

PROPERTIES OF TWO NEW M31 DWARF SPHEROIDAL COMPANIONS FROM KECK IMAGING¹

EVA K. GREBEL^{2,3} AND PURAGRA GUHATHAKURTA^{2,4,5}

Received 1998 October 14; accepted 1998 December 3; published 1998 December 23

ABSTRACT

We have obtained images in *V* and *I* of the newly discovered Local Group dwarf galaxies Pegasus dSph and Cassiopeia dSph and their surrounding field using the Keck 10 m telescope and Low-Resolution Imaging Spectrograph. The first stellar luminosity functions and color-magnitude diagrams are presented for stars with $V \lesssim 25$ and $I \lesssim 24$. The distances to the new dwarfs are estimated from the apparent *I* magnitude of the tip of the red giant branch to be $D_{\text{MW}}(\text{Peg dSph}) = 830 \pm 80$ kpc and $D_{\text{MW}}(\text{Cas dSph}) = 760 \pm 70$ kpc, which are consistent with their belonging to the extended M31 satellite system. Both galaxies are dwarf spheroidals (dSph's) with red giant branch morphologies indicating predominantly old stellar populations and estimated mean metallicities, $\langle[\text{Fe}/\text{H}]\rangle$, of -1.3 ± 0.3 for Peg dSph and -1.4 ± 0.3 for Cas dSph. Their central surface brightness– $\langle[\text{Fe}/\text{H}]\rangle$ –absolute magnitude relationship follows that of other Local Group dSph, dwarf elliptical, and dwarf irregular galaxies. In contrast to four out of nine Milky Way dSph's (the four that lie beyond $D_{\text{MW}} = 100$ kpc), none of the six known M31 dSph's appear to have a dominant intermediate-age population.

Subject headings: galaxies: individual (Andromeda V, Pegasus dSph (Andromeda VI), Cassiopeia dSph (Andromeda VII), M31) — galaxies: luminosity function, mass function — galaxies: photometry — galaxies: stellar content — galaxies: structure — Local Group

1. INTRODUCTION

Recently, two groups have reported the independent discovery of new Local Group dwarf galaxies, which are potential companions of M31. Armandroff, Davies, & Jacoby (1998a) used a digital filtering technique to survey digitized POSS-II plates covering a 1550 deg^2 area surrounding M31 and found several candidate dwarf galaxies. They demonstrated that their first candidate, Andromeda V, is a dwarf spheroidal (dSph) galaxy sufficiently close to M31 to be its satellite. An additional candidate, which was named Andromeda VI following van den Bergh's (1974) convention, was resolved into stars and found not to contain H II regions (Armandroff, Davies, & Jacoby 1998b, 1998c). The second group, Karachentsev & Karachentseva (1998a, 1998b), visually inspected film copies of POSS-II plates and detected four potential new dwarf companions of M31. The two brightest, granulated detections were deemed to be the most promising candidates. These were initially named Pegasus Dw and Cassiopeia Dw after their parent constellations (Karachentsev & Karachentseva 1998a, 1998b), and later renamed Peg dSph and Cas dSph by Tikhonov & Karachentsev (1998). Note that Peg dSph is equivalent to And VI and was discovered independently by the two groups. The galaxy Cas dSph is located in an area for which no POSS-II plate scan was available to Armandroff et al. (1998a). We will adopt the designations Peg dSph and Cas dSph throughout this Letter.

These three newly discovered candidate M31 dSph's, And V, Peg dSph, and Cas dSph, double the census of known M31 dSph's. It is important to test whether the M31 dSph's follow the same relations between absolute magnitude, surface brightness, metallicity, *M/L* ratio, and galactocentric distance as the Milky Way dSph satellites. Do environment and distance

from M31 affect their formation histories as one might expect from van den Bergh's (1994) ram pressure/tidal stripping scenario?

