEN CLUSTERS

It is of interest to return to the point made in Section IIc concerning the position of the giant branches in clusters of different age and chemical composition. Very much recent work on intermediate age open clusters, especially in the galactic anticenter beyond the solar circle, shows that metal poor galactic clusters exist with a range of ages as young as ∿2 x 10^9 years (NGC 2420) to almost as old as NGC 188 (Mellote 66). The position of the giant branches as a function of [Fe/H], regardless of the age, is of special interest, in view of the discussion in Sections IIb and c.

Data from the literature on CM diagrams for metal poor clusters are summarized in Figure 4. In the code to the diagram, the magnitude difference between the horizontal branch (present in all the clusters at nearly the same M_v value regardless of age), is given, together with the literature value of [Fe/H], and the galactic longitude and latitude. The individual CM diagrams have been normalized in M_V by main sequence fitting to an adopted ZAMS for [Fe/H] = 0, with then corrections applied for the main sequence position as a function of [Fe/H] (Sandage 1970, Table 11; VandenBerg and Bell 1985, Fig. 5).

The data sources for the various clusters are: NGC 2158 from Arp and Cuffey (1962) and Janes (1979); NGC 2506 from McClure, Twarog, and Forrester (1981); NGC 2243 from Hawarden (1975) and Gratton (1982); NGC 2420 from McClure, Forrester, and Gibson (1974); Melotte 66 from Anthony-Twarog, Twarog, and McClure (1979) and Gratton (1982); and NGC 2204 from Hawarden (1976) and Geisler (1987).

The important features of Figure 4 are (1) all giant branches are closely in the same place as regards color, with only a slight variation due to mass (age), consistent with theoretical expectations (Green, Demarque, and King 1987), (2) the stubby red HB's are all at closely the same M_V value, regardless of age (Section IIb), (3) hence the magnitude difference between the HB and the turn-off is a monotonic function of age, (4) as mentioned earlier, many of these low metal abundance clusters are in the galactic anticenter, beyond the solar circle (Geisler 1987).

A similar diagram for more metal rich clusters is shown in Figure 5. The data sources are: NGC 188 from Eggen and Sandage (1969); M67 from Eggen and Sandage (1964); IC 4651 from Anthony-Twarog and Twarog (1987); NGC 7789 from Burbidge and Sandage (1958); NGC 3680 from Eggen (1969) and McClure (1972); and NGC 2477 from Hartwick, Hesser and McClure (1972).

The points to note in Figure 5 are (1) four of the six giant branches are closely in the same place as to color, and this position is displaced redward from the giant sequences in Figure 4, as expected due to the higher metallicity, (2) the red stubby horizontal branches are in closely the same place at $M_V \sim +0.9$ as in Figure 4, independent of the age, (3) the position of the giant branch in NGC 188 is redward from that in M67 by an amount larger than that predicted by the isochrones as a function of mass alone, suggesting that [Fe/H] for NGC 188 is higher than for M67, (4) the giant sequence in NGC 2477 is bluer than expected for the adopted metallicity, although it is displaced in the correct sense to be due partly to a greater mass (younger age) than for NGC 7789 and the other clusters.

VI. COLOR OF THE HORIZONTAL BRANCH AS AN AGE DISCRIMINANT?

Norris and Green (1988) have argued that the red color of Eriksson giants in Figure 3 proves that the bulk of these stars must be younger than 47 Tuc, and therefore that the thick disk is, itself, much younger than 47 Tuc, similar in age to the intermediate age open clusters. The age gap between the disk and the halo would then be very large-suggested by them to be as large as 6 Gyr. Note that they base this conclusion on the fact that the color distribution of all but 4 of the Eriksson giants is redder than the reddest of the 47 Tuc HB stars, imitating the color distribution of the HB's of the intermediate age open clusters.

