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Abundances in Outer Halo Globular Clusters and Field Stars

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Abstract
We report on the observations of element abundance ratios in metal-poor halo field stars and globular clusters, emphasizing the recent discovery of the lower [X/Fe] ratios for certain elements in outer halo stars and (potentially) globular clusters.

1.1 Introduction

The traditional explanation for the chemical evolution of the Galactic halo was put forth by Tinsley (1979) and is based on the differing products of the two main types of supernovae. Type Ia supernovae produce mainly Fe-group elements, while Type II supernovae produce lighter elements (including the so-called ‘alpha’ elements) as well as some Fe-group and heavier elements. Since the time between star formation and explosion differs between the two types, there is a time in which the enrichment is from Type II SN. The stars created out of the ashes of these early Type II supernovae will be relatively rich in the alpha (and other light) elements until enough Type Ia supernovae can explode to ‘dilute’ the light elements with Fe-group elements. This overall pattern is seen observations of halo stars and clusters (see Wheeler et al. 1989 and McWilliam 1997 for reviews), and indicates that element ratios can be used as an indicator of the history of a stellar population.

Recent developments have shown that the chemical evolution of the halo is more complicated than the original Tinsley (1979) model. Nissen & Schuster (1997) studied stars of intermediate metallicity ($-1.3 < $ [Fe/H] < -0.5) and found that there was a number of stars on halo-like orbits that exhibited significantly lower [α/Fe] ratios than the disk stars at similar metallicities. King (1997) found solar-like [α/Fe] ratios in the metal-poor proper motion pair HD 134439/40, and Carney et al. (1997) found sub-solar [α/Fe] ratios in the even more metal-poor star BD +80 245.

Following a suggestion in Nissen & Schuster (1997), Hanson et al. (1998) found that in a sample metal-poor halo giants, about a third of the stars on retrograde orbits showed low values of [Na/Fe], compared to none of the stars on prograde orbits.

1.2 Trends in Metal-poor Field Stars

To help clarify the issue, Stephens (1999), Fulbright (2000, 2002) and Stephens & Boesgaard (2002) studied large numbers of metal-poor stars. Stephens (1999) and Stephens & Boesgaard (2002) undertook a survey of 56 metal-poor stars selected for their extreme orbits, while Fulbright (2000, 2002) analyzed 168 stars covering a wider range of metallicity

