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THE ABUNDANCES AND VELOCITIES OF THE LEO DWARF SPHEROIDALS[a)]

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ABSTRACT

Moderate (6 Å) resolution spectra obtained with the Multiple Mirror Telescope are reported for two red giants in the Leo I dwarf spheroidal galaxy and three giants in the Leo II dwarf. The calcium and magnesium line strengths imply mean metallicities of -1.9 ± 0.2 dex for Leo II and -1.5 ± 0.25 dex for Leo I, values that support the existence of an abundance/absolute-magnitude relation that extends smoothly through the lowest-luminosity early-type galaxies. The radial velocities derived from our spectra are in good agreement with earlier measurements based on carbon stars. We also report the first measured velocity for the Galactic globular NGC 5053.

I. INTRODUCTION

The Leo I and II dwarf spheroidal galaxies are two of seven such systems known to surround the Milky Way. They were discovered by Harrington and Wilson (1950) from the Palomar Sky Survey plates. Most succeeding work has been on the variable stars (Swope 1967, 1968; Hodge and Wright 1978), the structure (Hodge 1962, 1963), and the stellar population (Swope 1967; Aaronson, Olszewski, and Hodge 1983; Demers and Harris 1983; Azzopardi, Lequeux, and Westerlund 1985; Aaronson and Mould 1985).

In this paper, we report moderate-resolution spectroscopy of individual Leo I and II giants, which provides an estimate of the metal abundance and a measurement of the radial velocities of these two galaxies. At 200 kpc, the Leo dwarfs are the most distant of the outer satellites, and their metallicities may constrain halo-collapse models, as well as yielding information on the abundance/luminosity diagram of the dwarf spheroidals and of elliptical galaxies in general (Aaronson and Mould 1985; Buonanno *et al.* 1985; Aaronson 1986). To date Leo I and II have poorly known systemic velocities (Aaronson, Olszewski, and Hodge 1983); if in orbit about the galaxy, they give important leverage for deduction of the Galactic mass (Lynden-Bell, Cannon, and Godwin 1983; Olszewski, Peterson, and Aaronson 1985).

II. OBSERVATIONS AND PRELIMINARY REDUCTIONS

The observations reported here were obtained on two observing runs, 30 and 31 January 1984 (UT), and 30 and 31 March 1984 (UT), with the MMT spectrograph, the intensified Reticon detector, the 300 l/mm grating blazed at ~4300 Å, and $1'' \times 3''$ dual apertures aligned in elevation. This setup gives an effective resolution of 5.6 Å (FWHM) sampled at 1.1 Å, and a wavelength coverage of 3500–7700 Å. On each night, a spectrophotometric standard, Ross 627 (Oke 1974), was observed, as well as globular cluster abundance standards. An exposure of a He-Ar emission-line source was also made before and after every standard. The exposures of Leo I and Leo II stars, which ranged from 1–2 hr, were typically interrupted every 20 min to obtain these wavelength-calibration spectra, which allow the flexure of the spectrograph to be monitored and removed. Integration times were such that the average numbers of photons per channel were 100 at H and K, and 300 at 5000 Å. For the Leo giants, the signal in the star aperture, which is the sum of star plus sky plus dark counts, was generally 1.5 times the signal in the "sky" aperture.

The data were processed with the SD data-reduction system at Mount Wilson. Spectra were divided by nightly observations of an incandescent lamp, sky subtracted, wavelength calibrated, corrected for atmospheric extinction, and brought to absolute fluxes by comparison with nightly observations of Ross 627 corrected to the Hayes calibration of Vega (Hayes 1970, 1982). The wavelength calibration was done in a two-step process. First, a nightly fifth-order polynomial solution was calculated based on the sum of all the comparison spectra for each night, which takes out the higher-order distortions due to the image tube. Second, each separate comparison spectrum was recalibrated to first order, leaving the higher-order terms constant. This step is necessary to take out zero-point shifts during the night. This wavelength solution was then applied to the concurrent stellar spectrum. The monochromatic extinction correction for the MMT was calculated according to the procedure given in Hayes and Latham (1975), assuming aerosol parameters of $A_0 = 0.1866$ and $\alpha = -0.8$, which are the best-fit values to the KPNO extinction given by Hayes (1982). The extinction was scaled to the elevation of the MMT observatory. For each object observed, three calibrated spectra were produced: stellar spectrum, sky spectrum, and He-Ar comparison spectrum. Figure 1 shows spectra of a Leo I and a Leo II giant, sandwiched between spectra of stars in NGC 5053 and M3, which roughly bracket the metallicities of the program objects. The Leo spectra, although quite noisy, have rather weak H and K lines of Ca II, and weak *G* bands, indicative of a metal-poor giant. Since these stars were picked by magnitude and color to lie on the Leo I and II giant branches, and have now been shown to be giants, they are extremely probable members of the two dwarf galaxies. An interloper would need to be a giant at ~200 kpc, the distance to the Leo systems. Table I lists the clusters observed, with reddenings, abundances, and references to these quantities. Generally, each abundance standard was observed once on each of the two runs.

