THE CHEMICAL ABUNDANCES OF THE HALO CLUSTERS OF THE GALAXY

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1. INTRODUCTION

Photometric metal abundances of individual red giants in eight extremely distant halo globular clusters and the Draco and Ursa Minor dwarf spheroidal galaxies have been obtained using the Washington broad-band system, C, M, T_1, T_2 (Canterna 1976). Observations were made at the KPNO 2.1-m and CTIO 1.5-m telescopes. In Table I we list for each system the mean value of [Fe/H], the number of stars observed in each system, n, the Galactocentric distance, R_{GC}, the intrinsic color of the giant branch at the level of the horizontal branch (HB), $(B-V)_{o,g}$, and the fraction of HB stars bluer than the RR Lyrae gap, f_B. Sources for unpublished color-magnitude diagram (CMD) data are: Pal 11 (Canterna and Schommer), Pal 12 (Canterna and Harris), and Ursa Minor (Schommer, Olszewski and Kunkel).

TABLE I

System	[Fe/H]	n	R_{GC}	$(B-V)_{o,g}$	f_B
Draco	-2.3	3	65 kpc	$0^m.95$	0.07
Ursa Minor	-2.1	3	70	0.70	0.75
Pal 3	-2.3	2	100		
Pal 4	-2.4	3	95	0.81	0.00
Pal 11	-0.7	4	7		
Pal 12	-1.6	3	18	0.93	0.00
Pal 13	-1.9	3	25	0.90	0.00
NGC 2419	-2.2	4	100	0.70	0.75
NGC 5053	-2.4	4	15	0.67	0.70
NGC 7006	-2.0	4	32	0.72	0.16

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2. THE HEAVY-ELEMENT ABUNDANCE OF THE GALACTIC HALO

In Fig. 1 we present a plot of [Fe/H] vs. R_{GC} for each system listed in Table I and M92 and M71. No appreciable [Fe/H] gradient beyond 20 kpc is shown in Fig. 1. A mean value of [Fe/H] = -2.2 ± 0.3 for the outer halo satellites is found. The most distant galactic halo systems have nearly the same heavy-element abundances as the nearby globular clusters M92 and M15. This result is consistent with the low-dispersion spectroscopic survey of red giants in the outer halo systems by Cowley, Hartwick, and Sargent (1977; hereafter CHS), who find no gross differences between the spectral features of these giants and those in M92 and M15; none were found to be more metal-deficient that the M15 giants.

A few field halo-population stars are known that are somewhat more metal-deficient than the stars in the halo clusters (Wallerstein et al. 1963; Sneden 1974; Bond 1977), but such stars are extremely rare. No galactic stars are known with [Fe/H] $\lesssim -3.0$.

We believe that these observations imply one of the following conclusions: (a) the primordial material from which the first stars formed in the proto-Galaxy had [Fe/H] ≈ -2.2 to -3.0, in contradiction to current theories of big-bang nucleosynthesis; (b) the primordial material had [Fe/H] $<< -3.0$, but old stars, especially those in clusters, no longer reflect the primordial composition because of mixing, accretion, or other processes that alter the stellar surface composition; or (c) low-mass stars cannot form from primoridal material because a certain minimum heavy-element content is required.

3. THE ANOMALOUS COLOR-MAGNITUDE DIAGRAMS OF THE OUTER HALO SYSTEMS

Since the heavy-element abundances of the outer halo systems are similar to those in M92 and M15, it is instructive to compare correlations of [Fe/H] with established CMD parameters, such as HB type, S, ΔV, and $(B-V)_{o,g}$, between the nearby globular clusters and the outer halo systems. With the exception of NGC 2419 (Racine and Harris 1975) and Ursa Minor (Schommer et al.) the outer halo satellites have one common property, a highly populated red HB that is usually seen in metal-rich clusters. This anomaly was first pointed out by Sandage and Wildey (1967) from their investigation of NGC 7006. Rood (1973) has shown that the anomaly can be explained by a lower helium abundance, a higher CNO abundance, or a younger age for the anomalous clusters.