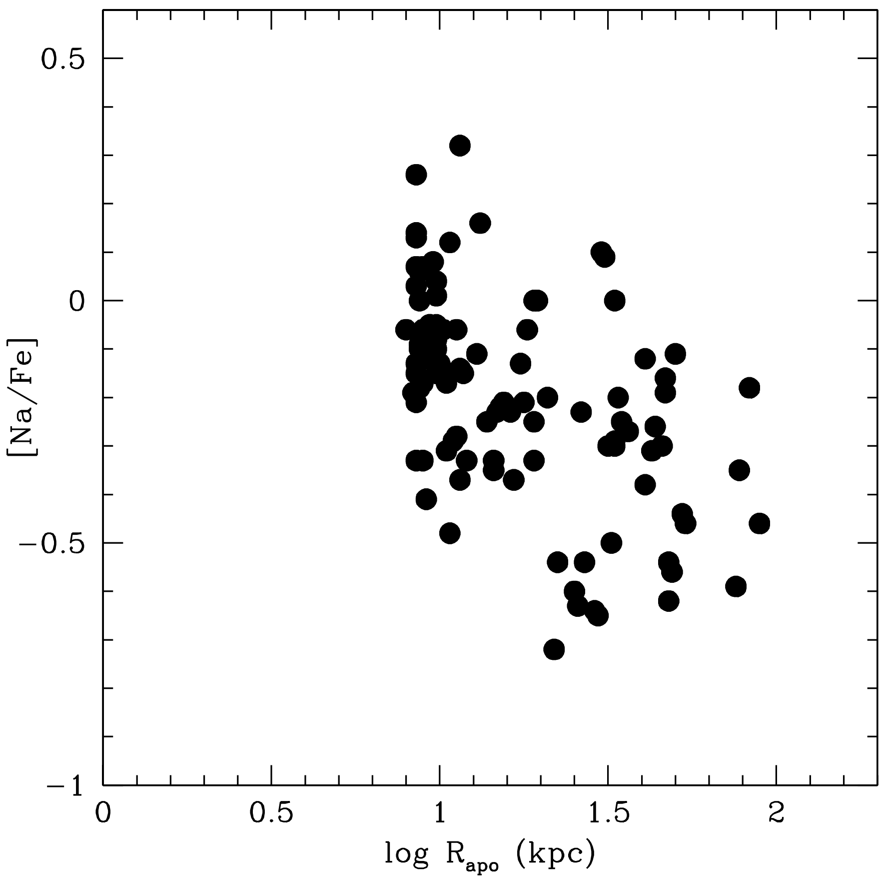

Fig. 1.1. The [Na/Fe] ratios of the metal-poor ([Fe/H] < -1) field stars from Fulbright 2002 and Stephens & Boesgaard 2002 plotted as a function of their orbital apogalacticon radii. The [Na/Fe] ratio drops for stars whose orbits reach into the outer halo. There are no stars with [Na/Fe] < -0.5 and $R_{apo} <$ 20 kpc.

and kinematic parameters. For this proceeding, we will combine both data sets and review the results found by both groups.

The primary result is that the enhancement of light elements, including the α-elements, with respect to iron decreases with increasing apogalactic radius. For stars with [Fe/H] < -1, the element ratio showing the largest decrease with radius is [Na/Fe]. As can be seen in Figure 1, the mean [Na/Fe] ratio for stars with R_{apo} = 8 kpc is about solar, but the mean ratio drops to about −0.5 for stars with orbits that reach out to 100 kpc. At a given radius, there is still considerable scatter (larger than what would be expected from observation uncertainty alone) in the [Na/Fe] values.

Other elements that show the same trend include Mg, Al, and Si. The elements Ca and Ti show weaker trends, as do the heavier elements Ni, Y, and Zr. A summary of the results for stars with $-1 >$ [Fe/H] > -2 can be seen in Figure 2. In this plot, the stars are grouped