[a)] Observations reported in this paper were obtained at the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

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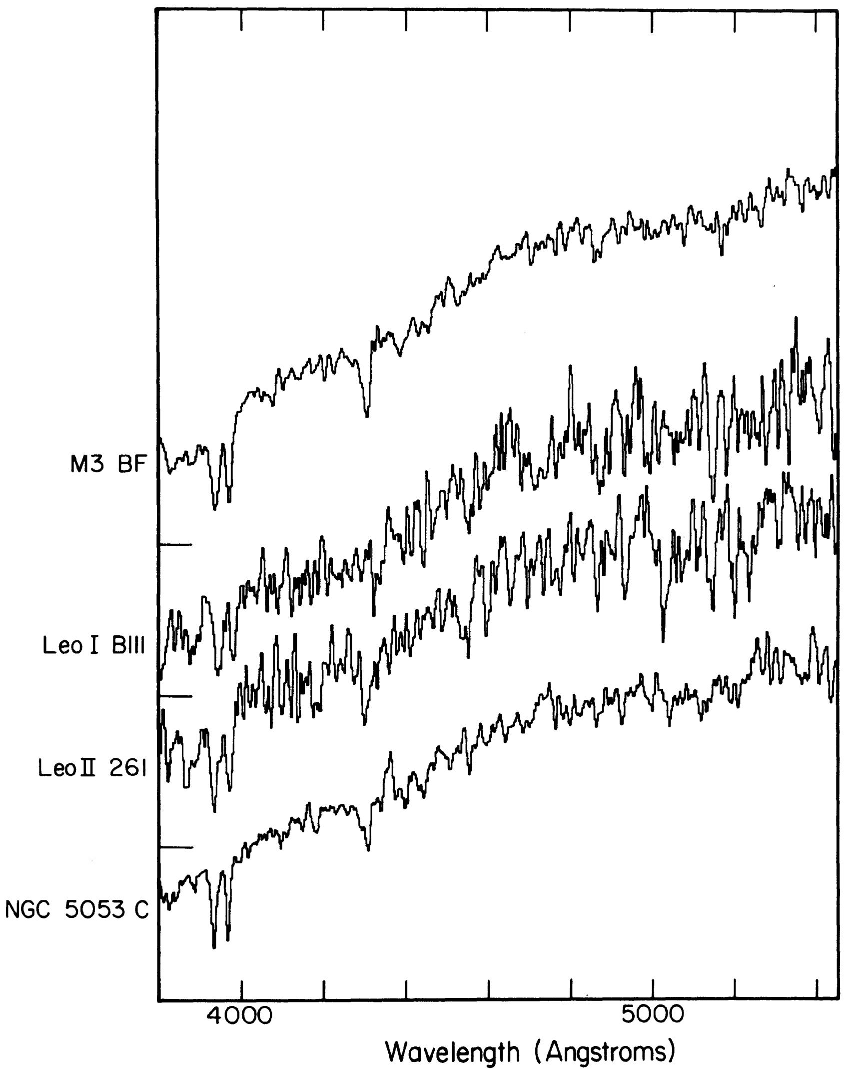

FIG. 1. Representative spectra of Galactic globular cluster and Leo dwarf galaxy giants. The vertical scale is linear in F_λ, with each spectrum scaled by a multiplicative constant, rebinned to 3 Å per channel, and smoothed by a 5 Å (FWHM) Gaussian for display purposes. The level of zero flux is given by either the lower axis or the horizontal tick marks on the left-hand side of the figure. All four giants have similar $(B-V)$ colors. The emission feature at 4360 Å in this NGC 5053 giant is residual Hg emission from terrestrial lamps.