In Figure 6 we have set out the data for the Norris-Green test in detail to determine if this conclusion is inevitable. Shown in the top two panels are the B-V color distributions for the same stars that are shown in the top two panels of Figure 3. In the lower panel of Figure 6 are the color limits of the horizontal branches of all clusters shown in Figures 4 and 5, ordered progressively by [Fe/H], taken from the literature. The redward progression of color as [Fe/H] becomes more metal rich is evident for all clusters except NGC 2477 - the cluster with the least certain data. This redward progression is clearly a function of [Fe/H] alone, regardless of age, as shown by the random order of the magnitude differences between the HB's and the main sequence TO's listed in the code as the last column.

The conclusion is that the redness of most of the Eriksson giants says nothing directly about age differences between 47 Tuc and these field giants, but states only again the fact, shown in Figure 3, that these field giants have larger [Fe/H] values than 47 Tuc.

To infer an age dating from these color data then, as emphasized in Section II, again requires appeal to an age-metallicity relation that would exclude such high [Fe/H] values at 47 Tuc ages in the galactic pole at the solar circle. Note that higher [Fe/H] values than 47 Tuc exist for most of the disk globulars (see the comparison in Figure 3), which may themselves have 47 Tuc ages - but note also that all of these disk clusters are inside the solar circle (Zinn 1985, Fig. 12). We are thus required to inquire about the differences in the age-metallicity relation as a function of distance from the galactic center and height above the plane.

VI. THE AGE-METALLICITY RELATION AS A FUNCTION OF GALACTIC POSITION

Geisler (1987), using age and metallicity data on the intermediate age open clusters which we have used in Figure 4, showed that the rate of increase of [Fe/H] in the anticenter beyond the solar circle is shallow, similar to that of LMC and SMC (Smith and Stryker 1986) rather than to the very steep rise of [Fe/H] with time known to apply to the solar neighborhood, as mentioned earlier.

Data also exist for the galactic center from the work of Whitford and Rich (1983) and Rich (1988) where $<[Fe/H]> \sim +0.3$ applies at the present epoch in the center, much higher than in the solar neighborhood, giving two points for the general chemical gradient over the galactic disk, a gradient that has been studied by Janes (1979) using galactic clusters.

Combining these pieces into a suggestion for the differences in the rate of metal enrichment as a function of time for various galactic positions results in Figure 7, which shows the progressive change of the enrichment rate outward form the galactic center over the past 13.5 Gyr. A vertical cut at any given age gives, then, the gradient d[Fe/H]/dR that is expected as function of position.

Figure 7 is highly schematic. The details relevant for the present discussion of the age of the disk are concentrated at the left hand edge of the diagram near T = 13 Gyr, namely the difference in the slope of the two curves at the solar circle for z = 0 and at the solar circle for z = 0.5 kpc at early times so as to say if the Eriksson giants in the last section with $<[Fe/H]> \sim -0.4$ must be younger than 47 Tuc. Knowledge of this fine a detail is clearly lacking at the level needed to use [Fe/H] as an age discriminant, especially because the next to oldest open cluster known (NGC 188) has such a high metallicity, yet it is very old, showing the semi-stocastic nature of the time rate of change of the metal enrichment with position.

VII. CONCLUSION

The outcome of this discussion is highly unsatisfactory because it is our view that no definitive test has yet been isolated that permits a convincing answer to be given if older disk stars exist than NGC 188 at ~10 Gry. The new data of Janes on NGC 5791, suggesting an age of 12.5 Gyr at this preliminary stage of his analysis, would clearly put the age gap between the oldest disk objects and 47 Tuc at a small value, near 1 Gyr. Then the question arises if all halo clusters are the same age as 47 Tuc. As emphasized often in this conference, the answer to this question is strongly dependent on the question of the oxygen enhancement as [Fe/H] decreases - namely on the problem of chemical composition (O and Ne) as a function of chemical composition (Fe) for the oldest stars.

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FIGURE CAPTIONS

Fig. 1. Representative isochrones for various ages and metal abundances (marked in Gyr and [Fe/H] values) from the revised Yale isochrones (1988). Note the non-uniqueness of the color of the Hyashi track as an *age* discriminant.