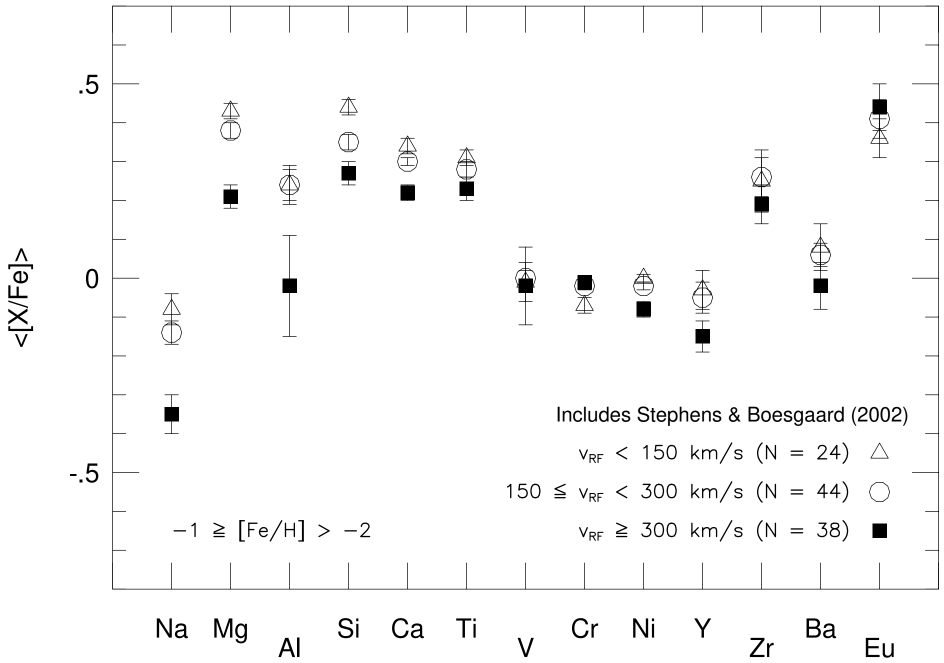

Fig. 1.2. The mean [X/Fe] ratios for three Galactic rest-frame velocity groups taken from the 106 intermediate metallicity stars in Fulbright 2002 and Stephens & Boesgaard 2002. The highest velocity stars show lower mean ratios for the elements Na, Mg, Al, Si, etc.

by their galactic rest-frame velocity rather than orbital parameters. The advantage of this choice is that the results are not subject to the choice of galactic potential model. Nearly all of the stars observed are presently within 1 kpc of the Sun, so the stars that have orbits that go to the outer halo must have very elliptical orbits (the mean ellipticity of all 106 stars included in Figure 2 is 0.71). Many of these stars pass within 1 kpc of the Galactic Center, so their orbital parameters are sensitive to the chosen galactic potential.

The elements Al, V, Zr, and Eu were not included in the analysis of Stephens & Boesgaard (2002), and not every element was observed for every star in the sample. For example, the large scatter in the [Al/Fe] ratio seen in the high-velocity bin is partially due to only 6 of the 38 stars in that velocity group having observable Al abundances.

Figure 3 shows that stars that have lower [Na/Fe] ratios also have lower [Mg/Fe] ratios. Although not plotted here, the [X/Fe] ratios of the other elements showing the same trends with R_{apo} (Al, Si, etc.) also correlate with [Na/Fe].

These plots, however, may not show the whole story. One potential problem is that these intermediate metallicity stars may not all be true halo stars. There could be significant contamination from the low-metallicity end of both the thick and thin disks. However, the