III. RADIAL VELOCITIES

The radial velocities were determined by cross correlating all the spectra with a single template. The stellar template was constructed from a sum of all M3 spectra, with the regions near the night-sky emission lines masked out. This spectrum was set to a velocity of 0 km s^{-1}. A single night-sky emission-line template was also formed from the sum of all the sky spectra that were uncontaminated with stellar features, masking out all regions except those near the emission lines. A He-Ar template was also constructed from a sum of all the He-Ar spectra.

TABLE I. Reddenings and abundances of clusters and Leo dwarfs.

Cluster	Reddening E$(B-V)$	Ref.	Abundance [Fe/H]	Ref.
M67	0.06	a	− 0.3	d
M53	0.00	b	− 2.04	e
M3	0.00	b	− 1.66	e
NGC 5053	0.01	b	− 2.58	e
M5	0.03	b	− 1.40	e
NGC 2158	0.43	c	—	
Leo I	0.02	b	—	
Leo II	0.01	b	—	

[a] Eggen and Sandage 1964.
[b] Webbink 1985.
[c] Arp and Cuffey 1962.
[d] Geisler 1984.
[e] Zinn and West 1984.

The cross correlation of the individual He-Ar spectra against the He-Ar template yielded a velocity distribution with a mean of 0.5 km s^{-1} and a dispersion of 3.9 km s^{-1}. This reflects the accuracy of the wavelength calibration. The night-sky spectra, which were taken at the same time and on the same optical path as the stellar spectra, represent a better estimate of the residual zero-point shifts. These velocity shifts from the night sky were typically ± 20 km s^{-1}. The final, instrumental, radial velocities were calculated from a cross correlation of the stellar spectra from 4350 to 5400 Å, minus the zero-point shift from the night sky, plus the heliocentric correction. The final zero-point correction for each run was made by forcing the mean instrumental velocities of M67, M3, and M5 to their published values. With this final zero-point correction of -142 and -165 km s^{-1} for the respective runs, the mean of two twilight sky velocities was 17 km s^{-1}, which is within 1σ of the expected value of 0.

TABLE II. Instrumental, standard, and derived velocities of clusters and dwarfs.

Object	$\langle V \rangle$ this paper	σ	N	V_r literature	Ref.
M67	28	19	6	34	1
M3	− 146	19	7[a]	− 147	2
M5	57	14	6	52	2
M53	− 47:	28	5[a]	− 79	2
Leo I C18[b]	215				
Leo I C18	217				
Leo I B111	130				
Leo I B111	237				
Leo II 261[c]	128				
Leo II 301	66				
NGC 5053[d] C	22				
NGC 5053 L	− 11				
Twilight sky	17				

[a] One spectrum from Table III not included because of bright sky.

[b] This is a numbering scheme in unpublished photographic photometry by E. W. Olszewski. We identify here the two Leo I giants in this study and the noncarbon stars observed by Aaronson and Mould (1985). The measurements are offsets in millimeters from numbered stars in Fig. 3 of Azzopardi, Lequeux, and Westerlund (1985). B111—lower right star in a little clump 12.7 mm south of star 5; C18—11.4 mm north and a tiny bit west of star 5; A8—off picture; A24—29.5 mm E, 5 mm S of star 15; B76—14 mm E, 10 mm S of star 3; B101—off chart; B201—off chart; C108—fainter of the two bright stars 18 mm W, 43 mm N of star 5; C116—36 mm N of star 7; D108—off chart; D118—the more westerly of the two 34 mm E, 38 mm N of star 15; D132—29 mm N, 4 mm E of star 15.

[c] Numbers from Demers and Harris (1983).

[d] From Sandage, Katem, and Johnson (1977).

References to TABLE II

1. Mathieu 1983.
2. Webbink 1981.

TABLE III. Pseudoequivalent widths of abundance-sensitive features.

