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MAGNESIUM, SILICON, AND IRON ABUNDANCES AND THE CLUSTER METALLICITY SCALE

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ABSTRACT

Abundances have been determined for giants in a number of open and globular clusters from Washington photometry and echelle spectroscopy. Fe abundances derived from these two very different techniques agree to within the uncertainties over the entire range of cluster abundances. The classical metal-rich globular clusters NGC 6352, M69, and M71 are found to have [Fe/H] values $\lesssim -1$. The metal-poor open clusters NGC 2141, 2158, 2506, and Melotte 66 have [Fe/H] values ranging from -0.5 to -1.2, thus reaching Fe abundances as low as some globular clusters. Mg and Si are significantly enhanced relative to Fe in many of these clusters. A much better correlation is found between the color of the cluster giant branch and the mean (Mg + Si + Fe) abundance than with the Fe abundance alone. It is thus possible to resolve low echelle Fe abundances and high classical metallicities by including the Mg and Si abundances. The most metal-rich globular clusters have a metallicity, i.e., [⟨Mg + Si + Fe⟩/H], near -0.7.

Subject headings: clusters: globular — clusters: open — stars: abundances

I. INTRODUCTION

Since the suggestion by Pilachowski, Canterna, and Wallerstein (1980) and Cohen (1980) that 47 Tuc and M71 had [Fe/H] ≈ -1.2, or some 5–10 times lower than traditional values, the absolute abundances of metal-rich globular clusters have remained highly controversial. Abundances of open clusters with similar classical metallicity indices must be similarly suspect. This *Letter* presents abundance determinations in a sample of old open and metal-rich globular clusters in the Galaxy in order to explore their Fe abundances and to obtain information which may be useful for resolving the controversy. Two very different techniques—broad-band Washington photometry and high-resolution echelle spectroscopy—have been employed in an effort to avoid possible biases or sources of systematic error in either of these methods. We find that both techniques yield similar, low Fe abundances for metal-rich globulars as well as metal-poor open clusters, strengthening the "new" abundance scale (Zinn 1980*b*) for Fe. However, when the abundances of the major elements contributing to many classical metallicity indices (Mg, Si, and Fe) are included, the "old" metallicity scale (Zinn 1980*a*) is more nearly obtained.

II. OBSERVATIONS AND RESULTS

a) *Spectroscopy*

High-dispersion spectrograms of bright giants in several clusters were obtained in 1981 July and 1982 January with the Cerro Tololo Inter-American Observatory and Kitt Peak National Observatory 4 m echelle spectrographs, respectively. The 31.6 line mm^{-1} echelle grating, 226-1 cross disperser, and Singer camera (CTIO) or red long-focus camera with an image tube (KPNO) were used, giving a resolution of $\lesssim 0.3$ Å. The central wavelength was 5800 Å, giving useful coverage from about 5500 Å to 7000 Å. The spectra were trailed to a width of ~ 0.3 mm on baked IIIa-J plates. When possible, two spectra per star were obtained. Except for M4, only one star per cluster was observed.

A differential curve-of-growth model atmosphere analysis was employed to compute the abundances relative to the standard stars ε Virginis and the Sun. Reductions followed the procedures of Pilachowski, Wallerstein, and Leep (1980) except that the initial effective temperature and metallicity were provided by the Washington photometry. The model metallicity was varied until it agreed with the mean abundance of [Mg/H], [Si/H], and [Fe/H]. A change in model metallicity of $+0.5$ changes these quantities by $\lesssim +0.1$. The final model atmosphere parameters and sources for the star designations are given in Geisler (1983). We estimate the uncertainties in the parameters to be ± 200 K, ± 0.3 in $\log g$, and ± 0.5 km s^{-1} in microturbulent velocity.

Logarithmic abundances of Mg, Si, and Fe with respect to the Sun are given in Table 1. The number of lines from which the final abundances were computed is also given. Note that the Mg and Si abundances are determined from only a few lines, so that the uncertainties are large. The errors in the abundances are ~ 0.3 dex for Mg and Si and 0.2 dex for Fe.