This Letter presents results from Keck imaging of Peg dSph and Cas dSph that address some of these questions; preliminary results were presented by Grebel (1999). Our Keck results are also compared with the results from three other recent/ongoing studies of a similar nature targeting these galaxies (Tikhonov & Karachentsev 1998; Hopp et al. 1998; Armandroff et al. 1998c, 1998d).

2. OBSERVATIONS AND DATA REDUCTION

In preparation for a stellar spectroscopy program of M31's dSph companions, Peg dSph and Cas dSph were imaged with the Keck II 10 m telescope in 1998 August–September, using the Low-Resolution Imaging Spectrograph (LRIS) (Oke et al. 1995) with a 2048^2 CCD and a scale of $0''.215 \text{ pixel}^{-1}$. Short exposures were obtained in the *V* and *I* bands: 1×300 and 3×200 s, respectively, per galaxy. Observing conditions were photometric, and the seeing ranged from $0''.7$ to $1''.0$ (FWHM). The overlapping field of view of the final, combined images is $4'.6 \times 7'.1$. Resolved objects (galaxies) and regions around bright, saturated stars are excluded from further analysis (cf. Reitzel, Guhathakurta, & Gould 1998). Stellar photometry is carried out with the DAOPHOT/ALLFRAME programs (Stetson 1994). The photometric transformation uses air-mass coefficients from Krisciunas et al. (1987) and observations of faint secondary standards (P. B. Stetson 1998, private communication) in Landolt (1992) fields.

3. MORPHOLOGICAL APPEARANCE

Peg dSph and Cas dSph have the appearance of typical low surface brightness spheroidal galaxies without recognizable concentrations of bright stars, H II regions, or obvious globular clusters (Fig. 1). Peg dSph is not detected in H α , indicating the absence of currently star-forming regions (Armandroff et al. 1998a). An ellipticity of 0.3 is estimated for both galaxies, along with position angles of $160^\circ \pm 20^\circ$ and $55^\circ \pm 20^\circ$ for

¹ Lick Observatory Bulletin No. 1382.

² University of California Observatories/Lick Observatory, University of California at Santa Cruz, Santa Cruz, CA 95064.

³ Hubble Fellow.

⁴ Visiting Astronomer, W. M. Keck Observatory, jointly operated by the California Institute of Technology and the University of California.

⁵ Alfred P. Sloan Research Fellow.