	Object	$(B-V)_0$	N	H + K(Å)	m_{Mg}
M67[1]	IV-202	1.55	2	32.88[a]	1.076[a]
	T626	1.46	2	33.38	1.066
	F105	1.26	2	30.44	0.993
M53[2]	K	1.58	2	22.5:	0.794
	3-2-22	1.20	2	22.77	0.815
	f	1.06	2	20.86	0.799
M3[3]	AA	1.56	3	29.92	0.882
	III-28	1.37	2	28.09	0.829
	BF	1.09	3	26.63	0.825
M5[4]	II-85	1.59	2	30.85	0.918
	IV-59	1.34	2	29.15	0.848
	I-71	1.20	2	28.23	0.861
NGC 5053[5]	C	1.11	1	18.77	0.797
	L	1.00	1	18.65	0.795
NGC 2158[6]	S4R2-69	2.02	1	—	1.070
	S3R2-77	2.14	1	—	1.049
Leo I[7]	C18	1.61	1[b]	30.02	0.897
	B111	1.24	1[b]	33.33	0.905
Leo II[8]	301	1.12	1	22.01	0.823
	261	1.09	1	26.75	0.890
	244	0.98	1	19.66	0.885

[a] The derived indices in this table have not been corrected for reddening. The reddening effects are negligible, excepting H + K in NGC 2158, which was not derived.

[b] Sum of two spectra.

Notes to TABLE III: Star identification and colors

1. Eggen and Sandage (1964); Eggen 1972.
2. Cuffey 1965.
3. Sandage and Katem 1982; Johnson and Sandage 1956.
4. Simoda and Tanikawa 1970; Arp 1955.
5. Sandage, Katem, and Johnson 1977.
6. Arp and Cuffey 1962.
7. See the text for $B-V$.
8. Demers and Harris 1983; see the text for discussion of $B-V$.

Table II lists the final mean velocity, dispersion in the mean velocity, and literature velocity for the clusters, as well as the derived velocities for the Leo stars. When a particular Leo giant was observed on more than one night, the velocity from each night is listed. We could not measure a reliable velocity for Leo II 244. Although the dispersion of 20 km s^{-1} represents 1/20 of a resolution element and attests to the excellent stability of the MMT spectrograph, the Leo giants have much larger velocity errors due to noise in the spectra. The formal mean velocities of Leo I and II from these data are 200 ± 30 km s^{-1} and 95 ± 30 km s^{-1}. For comparison, Aaronson, Olszewski, and Hodge (1983) reported velocities of 170 ± 40 km s^{-1} for Leo I and 90 ± 30 km s^{-1} for Leo II, based on one and two carbon stars, respectively, in very good agreement with the present results. Combining all the data, we find V_r (Leo I) $= 185 \pm 25$ km s^{-1} and V_r (Leo II) $= 95 \pm 25$ km s^{-1}.

We have also derived a radial velocity for the globular cluster NGC 5053, which has not been measured in any other study. The heliocentric value is 5 ± 20 km s^{-1} leading to a galactocentric velocity of -5 km s^{-1}. The correction from heliocentric to galactocentric velocity is described in Suntzeff, Olszewski, and Stetson (1985).

IV. PHOTOMETRY AND ABUNDANCE ESTIMATES

Table III presents the photometry and spectral abundance indices for the program stars. The reduced spectra were convolved with the B and V filter functions unweighted for atmospheric extinction given by Ažusienis and Straižys (1969), with the V filter truncated redward of 6600 Å to avoid second-order contamination. These spectrophotometric BV colors are plotted in Fig. 2 versus the values from the literature for stars observed at airmasses less than 1.17. The regression shown has a slope of 1.07 with a total estimated parent standard deviation of 0.058, which represents both the spectrophotometric errors and the errors in the published values. This regression was applied to the Leo I and II colors. The three Leo II giants also have colors given in Demers and Harris (1983); in the mean our colors are 0.25 mag bluer for these three stars. This is precisely the difference measured by Olszewski and Suntzeff (1986) between their deep CCD data and the photographic work of Demers and Harris, and results from the latter photometry being too faint by ~0.2 mag at V and ~0.4 mag at B. The adopted dereddened Leo II colors given in Table III are the average of the Demers and Harris values shifted by -0.25 and our spectrophotometric colors. The Leo I colors are the dereddened spectrophotometric values.