All stars whose radial velocities could be measured are definite velocity members. Additionally, the NGC 752 and 2506 stars are proper motion members, and the NGC 2506, 6121, and 6352 stars are all giants based on Washington photometry (see § II*b*).

The most important features of Table 1 are the low Fe abundances for the open clusters NGC 2506 and M67, and

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TABLE 1

ABUNDANCES FROM ECHELLE SPECTROSCOPY

NGC, Star	[Mg/H]	N	[Si/H]	N	[Fe/H]	N
752, 213	0.5	2	0.2	4	−0.15	52
2506, 22012......	0.1	2	0.1	3	−0.67	43
2682, 170	0.1	2	0.1	3	−0.49	36
6121, 3209.......	−0.5	1	−0.4	3	−0.98	40
6121, 4414.......	−0.5	2	−0.2	3	−0.91	46
6352, 37	−0.6	1	−0.2	3	−1.15	41
6637, C-IV-27 ...	−1.0	2	−0.2	3	−1.42	36
6723, I-70	−0.7	1	−0.5	3	−0.93	26

TABLE 2

ABUNDANCES FROM WASHINGTON PHOTOMETRY

Cluster						
NGC	Name	$[A/H]_{M-T_1}$	S.E.	$[A/H]_{C-M}$	S.E.	N
362	...	−1.04	0.14	−0.92	0.13	16
2141[a]	...	−0.88	0.12	−0.63	0.08	12
2158[b]	...	−1.19	0.10	−0.66	0.08	18
...	Melotte 66	−0.49	0.10	−0.21	0.10	4
2506[b]	...	−0.93	0.08	−0.51	0.05	16
6121	M4	−1.48	0.08	−1.09	0.10	21
6352	...	−0.92	0.18	−0.45	0.16	14
6637[b]	M69	−1.00	0.15	−0.64	0.07	14
6705	M11	−0.10	0.06	0.18	0.12	11
6723[b]	...	−1.29	0.15	−1.26	0.13	18
6791	...	−0.03	0.10	0.10	0.12	12
6838	M71	−0.98	0.18	−0.55	0.18	10
6882/5	...	−0.30	0.08	−0.32	0.14	6
6940	...	−0.26	0.04	−0.11	0.09	8

[a] No membership criteria available.
[b] All stars considered members.

the globular clusters NGC 6352 and M69, and the consistent enhancement of the light elements Mg and Si over Fe. This is not simply an odd/even effect, as other light elements, including O, Na, and Al, are similarly enhanced.

b) *Photometry*

Washington system photometry has been obtained for 104 stars in six globular clusters and 100 stars in seven open clusters. In addition to the original four-color system (Canterna 1976), the intermediate-band DDO 51 filter (Clark and McClure 1979) has been added to the Washington system. The filter measures absorption in the Mg I *b* triplet and Mg H bands near 5200 Å. These features are very sensitive to surface gravity for G and K stars and allow one to distinguish foreground dwarfs from cluster giants (Geisler 1984). This is an important consideration, since field star contamination can be severe for disk clusters and globular clusters lying in the direction of the galactic center. The revised Washington system then allows the measurement of effective temperature, separate abundances from the $M - T_1$ and $C - M$ colors, and a membership criterion for each star. The $M - T_1$ abundance index measures blanketing due to metals (predominantly Fe), while the $C - M$ index measures CN and CH, as well as metallic, absorption.

Observations were made with the University of Washington's Manastash Ridge Observatory 76 cm, the CTIO 91 cm, and 1.5 m, and the KPNO 1.3 m reflectors during 44 nights from 1980 May to 1982 September. The abundances were determined following the procedures outlined in Canterna (1976) and Canterna and Harris (1979). Table 2 presents the mean cluster abundances, their standard error, and the number of cluster stars observed. Field stars have been eliminated. The mean abundances have internal uncertainties $\lesssim 0.2$ dex.