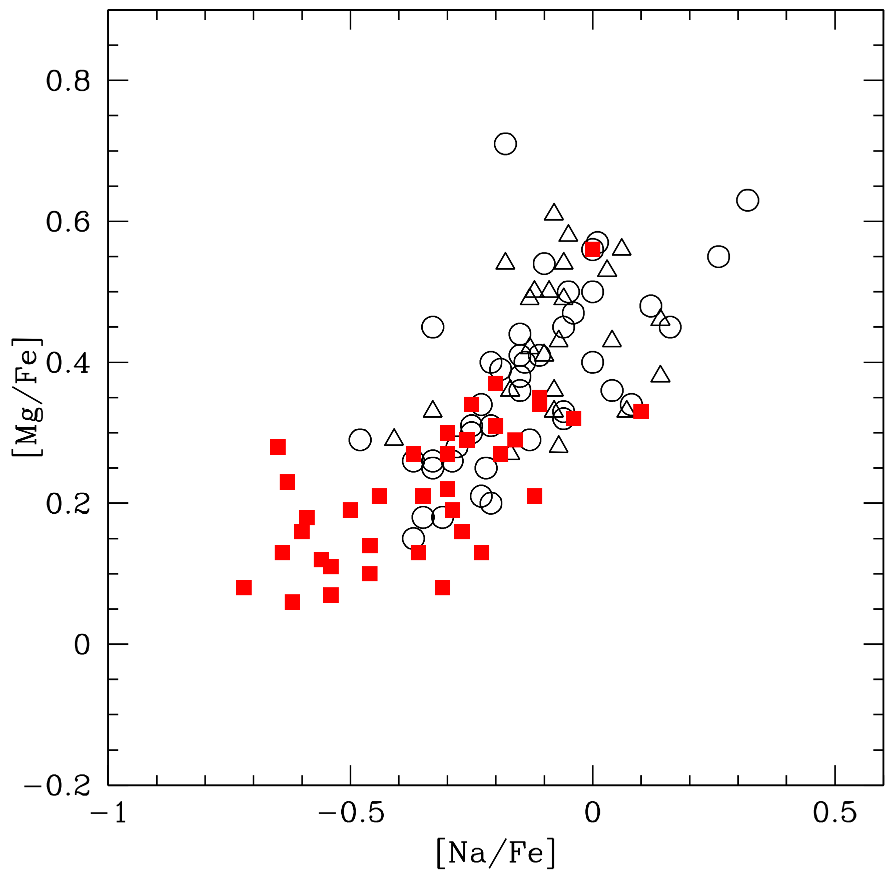

Fig. 1.3. The [Mg/Fe] ratios of the individual stars used in Figure 2 plotted as a function of their [Na/Fe] ratios. The symbols the same velocity group as in Figure 2. There is a clear correlation between these two ratios. The same kind of correlation with [Na/Fe] is found for the other varying element ratios. The slope of the correlation is not the same as what would be expected from random errors in the analysis.

same plots can be made only including stars on retrograde orbits and the same trends are observed. Other potential problems are based on the difficulty of conducting abundance analysis on field stars. These include uncertain distances and reddenings and the lack of good quality photometry (at least in the visible) for many well-known field stars.

Potentially one of the largest biases in the sample selection is that the selected stars are limited to those in the solar neighborhood. These trends only reflect a sample of outer halo stars that venture into the inner Galaxy and not an *in situ* sample of the outer halo.

1.3 Globular Clusters

There are several distinct advantages for using globular clusters as probes of the chemical evolution of the halo. These include the ability to use color-magnitude diagrams to obtain (relative) ages and distances for the clusters. The stellar parameters used in the abundance analyzes also have to be consistent with cluster membership. For example, cluster stars are generally believed to have a single [Fe/H] value (with the exception of Omega Cen and possibly M54). Any analysis that returns a wide range of [Fe/H] values for several stars in a cluster may suffer from problems.

One difficulty of using cluster stars as probes of galactic evolution is that the abundances of several elements vary between stars inside individual clusters. These elements include C, N, O, Na, Mg, and Al. For our purposes, it may be difficult to give a single representative value of any of these abundances to a given cluster. Therefore, we have chosen to use Si to be a surrogate for the lighter α-elements. Unfortunately, [Si/Fe] does not show the same range star-to-star as [Na/Fe] (~ 0.3 dex vs. ~ 1 dex).

Ivans et al. (1999 and 2001) has found that the [Si/Fe] ratios within M4 and M5 have small scatter within the individual clusters, but the mean value of [Si/Fe] for the two clusters is greatly difference. Although both clusters have nearly identical overall abundances ([Fe/H] = -1.18 and -1.17) and ages, M4 has an [Si/Fe] ratio about 0.3 dex greater than that of M5. The orbit of M4 has R_{apo} = 5.8 kpc, while M5 has R_{apo} = 35.4 kpc. This means the two clusters follow the same pattern as seen in the field sample.

In Figure 4 and 5 we plot the [Si/Fe] ratios as a function of log R_{apo}. Figure 4 only includes the metal-poor field star data of Fulbright (2000) and Stephens & Boesgaard (2002). The lack of stars with log $R_{apo} < 0.9$ (about 8 kpc) is a relic of the star selection process. Nearly all of the stars in the two samples are presently within a few hundred parsecs of the Sun, eliminating inner halo stars from the sample.

The dotted line is a least-squares fit to the field star data. In Figure 5 the mean [Si/Fe] ratios for a sample of cluster analyzes are plotted as solid points. These include all the clusters of the so-called Lick/TX group (Ivans et al. 2001 and references therein), Brown & Wallerstein and collaborators, and those clusters included in the Carney (1996) review. Also included are the clusters analyzed by Lee & Carney (2002). The two clusters with blue points are NGC 5053 and M53, presently under study by the author using data obtained at the Hobby-Eberly Telescope through the NOAO. The analysis of these clusters follows the procedures of the Lick/TX group. No author-to-author corrections have been made to insure the [Si/Fe] abundances are all on the same system, although many of the clusters have been studied by the Lick/TX group.