Fig. 2. Distribution of [Fe/H] for the Hartkopf-Yoss and the Yoss, Neese, Hartkopf giants in the galactic polar caps compared with the [Fe/H] distribution of the disk globular clusters from Zinn.

Fig. 3. Same as Fig. 2 but for the Eriksson giants in the pole.

Fig. 4. Composite CM diagram for metal poor open clusters compared with 47 Tuc.

Fig. 5. Composite CM diagram for metal rich open clusters.

Fig. 6. Comparison of the colors of the Eriksson polar giants with the colors of the horizontal branches of the clusters shown in Figures 4 and 5. The redness of the branches is a function of [Fe/H] and not of age *per se*.

Fig. 7. Schematic suggestion of the different shapes of the age-metallicity relation for different regions of the galaxy.

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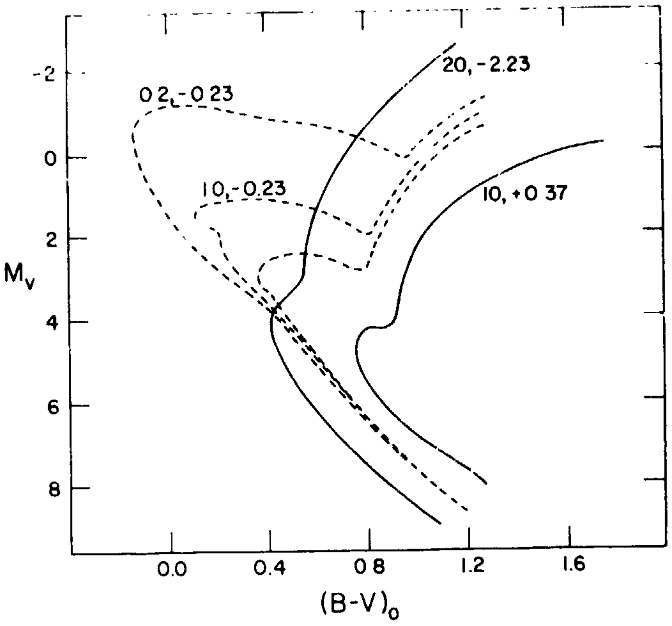

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M_V
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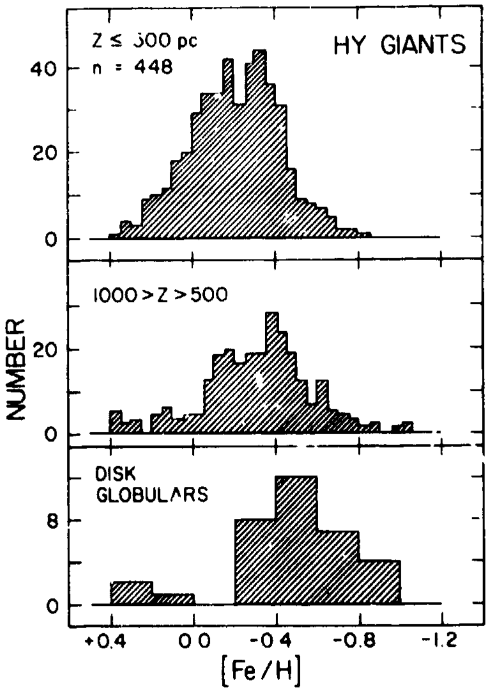
20, -2.23
10, +0.37