The $M - T_1$ abundances in Table 2 indicate quite low Fe abundances for several metal-rich globular clusters (NGC 6352, M4, M69, and M71) and metal-poor open clusters (NGC 2141, 2158, 2506, and Melotte 66). For many of these clusters, the $C - M$ abundance is significantly higher than that derived from $M - T_1$, indicating enhanced CN and/or CH absorption.

III. DISCUSSION

A number of globular and open clusters have abundances derived from both echelle spectroscopy and Washington photometry. Combining all available abundance information, we plot in Figure 1 the Washington system $M - T_1$ abundance versus the echelle [Fe/H]. The echelle values were taken mainly from this study and the compilation of Pilachowski, Sneden, and Wallerstein (1983). The values agree over the full range of cluster abundances to within ± 0.3 dex. The scatter is random and no worse than that expected from the observational errors and errors in the abundance analyses. The good

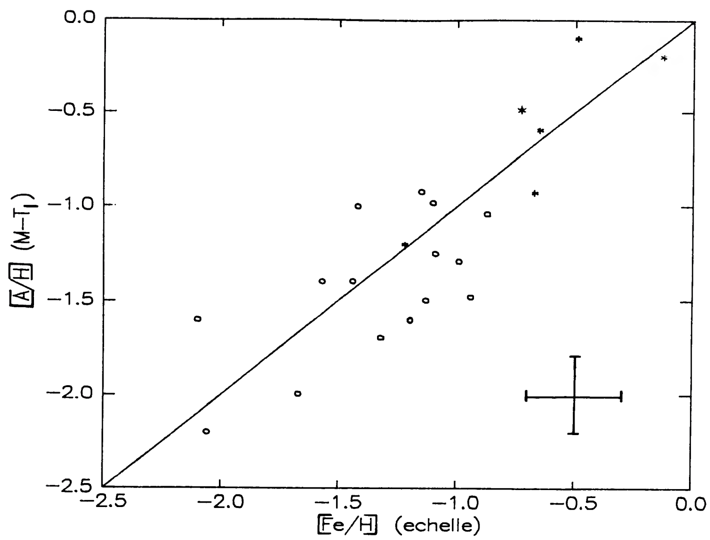

FIG. 1.—The Washington system $M - T_1$ abundance vs. [Fe/H] derived from echelle spectroscopy for open clusters (*asterisks*) and globular clusters (*circles*). The line shows perfect correlation.

TABLE 3

CLUSTER ABUNDANCES

NGC	$(B - V)_{0,g}$	$[\mathrm{Fe/H}]_{W/E}$	$[\langle\mathrm{Mg + Si + Fe}\rangle/\mathrm{H}]$
104	0.99	−1.17	...
288	0.84	−1.45	...
362	0.83	−0.96	...
752[a]	1.03	−0.16	0.18
2243[a]	0.98	−1.21	−1.04
Melotte 66[a]	1.05	−0.61	−0.54
2420[a]	1.04	−0.63	−0.68
2506[a]	1.00	−0.80	−0.21
2682[a]	1.03	−0.30	−0.05
2808	0.75	−1.06	−0.89
3201	0.79	−1.00	−0.90
4833	0.65	−1.37	...
5024	0.71	−1.85	...
5272	0.85	−1.49	−1.44
5466	0.70	−1.50	...
5904	0.79	−1.31	(−1.01)
6121	0.92	−1.21	−0.68
6171	1.02	−1.05	...
6205	0.79	−1.42	−1.50
6254	0.80	−1.51	...
6341	0.70	−2.13	...
6352	1.05	−1.03	−0.61
6362	0.97	−1.00	...
6397	0.71	−2.21	−1.94
6637	1.05	−1.21	−0.79
6656	0.72	−1.83	−1.32
6723	0.91	−1.14	−0.78
6752	0.81	−1.32	...
6838	1.01	−1.04	−0.68
7078	0.76	−1.76	−1.87

[a] Open cluster.

agreement between the Fe abundances given by th se two very different techniques is encouraging.