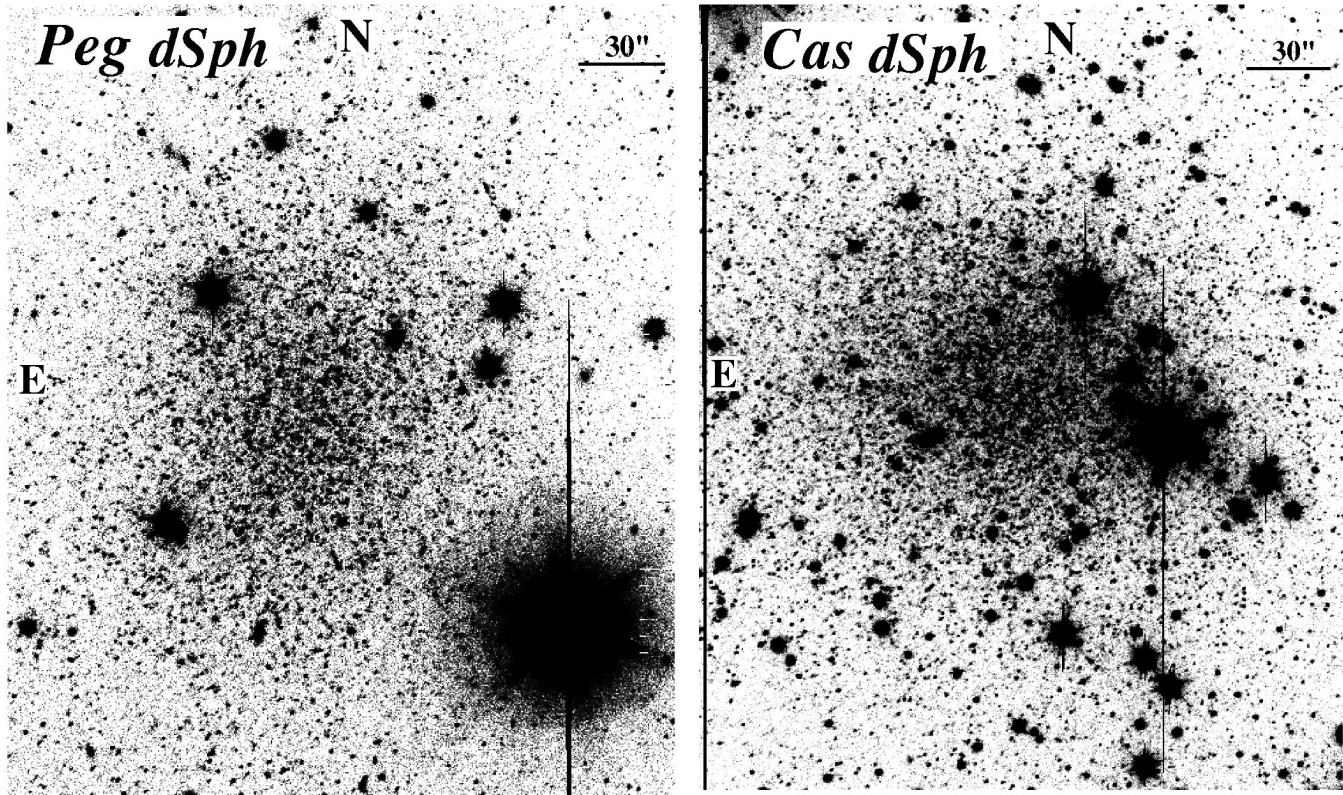


FIG. 1.—A negative gray-scale representation of V-band images of Peg dSph and Cas dSph (1×300 s for each galaxy) obtained with the LRIS on the 10 m Keck II telescope in 1998 August. The FWHM seeing for these observations was $0''.7$ – $1''.0$.

Peg dSph and Cas dSph, respectively. Hopp et al.'s (1998) measurement of the Peg dSph structural parameters is in agreement with these estimates. The ellipticities of Peg dSph and Cas dSph are similar to those of Galactic dSph satellites at larger distances from the Milky Way (see, e.g., Caldwell et al. 1992), suggesting little or no distortion through tidal effects. A detailed analysis of the galaxies' structural parameters will be presented in a later paper (Guhathakurta & Grebel 1998).

4. STELLAR LUMINOSITY FUNCTIONS AND DISTANCES

The cumulative stellar I -band luminosity function (LF) for both galaxies is shown in Figure 2. The LF of Cas dSph rises at $I \approx 20.7 \pm 0.1$, and this is interpreted as the tip of the red giant branch (TRGB). The LF upturn is more gradual for Peg dSph, with $I_{\text{TRGB}} \approx 20.7 \pm 0.1$. The Galactic line-of-sight reddening is estimated from DIRBE/IRAS maps (Schlegel, Finkbeiner, & Davis 1998) to be $E_{B-V} = 0.04 \pm 0.01$ and 0.17 ± 0.03 , or $A_I = 0.09 \pm 0.01$ and 0.35 ± 0.06 , for Peg dSph and Cas dSph, respectively. An absolute magnitude of $M_I = -4$ for the TRGB (Lee, Freedman, & Madore 1993) implies true distance moduli of $(m - M)_0 = 24.6 \pm 0.2$ and 24.4 ± 0.2 for Peg dSph and Cas dSph, respectively, where the errors include uncertainties in the exact location of the TRGB (Poisson error, possible presence of intermediate-age stars brighter than the TRGB), reddening, and photometric calibration.

Tikhonov & Karachentsev (1998) find apparent distance moduli for Peg dSph and Cas dSph that translate into true distance moduli of $(m - M)_0 = 24.52$ and 24.36 , respectively, when the above foreground extinction correction is applied.