Many of the clusters have orbits determined by Dinescu et al. (2002). Those clusters without orbits have their names quoted in parentheses and their present log R_{GC} (galactocentric distance) values are plotted. Only clusters and field stars with [Fe/H] < -1 are plotted.

The most striking feature in Figure 5 is that the cluster distribution populates the same region as the field star sample. The three Lee & Carney inner halo clusters lie close to the line extrapolated from the field star data. This suggests that the same trends with apogalactic distance exhibited by the halo field star population may also exist throughout the halo cluster population.

Along the bottom of the plot there are the names of several clusters (plotted vertically) that have not have full analyzes done and may help sample a range of log R_{apo} and age (see below) values.

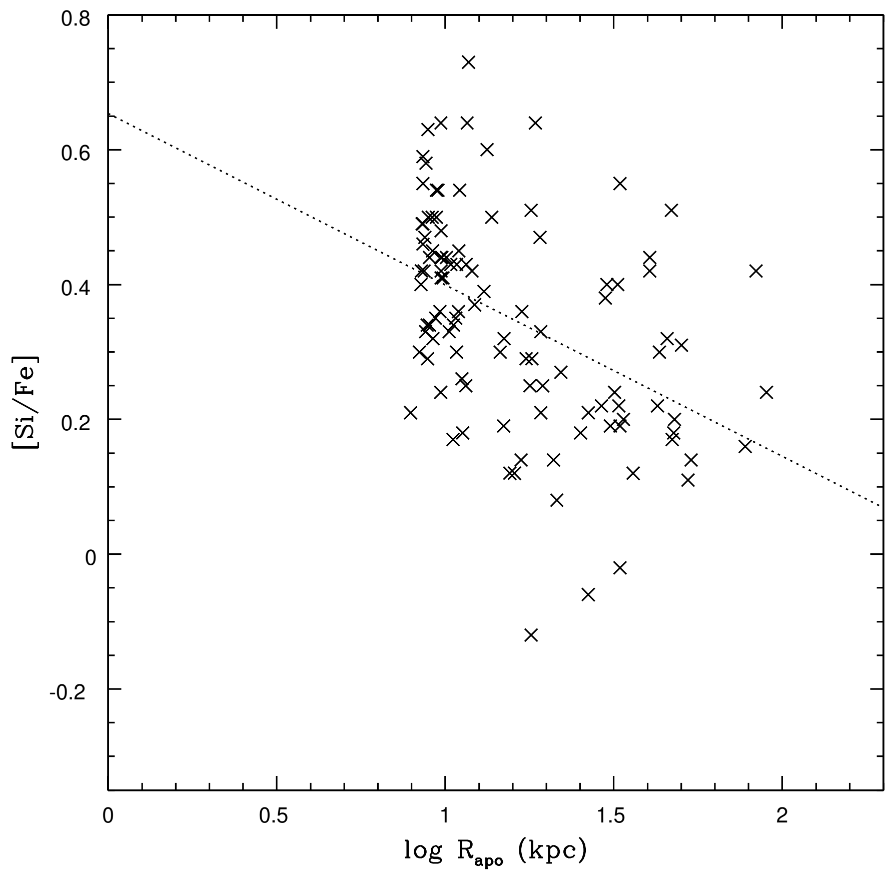

Fig. 1.4. The [Si/Fe] ratio of metal-poor field stars from Fulbright (2002) and Stephens & Boesgaard (2002) as a function of the log of their orbital apogalacticon distance. The dotted line is a least-squares fit to the field star data.

1.4 Age and α-Enhancement

The [α/Fe] ratio of interstellar gas is a function of the types supernovae that enriched the material. Models of Type II supernovae (such as Woosley & Weaver 1995), suggest that supernovae from the most massive progenitors produce the largest amounts of O and Mg with respect to Fe. Lower mass progenitors produce proportionally more of the heavier α-elements, including Ca and Ti.