The strengths of the Ca II H and K line absorptions, and Mg I plus MgH features listed in Table III, have been measured with a technique similar to the one given in Suntzeff (1980). The pseudoequivalent width of H + K was determined between (3915, 3985) with continuum points defined in the passbands (3897, 3915) and (4000, 4035). The magnesium index m_{Mg} is defined in Suntzeff *et al.* (1986a). The passbands were shifted to reflect the geocentric velocity of each cluster before the measurements were made. From the multiple measurements of the abundance standards, the error of a single measurement is 1.5 Å in EW (H + K) and 0.02 in m_{Mg}. (The abundance standards were generally ob-

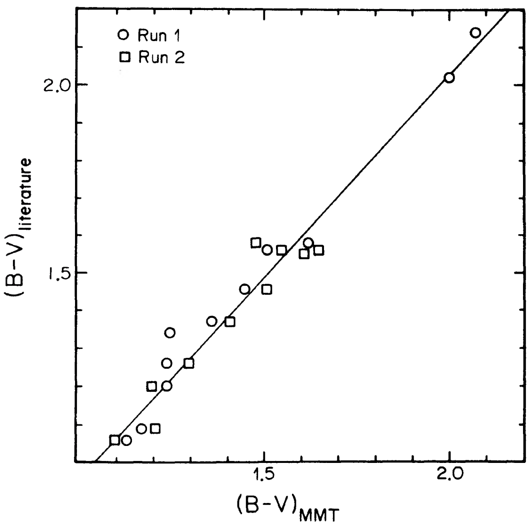

FIG. 2. Comparison of the $(B-V)$ colors synthesized from the MMT spectrophotometry of cluster stars to the published $(B-V)$ colors taken from the literature. The two runs are plotted with different symbols to show that there is no systematic shift between runs. The least-squares fit is also shown.

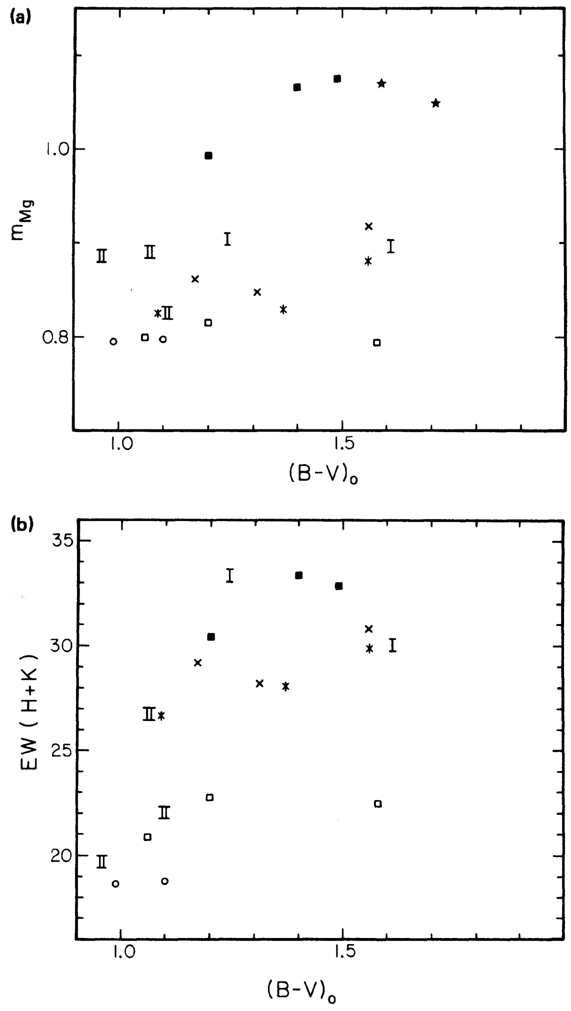

FIG. 3. (a) m_{Mg} index, which measures the strength of the Mg I triplet and MgH features near 5165 Å, plotted as a function of dereddened $(B-V)$. Giants are represented by the following symbols: dark squares for M67, stars for NGC 2158, crosses for M5, asterisks for M3, light squares for M53, light circles for NGC 5053, and Roman numerals I and II for Leo I and II. (b) The pseudoequivalent width of the Ca II H and K lines, in units of Ångstroms, plotted against dereddened $(B-V)$. The symbol key is the same as in (a).

served at least twice, so the uncertainties are actually better than this.) The error for the Leo giants should be about twice these values. The abundance indices are plotted against dereddened $B-V$ color in Fig. 3.