Corrected in the same manner, Hopp et al.'s (1998) finding corresponds to $(m - M)_0 = 24.43 \pm 0.2$ for Peg dSph. These results are in excellent agreement with the results of this study, when the uncertainties in the measurements are taken into account.

5. COLOR-MAGNITUDE DIAGRAMS AND METALLICITY ESTIMATES

The color-magnitude diagrams (CMDs) of Peg dSph and Cas dSph show prominent red giant branches (RGBs) and no evidence of young blue stars (Fig. 3). The surrounding $R > 3'$ "field" CMDs in Figure 3 are drawn from a region whose area is about 45% that of the $R < 3'$ galaxy area. The field CMDs are slightly contaminated by stars on the outskirts of the dSph galaxies ($<10\%$ of the number of stars in the corresponding $R < 3'$ galaxy CMD), but this is unimportant for the purposes of this study since no significant radial gradient appears to be present in the galaxies' properties. The Cas dSph RGB is more densely populated than that of Peg dSph, a reflection of Cas dSph's higher stellar surface density. A small metal-rich ($[\text{Fe}/\text{H}] < -1$) population appears to be indicated by stars with $V - I \geq 2$ near the TRGB in Cas dSph (Fig. 3). The density and color distribution of stars above the Cas dSph TRGB are similar to that in the corresponding field CMD, but the presence of a small intermediate-age asymptotic giant branch (AGB) population cannot be ruled out. The Peg dSph CMD displays an excess of stars above the TRGB relative to the field CMD; this is also seen as a tail in the LF brighter than the TRGB. These super-TRGB stars may indicate the presence of a significant intermediate-age AGB population in

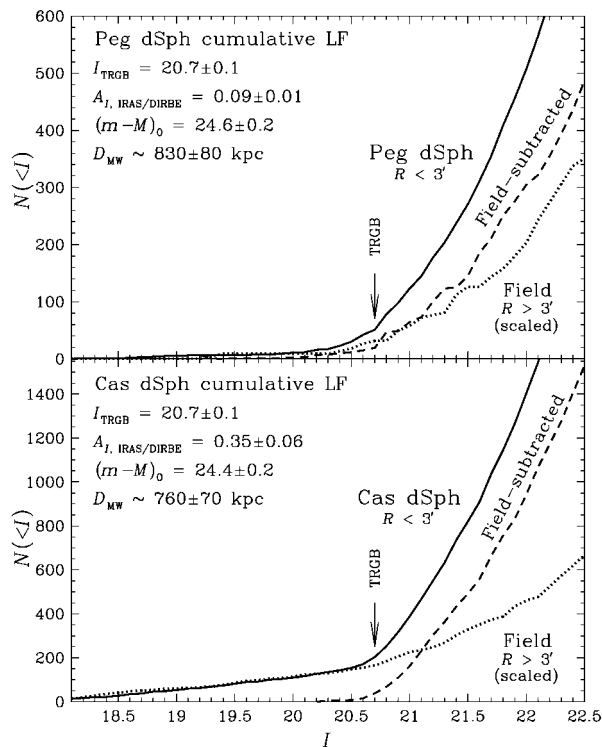


FIG. 2.—Cumulative I -band LFs of the central $R < 3'$ regions of Peg dSph and Cas dSph (solid line) and of the surrounding $R > 3'$ field regions (dotted line) (scaled to match the area of the inner $R < 3'$ region). The arrows mark the adopted position of the TRGB in the field-star-subtracted LF (dashed line). The bright end of the field-star-subtracted LF appears to extend to slightly brighter magnitudes than the adopted TRGB location, especially for Peg dSph; this may indicate the presence of luminous AGB stars.

Peg dSph; they are not likely to be artifacts of blending (cf. Grillmair et al. 1996; Martínez-Delgado & Aparicio 1997).