The dependence of production on progenitor mass means that altering the form of the initial mass function can lead to a wide range of [α/Fe] ratios in the resulting ejecta, but nearly all combinations of reasonable nucleosynthesis models and initial mass functions return [α/Fe] ratios greater than solar. Therefore to obtain the sub-solar [α/Fe] ratios seen in stars like BD +80 245, there needs to be another mechanism to alter the ratio. Ivans et

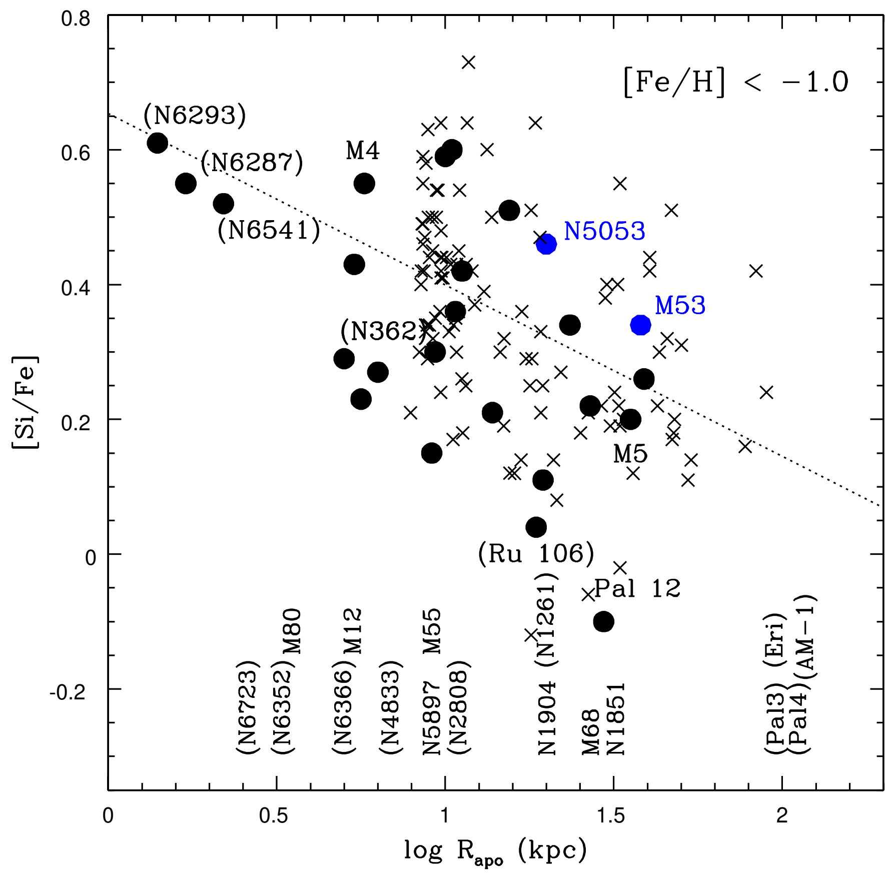

Fig. 1.5. Same as Figure 4, but the solid dots are the mean [Si/Fe] ratios for metal-poor globular clusters. The three innermost clusters (NGC 6293, NGC 6287 and NGC 6541) are from Lee & Carney (2002). Apogalacticon data are from Dinescu et al. (2002). Clusters for which no orbits have been determined have their names quoted in parentheses. The cluster names along the bottom of the figure are examples of other clusters that may be of interest for future investigation.

al. (2003) thoroughly investigated this possibility and found that the abundance ratios in low-alpha stars is consistent with significant Type Ia supernova enrichment.

As mentioned in the Introduction, Tinsley (1979) modeled the chemical evolution of the Galaxy using a mix of Type II and Type Ia supernovae. The requirement for a delay on the order of 1 Gyr between Type II and considerable Type Ia enrichment implies that stars that formed out of the ejecta would be younger than the α-rich stars that formed out of Type II ejecta only.