Suntzeff *et al.* (1986a) have shown that m_{Mg} is sensitive to [Fe/H] in globular cluster giants with metallicities higher than about -1.3 dex, but loses sensitivity below this value. Our data verify this result, since the moderately metal-poor old-disk clusters M67 and NGC 2158 clearly separate from the metal-poor globular clusters. The latter globulars order themselves as would be expected from the metal abundances listed in Table I, but the spread is only a few times the observational error. The Leo giants are clearly metal poor from their position in the diagram, but due to the poor separation as a function of [Fe/H] and the much larger measurement errors for these stars, we can only put an upper limit of roughly -1.2 dex to their metallicity.

A comment about the abundance of NGC 2158 should be made. We did not put the abundance of this cluster in Table I because of the scatter of values in the literature and the large and uncertain reddening. Christian, Heasley, and Janes (1985) summarize the metallicity estimates for NGC 2158. From our m_{Mg} diagram, we derive that the abundance of NGC 2158 is slightly more metal poor than that of M67. Such a value is consistent with the preferred value in Christian, Heasley, and Janes (1985).

As demonstrated by Suntzeff (1980), the H + K index is quite sensitive to [Fe/H] for very metal-poor stars, but loses sensitivity at the metal-rich end of the globular cluster abundance scale (see also Suntzeff *et al.* 1986a). Our results in Fig. 3(b) verify this trend as well. The globular clusters separate quite well according to their metallicities; M67, however, has only moderately stronger H + K pseudoequivalent widths than M3 and M5 despite a factor of 10 higher abundance.

From the mean positions of the H + K line strengths in Fig. 3(b), it is clear that Leo II is more metal poor than Leo I. The average abundance of the three Leo II giants is -1.9 ± 0.2 on the abundance scale given in Table I. Leo II 301 has a larger pseudoequivalent width than the other two giants and thus may be more metal rich. While the evidence for an abundance spread in several other dwarf spheroidals has grown stronger (e.g., Aaronson 1986 and references therein), until more spectra are obtained it is premature to conclude that we have seen such an abundance spread in Leo II.

The metallicity of Leo I is more difficult to estimate since it is more metal rich. Conservatively, we place a lower limit of [Fe/H] = -1.75 dex on the abundances of the two giants. Thus, combined with the upper limit of -1.2 dex from the magnesium index, we estimate the abundance of Leo I to be [Fe/H] = -1.5 ± 0.25.

Aaronson and Mould (1985) also derived abundance estimates for the Leo systems (along with the Ursa Minor and

Draco dwarfs) from infrared photometry of bright giants. They gave two estimates based on the $J-K$ and $V-K$ positions of the giant branch at $M_K = -5.5$ mag, but unfortunately these differed in the mean by ~0.45 dex. They suggested this problem arose from the $V-K$ temperature scale, as the $J-K$ results from Draco and Ursa Minor were in good agreement with prior spectrophotometric measures. For Leo II our abundance agrees well with the Aaronson and Mould estimate of -1.95 dex from $J-K$; both these values would be reconciled with those authors' $V-K$ estimates if allowance was made for the possible V photometry errors suggested earlier. For Leo I, our abundance would seem to be closer to the Aaronson and Mould estimates of -1.45 dex from $V-K$ than their value of -1.85 dex from $J-K$. If an abundance spread is present in both systems, all of these comparisons are made ambiguous by the fact that there is no overlap in the sample of Leo stars observed by Aaronson and Mould and ourselves. We believe the spectrophotometric measures carry more weight, though more spectra, especially for Leo I, would be desirable.

Demers and Harris (1983) found that the Leo II color-magnitude diagram was best fit by the globular M5, thus implicitly equating the metallicities of both objects. Our H + K line strengths rule this out, and the discrepancy can be understood by the apparent problem with the Demers and Harris photometry. (Had we in fact adopted the colors of the three giants as published by Demers and Harris, our estimate of the metallicity would have been even less by about 0.1 dex.)

Our [Fe/H] values for Leo I and II lend considerable support to the existence of a well-defined abundance/absolute-magnitude relationship for the dwarf spheroidal galaxies that joins smoothly onto that for giant ellipticals (e.g., Buonanno *et al.* 1985; Aaronson 1986; Suntzeff *et al.* 1986b). The presence of such a strong trend over the entire 10^5 range in early-type galaxy luminosity provides us with an important clue about the formation and evolutionary processes in these systems.

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