The mean metallicity is computed from the median reddening-corrected color, $(V-I)_0$, at $M_I = -3.5$ (Armandroff et al. 1993; Caldwell et al. 1998), computed over the range $1 < (V-I)_0 < 2$. Outside this color range, the surface density of objects is identical for the inner $R < 3'$ and surrounding $R > 3'$ regions, indicating that the majority of these objects are foreground or background sources. For Peg dSph, $(V-I)_{0,-3.5} = 1.46 \pm 0.02$ for $21.1 \leq I \leq 21.3$, which yields $\langle [Fe/H] \rangle = -1.35 \pm 0.07$. For Cas dSph, $(V-I)_{0,-3.5} = 1.43 \pm 0.01$ for $21.1 \leq I \leq 21.3$, which yields $\langle [Fe/H] \rangle = -1.42 \pm 0.04$. These errors are the formal errors of the mean; the overall uncertainty in the mean metallicities is conservatively estimated to be ± 0.3 dex because of systematic errors in the photometry/calibration. These metallicity estimates are in good agreement with those derived from the standard globular cluster RGB fiducials (Da Costa & Armandroff 1990) shown in Figure 3.

The observed width of the RGB in the Peg dSph and Cas dSph CMDs, $\delta(V-I) \approx 0.4$, corresponds to a metallicity spread of roughly 1 dex. The formal uncertainty in the color measurement (see Fig. 3) is significantly smaller than the observed spread in bright RGB color. The effect of systematic errors (e.g., crowding, flat-fielding), however, may be as large as $\sigma(V-I) \sim 0.1$, judging from a comparative analysis of a subset of the data that was obtained in poorer seeing and at a different CCD orientation with respect to the primary data set. The fact that the RGB widths are similar for Peg dSph and

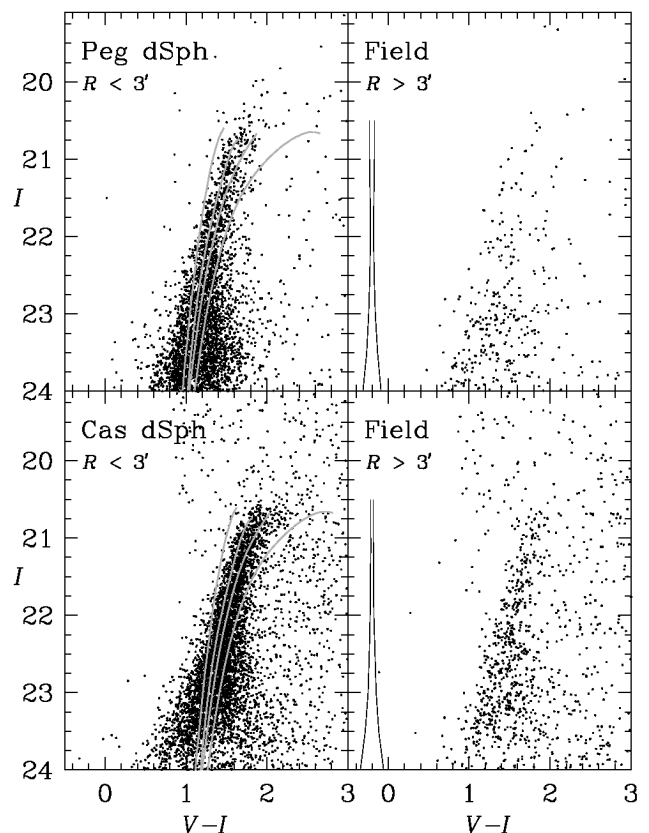


FIG. 3.—CMDs of the inner $R < 3'$ region of Peg dSph and Cas dSph, with their corresponding surrounding $R > 3'$ field regions (each field region has roughly 45% the area of the inner $R < 3'$ region). The error bands in the right panels represent the formal (DAOPHOT) $\pm 1 \sigma$ error in $V-I$ color; the overall errors are likely to be somewhat larger. Note that the “field” CMD is slightly contaminated by red giant stars in the outer regions (> 60 pc) of the dSph’s. The solid gray lines in the left panels are globular cluster fiducials from Da Costa & Armandroff (1990), which are appropriately reddened and shifted to the distance moduli of the galaxies, for a range of $[Fe/H]$ values (left to right): M15 (-2.2), NGC 6752 (-1.5), NGC 1851 (-1.2), and 47 Tuc (-0.7).