Fig. 1



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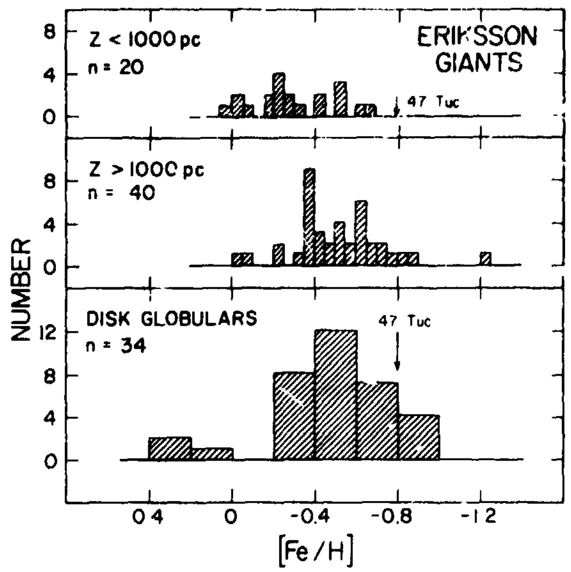
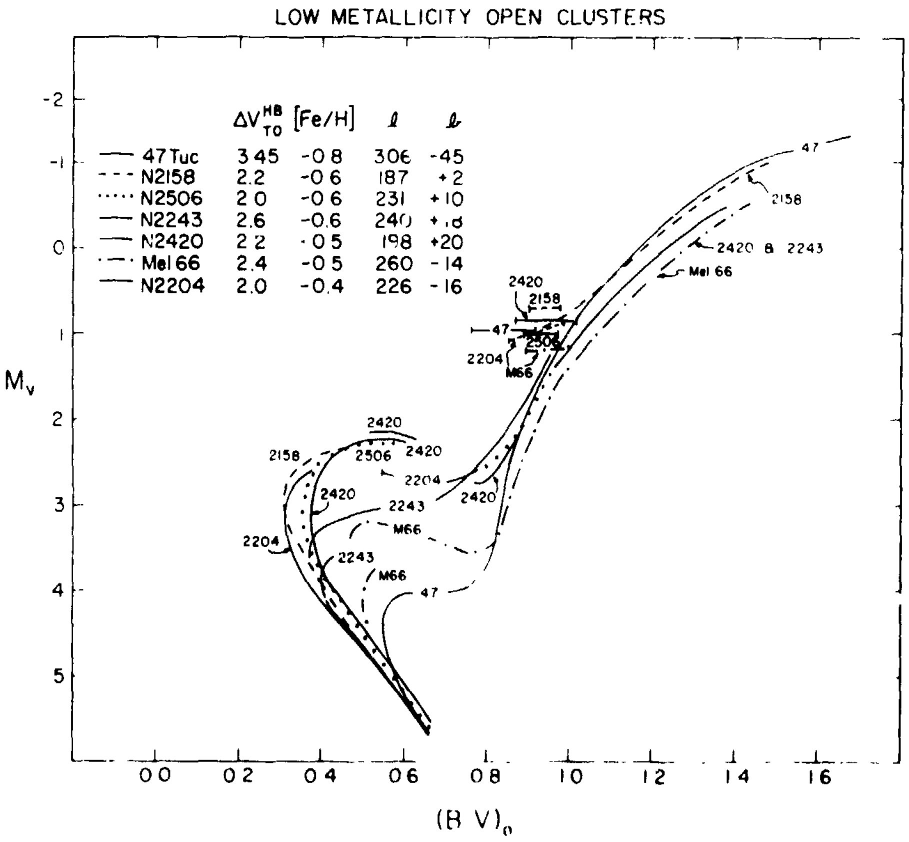
-0.4
-0.8
-1.2
[Fe/H]

Fig. 2



ERIKSSON GIANTS
Z < 1000 pc
n = 20
47 Tuc
Z > 1000 pc
n = 40
DISK GLOBULARS
n = 34
47 Tuc
NUMBER
8
4
0
12
0 4
0
-0.4
-0.8
-1 2
[Fe/H]

Fig. 3



LOW METALLICITY OPEN CLUSTERS
ΔV_{TO}^{HB} [Fe/H] l b
47 Tuc 3 45 -0 8 306 -45
N2158 2.2 -0 6 187 +2
N2506 2 0 -0 6 231 +10
N2243 2.6 -0.6 240 +18
N2420 2 2 -0 5 198 +20
Mel 66 2.4 -0 5 260 -14
N2204 2.0 -0.4 226 -16
M_v
(B V)$_0$
47
2158
2420 & 2243
Mel 66
2420
2158
47
2506
2204
M66
2420
2158
2506
2420
2204
2420
2243
2420
M66
2204
2243
M66
47
-2
-1
0
1
2
3
4
5
0 0
0 2
0 4
0 6
0 8
1 0
1 2
1 4
1 6