In Fig. 2 we present a second related CMD anomaly for these systems. Butler (1975) has shown that $(B-V)_{o,g}$ is strongly correlated with [Fe/H] for the nearby globular clusters. In Fig. 2

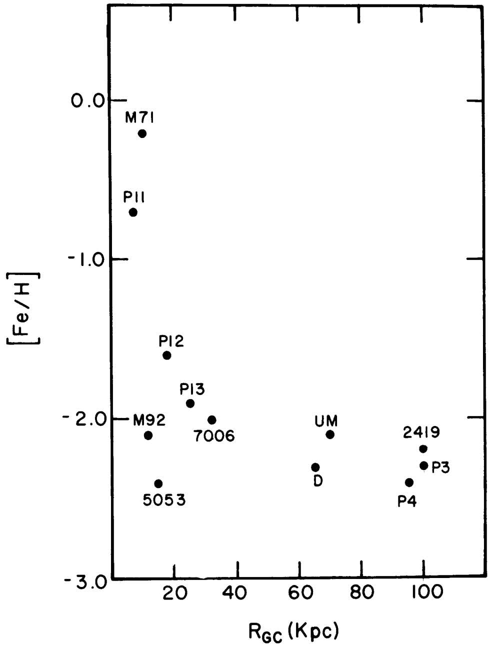

Fig. 1. [Fe/H] *versus* R_{GC}

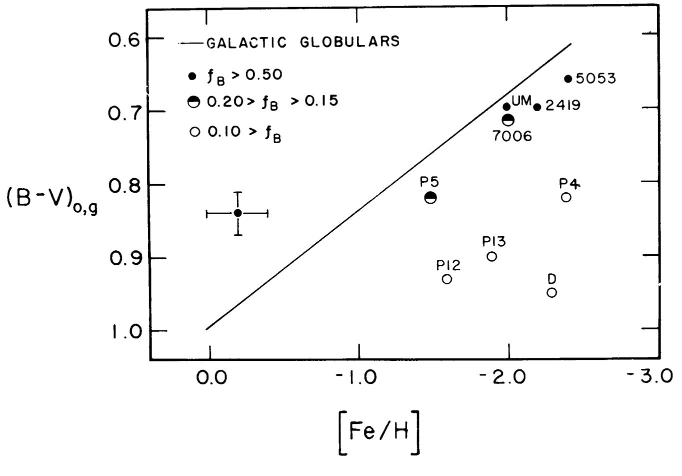

Fig. 2. $(B-V)_{o,g}$ *versus* [Fe/H]

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the solid line shows this relation for 14 well studied galactic globular clusters with R_{GC} < 15 kpc. We also present the data for the extremely distant halo systems, separating each system according to the fraction of HB stars bluer than the RR Lyrae gap. The results for Pal 5 (Sandage and Hartwick 1977), have also been included in Fig. 2. The subgiant branch colors of all extremely distant halo systems with no blue HB stars of $f_B \leq 0.07$ (Draco) are too red for their respective heavy-element abundance by $0^m.10$ or more in (B-V). This anomaly cannot be explained by large errors in the reddening estimates since these systems all lie at high galactic latitudes.

Knowledge of the He or CNO abundance parameters and the age of each system may provide an insight into which of these parameters is responsible for the CMD anomalies. It has generally been assumed when interpreting observations of globular cluster giants that any photometric or spectroscopic evidence for strong CN or CH bands is due to an enhancement of CNO/Fe in the entire system (Hartwick and McClure 1972). In view of the recent evidence for strong CN bands due to mixing in the atmosphere of giants in ω Cen (Dickens and Bell 1976) one should observe caution with this interpretation until high-dispersion spectroscopic data are available.

NGC 7006 does not show the red subgiant branch anomaly. Although Hartwick and McClure (1972) have shown evidence for enhanced CN bands in some giants in NGC 7006, which may explain the anomalous red HB, the CHS spectra and Washington photometry (Canterna and Schommer 1977) reveal that not all giants in 7006 exhibit strong CN bands. The strong CN stars in 7006 may be due to mixing in the atmosphere and not to a primoridal abundance difference in the CNO elements.