In Figure 6 we plot the cluster mean [Si/Fe] vs. the Salaris & Weiss (2002) age. The cluster Pal 12 sticks out as the best example of a relatively young, α-poor cluster. If Ru 106 can be confirmed as being ≈ 2 Gyr younger than the bulk of the metal-poor cluster

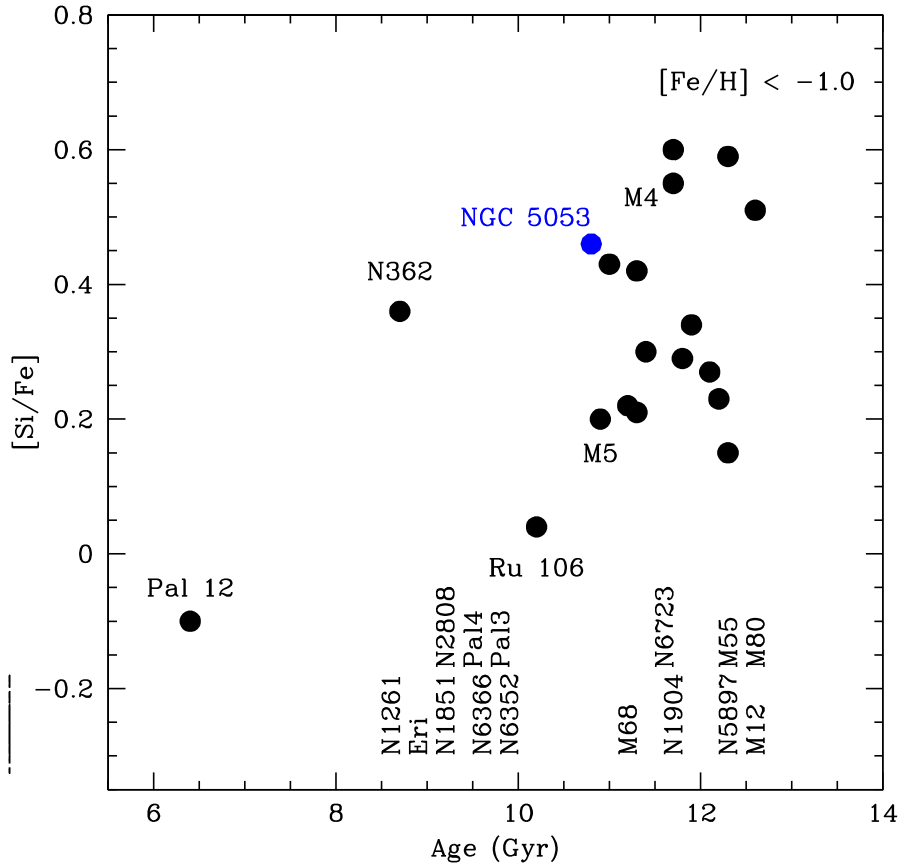

Fig. 1.6. The [Si/Fe] ratio plotted against their Salaris & Weiss (2002) stellar evolutionary age. The cluster Pal 12 is the best example of a relatively young, metal-poor, α-poor cluster.

population, it may be another example. However, if Pal 12 is removed from the sample it becomes much more difficult to believe that there is a trend with age, especially considering the uncertainties in age-dating clusters. The addition of the eight clusters with ages less than 10 Gyr may help clarify the issue.

The Salaris & Weiss (2002) ages were applied to Figure 6 mainly because the spread of cluster ages found by these authors is larger than found by Vandenberg et al. (2000) or Rosenberg et al. (1999). If the latter two papers are used as the source of ages, only Pal 12 would stand out as a relatively young, metal-poor cluster. Therefore, when using either the Rosenberg et al. or the Vandenberg et al. age determinations, it becomes even more difficult to detect any relationship between age and α-enhancement with the exception of Pal 12 and some relatively more metal-rich clusters like Terzan 7.

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