Fig. 4

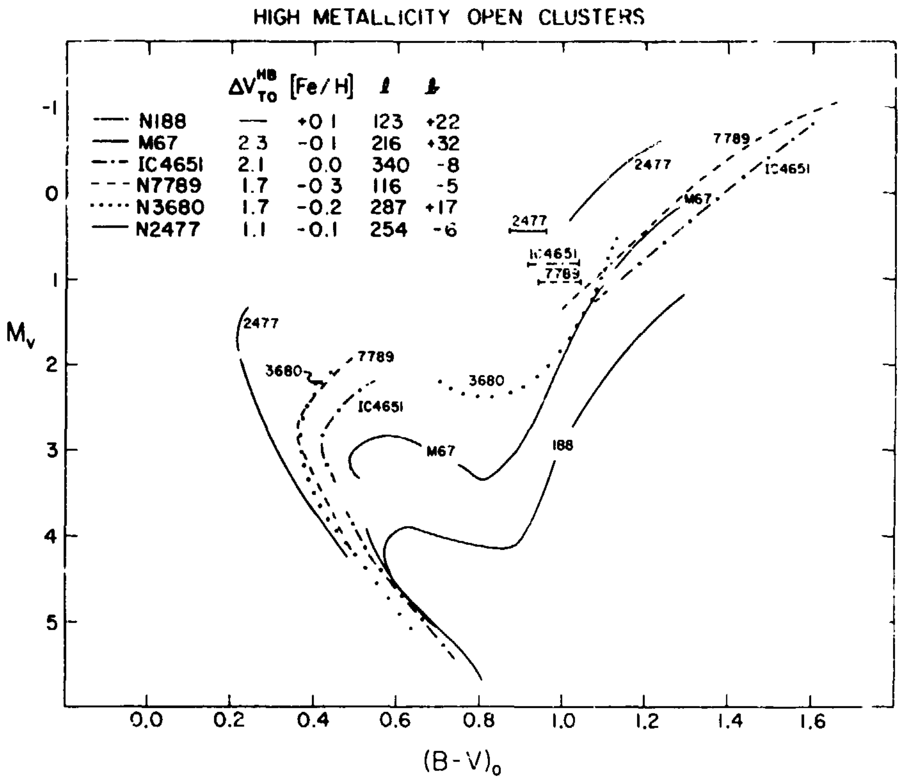

HIGH METALLICITY OPEN CLUSTERS
ΔV HB TO [Fe/H] l b
N188 — +0 1 123 +22
M67 2 3 -0 1 216 +32
IC4651 2.1 0.0 340 -8
N7789 1.7 -0 3 116 -5
N3680 1.7 -0.2 287 +17
N2477 1.1 -0.1 254 -6
M_v
-1
0
1
2
3
4
5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
(B-V)_0
2477
7789
IC4651
M67
2477
IC4651
7789
2477
3680
7789
IC4651
3680
M67
188