Cas dSph, despite the substantial difference in their stellar surface density, argues against the widths being caused by crowding-related photometric error. Finally, the apparent flaring of the Cas dSph RGB near its bright tip is strongly suggestive of a spread in $[Fe/H]$.

Measurements of the mean metallicity in three radial bins ($R < 1'$, $1' < R < 2'$, and $2' < R < 3'$), based on a wider I -magnitude range ($\Delta I = 0.5$ mag), place a robust upper limit on the radial metallicity gradient in the galaxies. The variation in median $(V-I)_0$ color over the inner $3'$ region is found to be less than 0.03 mag, corresponding to a variation in mean metallicity of less than 0.05 dex and comparable to the formal error in $\langle [Fe/H] \rangle$ quoted above. Thus, Peg dSph and Cas dSph show no evidence of a radial metallicity gradient, in contrast with what is seen in some dSph’s with substantial intermediate-age populations (see Grebel 1997 for a summary).

6. CENTRAL SURFACE BRIGHTNESS

The central surface brightness in the V band, measured in a $40''$ diameter aperture after subtraction of bright foreground stars and corrected for line-of-sight extinction (same procedure as in Armandroff et al. 1998a), is $\mu_{V,0} \approx 24.5$ and 23.6 mag arcsec $^{-2}$ for Peg dSph and Cas dSph, respectively; these

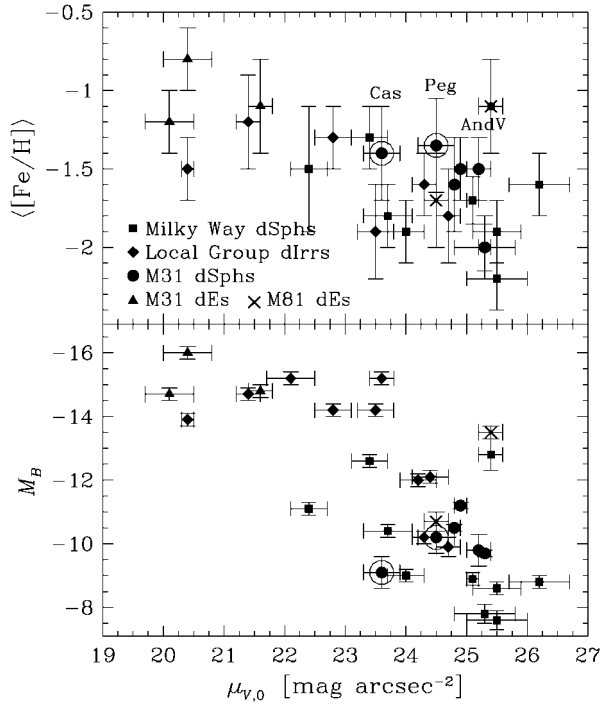


FIG. 4.—*Top panel*: mean metallicity, $\langle[\text{Fe}/\text{H}]\rangle$, plotted vs. central surface brightness in the V band, $\mu_{V,0}$, for nearby dwarf galaxies. The data are from Grebel (1997), Armandroff et al. (1998a), and the present study. Peg dSph and Cas dSph (the two encircled dots) follow the mean $\langle[\text{Fe}/\text{H}]\rangle$ vs. $\mu_{V,0}$ relation within the errors. *Bottom panel*: absolute B-band magnitude, M_B , vs. central surface brightness for the same galaxies that are plotted in the top panel. The M_B values are uncertain at the level of ± 0.5 mag (I. D. Karachentsev 1998, private communication). The data are from Mateo (1998) and the present study; the M_B value for And V is estimated following Armandroff et al. (1998a).