Hartwick and McClure (1974) have shown that giants in the Draco galaxy, the system that exhibits the most extreme subgiant branch anomaly, do not show any evidence for enhanced CN bands. This result has been verified by CHS and by Washington photometry. Hartwick and McClure suggest that the anomalous red horizontal branch of Draco can be explained if the helium abundance is lower than normal or if Draco is younger than clusters such as M92 or M15; both results are consistent with Castellani's (1975) analysis of the RR Lyrae variables in Draco.

On the other hand, giants in Pal 12 have been shown to possess extremely strong CH and CN bands from the results of CHS and Washington photometry. The intermediate metallicity of this cluster, [Fe/H] = -1.6, has been verified from the δ(U-B) excess of the two brightest giants. Canterna and Harris (Priv. Comm.) have concluded that a primordial abundance difference in the CNO elements is the only explanation for the anomalous red HB and subgiant branch of Pal 12. The age of Pal 12 is 14 ± 3 billion

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yrs., similar to that of M92 and M3.

There appears to be no one, common parameter that can completely explain the anomalous red HB and subgiant branch anomalies in the outer halo systems. We conclude that each halo system must be treated independently with regard to their age, He and CNO abundances. Separation of the progenitors of the Fe-peak, He, and CNO elements in the evolution of the proto-Galaxy and the collapse-enrichment scenarios are more complex than a simple free-fall collapse model. Although the observational evidence regarding the [Fe/H] abundances of the galactic halo can be explained by a one zone, free-fall model (Hartwick 1976), this simple enrichment-collapse scenario may not be coupled with the progenitors of the CNO or He elements, and cannot account for different epochs of star formation. Enrichment in isolated fragments, as proposed by Searle (1977), may account for these local variations.

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DISCUSSION

NORRIS: I would like to note that Bessell has found a southern giant, CD-38°425, in which [Ca/H]∿-3.5. Secondly I'd suggest that no present photometric system can handle abundances below [Fe/H]∿-2.5. So even if systems having such abundances existed in your sample you wouldn't necessarily know about it.

CANTERNA: I agree. The Washington system breaks down around -3, and we really can't differentiate between -3 and -4. However, in the Cowley, Hartwick and Sargent spectra, none of the giants had H and K or iron lines that were weaker than the M15 giants. So, it appears that none of the systems they've observed are more metal-poor than M15 or M92 which is in agreement with our results. I agree that if there are more metal-poor objects which we haven't observed, spectra must be used to distinguish between -3 and -3.5.

NORRIS: There is, however, growing evidence that the dwarf spheroidal galaxies contain a large range in abundance. In the Fornax system, in particular, there is apparently a range in the abundances of the globular clusters as shown by van den Bergh. According to Danziger et al. this system also contains a planetary nebula with a horrendously high metal abundance.

CANTERNA: I agree. Washington photometry of globular clusters verifies van den Bergh's result.

KRAFT: I suggest that you have to watch out for membership in discussing the metal abundance of individual stars in dwarf ellipticals.

ZINN: I would like to make another remark about the globular cluster survey made by Leonard Searle and myself. We have surveyed 19 clusters and the most distant of which is NGC 7006. We find that there is no evidence for a metal abundance gradient from 8 to 20 kpc from the galactic center. This agrees with your results. However, we find that the upper envelope of the plot of [Fe/H] vs. galactic radius is approximately [Fe/H] = -1.2, which is a signficantly higher metal abundance than your results indicate.

CANTERNA: I may agree with that, but our results pertain to systems beyond 20 - 30 kpc. We also get some clusters with a high metallicity around 15 - 20 kpc, such as Pal 12.

ZINN: Our results for NGC 7006, for example, are considerably different from yours.

CANTERNA: That may be true, but our results are in agreement with the spectra of giants in NGC 7006 from Cowley, Hartwick and Sargent.