Fig. 5

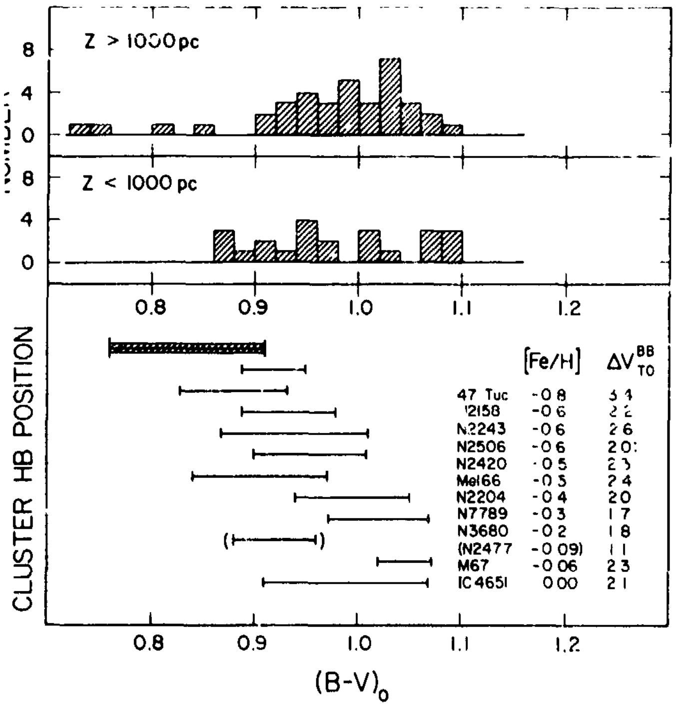

Z > 1000 pc
Z < 1000 pc
8
4
0
0.8
0.9
1.0
1.1
1.2
CLUSTER HB POSITION
[Fe/H] ΔV BB TO
47 Tuc -0 8 3 4
2158 -0 6 2 2
N2243 -0 6 2 6
N2506 -0 6 2 0
N2420 -0 5 2 3
Mel66 -0 3 2 4
N2204 -0 4 2 0
N7789 -0 3 1 7
N3680 -0 2 1 8
(N2477 -0 09) 1 1
M67 -0 06 2 3
IC 4651 0 00 2 1
(B-V)_0

Fig. 6

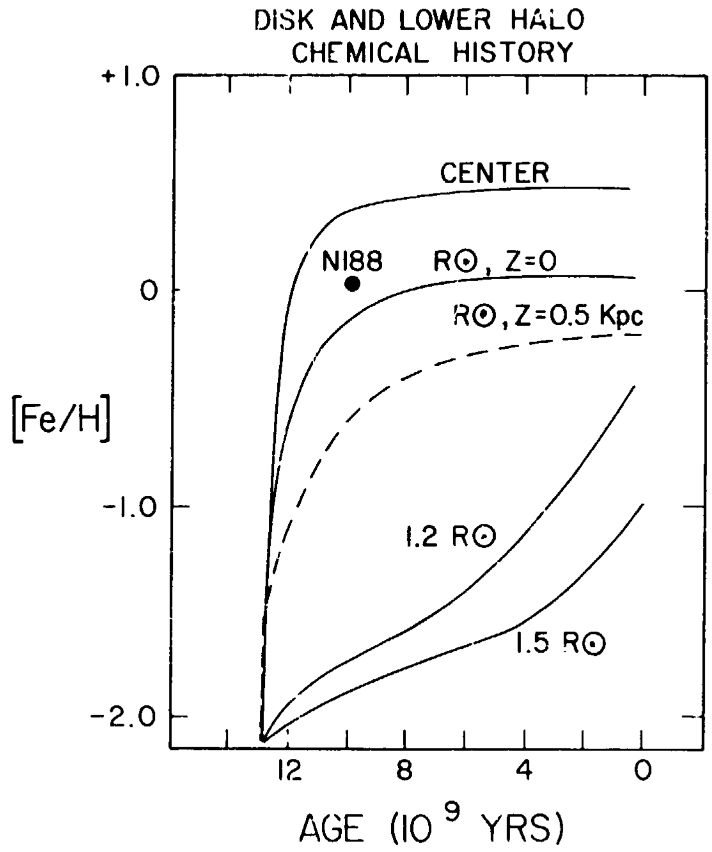

DISK AND LOWER HALO
CHEMICAL HISTORY
+1.0
0
-1.0
-2.0
[Fe/H]
CENTER
N188
R⊙, Z=0
R⊙, Z=0.5 Kpc
1.2 R⊙
1.5 R⊙
12
8
4
0
AGE (10 9 YRS)

Fig. 7