A compilation (Table 3) of Washington/echelle Fe abundances (when both are available, the mean is taken) for clusters shows that there are no globular clusters with [Fe/H] significantly greater than −1. Included are most of the classical metal-rich clusters, such as 47 Tuc(−1.15), NGC 6352(−1.05), M69(−1.2), and M71(−1.05). Open clusters with echelle abundances are also included. Tables 2 and 3 indicate that several open clusters approach and even overlap the globular clusters in abundance near [Fe/H] ≈ −1.

It is well known theoretically that the temperature of the giant branch depends primarily on the abundance of the heavy elements ("metals"), since they are the dominant electron donors at low temperatures and H^- is the primary opacity source. It is generally assumed that [Fe/H] and metallicity are synonymous. However, as evidenced by Figure 2, the correlation between giant branch color [as given by $(B - V)_{0,g}$] and Washington/echelle [Fe/H] breaks down for clusters with [Fe/H] ≈ −1.1. $(B - V)_{0,g}$ is from Sandage (1982) for the globular clusters and was computed for the open clusters with echelle abundances by interpreting the clump as the high-mass analog to the horizontal branch (Cannon 1970). Yale isochrone theoretical values were derived from Janes and Demarque (1983) and corrected for an α of 1.6 (VandenBerg 1983). Also shown are theoretical models from Demarque, King, and Diaz (1982). There is a very large scatter in $(B - V)_{0,g}$ for clusters near [Fe/H] = −1.1, and the values are generally far removed from the theoretical predictions. The same behavior is seen when $V - K$ is used. Clearly, the intrinsic colors of the cluster giant branches do not correlate well with [Fe/H] (Washington/echelle) or agree well with theoretical predictions for metal-rich globulars and metal-poor open clusters.

The solar abundances of Mg, Si, and Fe are very similar, as are their first ionization potentials. As a result, in cool giants with solar abundances, all three elements contribute approximately equal numbers of electrons. The contribution of other metals is insignificant. Furthermore, the availability of many more Fe than Mg or Si lines for measurement in such stellar spectra, combined with the general assumption that [Mg/Fe] = [Si/Fe] = 0, leads to the convention equating Fe abundance with metallicity. However, Table 1 suggests that a