brightnesses are higher than the $\mu_{V,0}$ values for the other M31 dSph's (Caldwell et al. 1992; Armandroff et al. 1998a): 24.9 (And I), 24.8 (And II), 25.3 (And III), and 25.2 mag arcsec $^{-2}$ (And V). Peg dSph and Cas dSph, along with the newly discovered And V dSph (Armandroff et al. 1998a), follow the general $\langle[\text{Fe}/\text{H}]\rangle$ versus $\mu_{V,0}$ relationship defined by Local Group dwarf elliptical (dE), dwarf irregular, and dSph galaxies (Fig. 4, *top panel*). Absolute B-band magnitudes, M_B , are computed from the total apparent magnitudes, B_T , estimated by Karachentsev & Karachentseva (1998a). Taking the M_B estimates at face value, Peg dSph lies on the mean M_B versus $\mu_{V,0}$ relation defined by other Local Group dwarf galaxies (Fig. 4, *bottom panel*), while Cas dSph is somewhat less luminous than other dwarfs of comparable $\mu_{V,0}$.

7. DISCUSSION

A summary of the properties of the two new dSph's, Peg dSph and Cas dSph, derived from Keck imaging is given in Table 1. Their mean metallicities resemble those of the M31 globular cluster system ($[\text{Fe}/\text{H}] = -1.2$; Huchra, Kent, & Brodie 1991) and the intermediate-age/old field populations in M31's dE companions, but they are higher than the $\langle[\text{Fe}/\text{H}]\rangle$ of the other four M31 dSph's (cf. Grebel 1997; Armandroff et al. 1998a). Peg dSph and Cas dSph also have the highest central surface brightnesses of the known M31 dSph's. Their detection

TABLE 1
PROPERTIES OF PEG dSph AND CAS dSph

Parameter	Peg dSph	Cas dSph
α (J2000)	23 51 39	23 26 31
δ (J2000)	24 35 42	50 41 31
l, b (deg)	106.0, -36.3	109.5, -9.9
Position angle (deg)	160 ± 20	55 ± 20
Ellipticity	0.3 ± 0.1	0.3 ± 0.1
E_{B-V}	0.04 ± 0.01	0.17 ± 0.03
$(m - M)_0$	24.6 ± 0.2	24.4 ± 0.2
D_{MW} (kpc)	830 ± 80	760 ± 70
D_{M31} (kpc)	280 ± 85	215 ± 75
D_{M33} (kpc)	340 ± 90	430 ± 80
B_T	14.5 ± 0.5^a	16.0 ± 0.5^a
V_T	14.1 ± 0.2^b	...
$\mu_{V,0}$ (mag arcsec $^{-2}$)	24.5 ± 0.2	23.6 ± 0.2
$\langle[\text{Fe}/\text{H}]\rangle$	-1.3 ± 0.3	-1.4 ± 0.3

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a From Karachentsev & Karachentseva 1998a.

^b From Hopp et al. 1998, corrected using Schlegel et al.'s 1998 extinction estimate.

may have been hampered by the presence of nearby, bright foreground stars (Fig. 1).

Heliocentric distances of 830 ± 80 kpc for Peg dSph and 760 ± 70 kpc for Cas dSph translate into distances of 280 ± 85 and 215 ± 75 kpc from M31, respectively, adopting the Cepheid-based distance of 770 ± 30 kpc to M31 (cf. Freedman & Madore 1990; Holland 1998). Thus, Peg dSph and Cas dSph are the most distant of the currently known M31 dSph satellites. The Leo I and Leo II dSph's are at comparable distances from the Milky Way, lending credence to Karachentsev & Karachentseva's (1998a) suggestion that Peg dSph and Cas dSph belong to an extended subsystem of M31 companions together with And V and LGS 3.