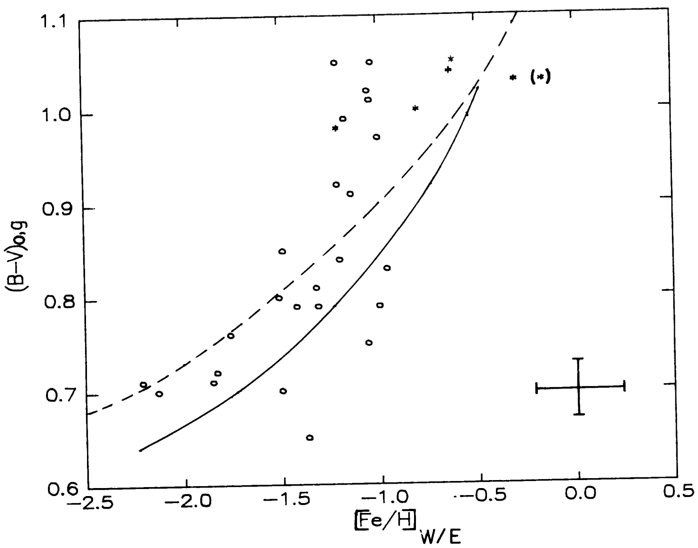

FIG. 2

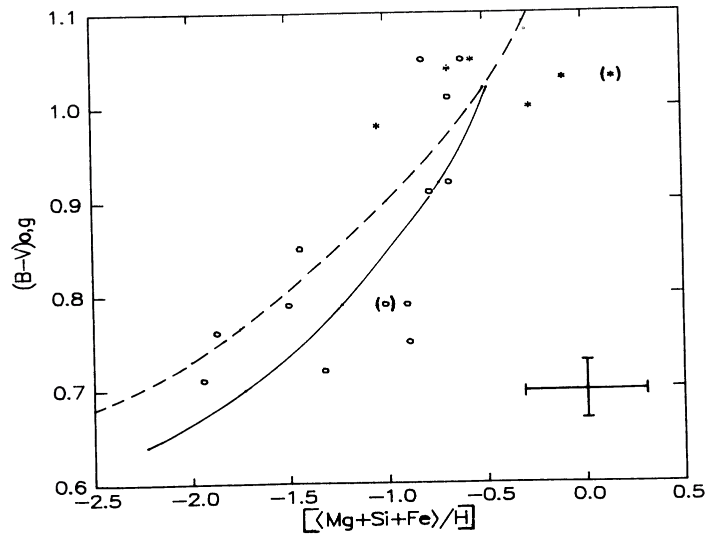

FIG. 3

FIG. 2.—Observed and theoretical cluster giant branch colors and Fe abundances. [Fe/H] values are derived from Washington photometry and/or echelle spectroscopy. Open cluster observations are shown by asterisks; globular clusters by circles. The solid curve is derived from the Yale isochrones corrected for $\alpha = 1.6$. The dashed curve is taken from the Demarque, King, and Diaz (1982) models.

FIG. 3.—Same as Fig. 2, except metallicity is now given by the mean abundance of Mg, Si, and Fe

much better indicator of metallicity should be the mean of the Mg, Si, and Fe abundances.

Peterson (1981) first proposed that substantial enhancements in Mg and Si could be responsible for the high classical metallicity of M71 and similar clusters, even though the Fe abundance was actually much lower. Table 3 gives values of [⟨Mg + Si + Fe⟩/H], the mean of the Mg, Si, and Washington/echelle Fe abundances. Figure 3 is identical to Figure 2, except metallicity is now given by [⟨Mg + Si + Fe⟩/H]. The agreement with theory is much better, and the scatter much less, than in Figure 2, especially for the intermediate-metallicity clusters. Although there are fewer clusters with measured Mg and Si abundances, the deviations are within the observational and theoretical uncertainties. The improvement is similar using $V - K$.

Thus, as expected, the giant branch color is controlled by the abundances of the primary electron donors—Mg, Si, and Fe. However, these elements can be uncoupled. Mg and Si can be significantly enhanced relative to Fe in some clusters. This supports the intriguing resolution to the abundance scale controversy first proposed by Peterson. The Fe abundances of metal-rich clusters such as 47 Tuc and M71 are indeed low, i.e., ~ -1.1, as indicated by Washington photometry and echelle spectroscopy. However, the enhanced Mg and Si abundances make these clusters metal rich, with an overall metallicity, i.e. [⟨Mg + Si + Fe⟩/H], of ~ -0.7, similar to classical [Fe/H] values derived from techniques sensitive to giant branch temperature. The indicated metallicity scale is, then, close to the "old" scale (Zinn 1980*a*), but with the proviso that Fe abundance and metallicity may be quite distinct. Note, however, that this result is based on very limited Mg and Si data. Abundances of many more stars in many more clusters are required to firmly establish its significance.

The suggestion that Mg and Si are strongly enhanced relative to Fe in disputed clusters, and therefore responsible for their high metallicity, does not solve the problem of why some strong lines in the blue generally attributed to Fe are stronger in the classical "metal-rich" clusters than in "metal-poor" clusters of the same $[Fe/H]_{W/E}$ (e.g., McClure and Hesser 1981; Canterna, Harris, and Ferrall 1982). A possible solution is that many of the features included in low-resolution spectroscopic and photometric abundance indices are actually due to species such as Mg, Si, Ca, Ti, CN, and/or CH, which can indeed be enhanced over Fe in these clusters (e.g. Hesser, Hartwick, and McClure 1977; Pilachowski, Sneden, and Wallerstein 1983). High-resolution spectra in the blue would be extremely useful in helping to resolve this question.

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