The fraction of stars belonging to an intermediate-age population shows a bimodal distribution among the Milky Way dSph's, with small intermediate-age fractions at small Galactocentric distances and dominant fractions at large distances (van den Bergh 1994). By contrast, all the M31 dSph companions appear to have small intermediate-age populations (with the possible exception of And II; Da Costa 1998), even though they are located at comparable distances from their more massive parent galaxy. The possibility of highly eccentric orbits in the M31/M33 system cannot be ruled out. Our planned spectroscopic observations will help constrain the orbits of the M31 dSph's through radial velocity measurements and should lead to more accurate metallicity and abundance spread determinations.

We thank Igor Karachentsev, Valentina Karachentseva, Taft Armandroff, and George Jacoby for helpful discussions and an anonymous referee for useful comments. Mike Bolte kindly provided IRAF and DAOPHOT scripts for reduction of the Keck data. We are indebted to Peter Stetson for making available his secondary standards, without which a reliable calibration would not have been possible. E. K. G. gratefully acknowledges support from Dennis Zaritsky through NASA LTSA grant NAG5-3501 and by NASA through grant HF-01108.01-98A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

- Armandroff, T. E., Da Costa, G. S., Caldwell, N., & Seitzer, P. 1993, *AJ*, 106, 986
- Armandroff, T. E., Davies, J. E., & Jacoby, G. H. 1998a, *AJ*, 116, 2287
- . 1998b, in *Dwarf Tales*, Vol. 3, ed. E. Brinks & E. K. Grebel, 2
- . 1998c, in *IAU Colloq. 171, The Low Surface Brightness Universe*, ed. J. I. Davies, C. Impey, & S. Philipps (San Francisco: ASP), in press
- . 1998d, in preparation
- Caldwell, N., Armandroff, T. E., Da Costa, G. S., & Seitzer, P. 1998, *AJ*, 115, 535
- Caldwell, N., Armandroff, T. E., Seitzer, P., & Da Costa, G. S. 1992, *AJ*, 103, 840
- Da Costa, G. S. 1998, in *Stellar Astrophysics for the Local Group: A First Step to the Universe*, ed. A. Aparicio & A. Herrero (Cambridge: Cambridge Univ. Press), in press
- Da Costa, G. S., & Armandroff, T. E. 1990, *AJ*, 100, 162
- Freedman, W. L., & Madore, B. F. 1990, *ApJ*, 365, 186
- Grebel, E. K. 1997, *Rev. Mod. Astron.*, 10, 29
- . 1999, in *IAU Symp. 192, The Stellar Content of the Local Group*, ed. P. Whitelock & R. Cannon (San Francisco: ASP), in press
- Grillmair, C. J., et al. 1996, *AJ*, 112, 1975
- Guhathakurta, P., & Grebel, E. K. 1998, in preparation
- Holland, S. 1998, *AJ*, 115, 1916
- Hopp, U., Schulte-Ladbeck, R. E., Greggio, L., & Mehlert, D. 1998, *A&A*, submitted
- Huchra, J. P., Kent, S. M., & Brodie, J. P. 1991, *ApJ*, 370, 495
- Karachentsev, I. D., & Karachentseva, V. E. 1998a, in *Dwarf Tales*, Vol. 3, ed. E. Brinks & E. K. Grebel, 1
- . 1998b, *A&A*, submitted
- Krisciunas, K., et al. 1987, *PASP*, 99, 887
- Landolt, A. U. 1992, *AJ*, 104, 340
- Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, *ApJ*, 417, 553
- Martínez-Delgado, D., & Aparicio, A. 1997, *ApJ*, 480, 107
- Mateo, M. 1998, *ARA&A*, 36, 435
- Oke, J. B., et al. 1995, *PASP*, 107, 375
- Reitzel, D. B., Guhathakurta, P., & Gould, A. 1998, *AJ*, 116, 707
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Stetson, P. B. 1994, *PASP*, 106, 250
- Tikhonov, N. A., & Karachentsev, I. D. 1998, *Astron. Lett.*, submitted
- van den Bergh, S. 1974, *ApJ*, 191, 271
- . 1994, *AJ*, 108, 2145