THE RR LYRAE DISTANCE TO THE DRACO DWARF SPHEROIDAL GALAXY

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ABSTRACT

We present the first CCD variability study of the Draco dwarf spheroidal galaxy. The data were obtained with the Fred Lawrence Whipple Observatory 1.2 m telescope on 22 nights, over a period of 10 months, covering a 22′ × 22′ field centered at α = 17h19m57.5s, δ = 57°50′05″ (J2000.0). The analysis of the BVI images produced 163 variable stars, 146 of which were RR Lyrae: 123 RRab, 16 RRc, 6 RRd, and one RR12. The other variables include a SX Phe star, four anomalous Cepheids, and a field eclipsing binary. Using the short distance scale statistical parallax calibration of Gould & Popowski and 94 RRab stars from our field, we obtain a distance modulus of (m − M)0 = 19.40 ± 0.02 (stat) ± 0.15 (syst) mag for Draco, corresponding to a distance of 75.8 ± 0.7 (stat) ± 5.4 (syst) kpc. By comparing the spread in magnitudes of RRab stars in B, V, and I, we find no evidence for internal dust in the Draco dwarf spheroidal galaxy. The catalog of all variables, as well as their photometry and finding charts, is available electronically via anonymous ftp and the World Wide Web. The complete set of the CCD frames is available upon request.

Key words: distance scale — galaxies: dwarf — galaxies: individual (Draco) — Local Group

On-line material: color figures, machine-readable tables

1. INTRODUCTION

Dwarf spheroidal galaxies (dSph’s) are probably the most common types of galaxies in the present-day universe. They are metal-poor galaxies with a metallicity Z < 0.001 (Mateo 1998), which resembles that found in galactic globular clusters. Most dSph galaxies show evidence for multiple star formation episodes, having populations of different ages. There are very few, namely Tucana, Draco, and possibly Ursa Minor, that host a single stellar population older than 10 Gyr (see Dall’Ora et al. 2003, and references therein).

The Draco dSph, a companion to the Milky Way, was discovered by Wilson (1955) and was first observed by Baade & Swope (1961) for variables. They found 261 variables in their 24′ × 24′ field, but only measured 137 for magnitudes. Of these, 133 were RR Lyrae variables, which they used to derive the distance to the galaxy. There have not been any recent variability studies of Draco, except for the survey by Kinemuchi et al. (2002) which is currently underway. The lack of high-quality CCD observations of the RR Lyrae in Draco dSph motivated us to do this project.

However, several studies of Draco’s stellar population have been conducted and for these CCD photometry has been obtained. Grillmair et al. (1998) present the color-magnitude diagram (CMD) obtained from observations with the Hubble Space Telescope (HST) and confirm that star formation in Draco was primarily single-epoch and that Draco is very similar to the globular clusters M68 and M92, but 1.6 Gyr older. It has a luminosity of 2 × 10^5 L_s, which places it among the least luminous galaxies known. Bellazzini et al. (2002) have done a comparative study of the Draco and Ursa Minor dSph’s with new V, I photometry. Recently, Rave et al. (2003) have released a catalog of photometry of ~5600 stars in Draco. They find 142 candidate variables from their colors, using photometry from five catalogs. However, a uniform data set taken with the same instrument would be more reliable for finding RR Lyrae and obtaining accurate photometry and periods for them.

In this paper, we present a catalog of variable stars found in Draco dSph. The paper is organized as follows: § 2 provides a description of the observations; the data reduction procedure, calibration, and astrometry is outlined in § 3; and the catalog of variable stars is presented in § 4. In § 5, we determine the distance to Draco, and in § 6 we summarize our results.

2. OBSERVATIONS

The observations of the Draco dSph were made with the 1.2 m telescope at the Fred Lawrence Whipple Observatory on Mount Hopkins, Arizona, between 1998 August 19 and 1999 June 20, over 22 nights. We used the “4-Shooter” camera (Szentgyorogyi et al. 2003), with four thinned and AR-coated Loral 2048 × 2048 pixel CCDs. The pixels are 15 μm in size and map to 0.53 pixel−1 on the focal plane, making each image 11′ on the side. The camera was centered at α = 17h19m57.5s, δ = 57°50′05″ (J2000.0). The data consist of 148 × 600 s exposures in the V filter, 44 × 900 s exposures in the B filter and 47 × 600 s exposures in the I filter. The median value of the seeing in V was 2.0′. The field was observed through air masses ranging from 1.12 to 1.55, with the median being 1.19. The completeness of our photometry starts to drop rapidly at about 22.5 in I and 23 mag in V and B. The CCDs saturate for stars brighter than 14 mag in I, 15 mag in V, and 15.5 mag in B. On one photometric night of the run, several images of standard Landolt (1992) fields were taken.

3. DATA REDUCTION, CALIBRATION, AND ASTROMETRY

Preliminary processing of the data was performed with standard routines in the IRAF1 CCDPROC package. The differential photometry for the variable stars was extracted using the ISIS image subtraction package (Alard & Lupton 1998; 1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.}
Alard (2000) from the I-band data. The DAOPHOT/ALLSTAR package (Stetson 1987) was used for the conversion into magnitudes. Mochejska et al. (2001) describe the procedure in detail.

On 1998 August 31, we observed two sets of three Landolt (1992) fields in the \textit{BVI} filters at air masses ranging from 1.18 to 1.99. The transformation from the instrumental to the standard system was derived for each chip in the following form:

\begin{align*}
b &= B + \chi_b + \xi_b (B-V) + \kappa_b X, \\
v &= V + \chi_v1 + \xi_v(B-V) + \kappa_v1 X, \\
v &= V + \chi_v2 + \xi_v2(V-I) + \kappa_v2 X, \\
i &= I + \chi_i + \xi_i(V-I) + \kappa_i X,
\end{align*}

where lowercase letters correspond to the instrumental magnitudes, uppercase letters to standard magnitudes, \(X\) is the air mass, \(\chi\) is the zero point, \(\xi\) the color, and \(\kappa\) the air-mass coefficient. Since most of the color coefficients are small, we used \(B-V = V-I = 1\) when transforming the magnitudes of our stars. Note that the \(B\)-band coefficients are larger, therefore our \(B\) magnitudes for red stars may be off by 0.1 or 0.2 mag (in chip 2), in the worst case.

Stetson (2000) has calibrated \(\sim 400\) stars in the Draco dSph as secondary standards. In chips 3 and 4, where our overlap was large, we normalized to his photometry using the brightest 80 stars (to 19.5 mag) and 66 stars (to 20th mag), respectively, to determine the offsets in \(V\). The difference between his photometry and ours in these chips was 0.04 and 0.02 mag. In chips 1 and 2 the overlap was too small for a meaningful comparison, thus we kept our own photometry. We then compared our normalized \(V\) photometry in chips 3 and 4 with the photometry of Grillmair et al. (1998) from the \textit{HST}. For 100 stars down to 19 mag, the differences between their photometry and ours were 0.06 and 0.03 mag. Bellazzini et al. (2002) have obtained \((V,I)\) photometry of the field and the agreement with
### Table 1: RR Lyrae in Draco Dwarf Galaxy

| Name                  | P (days) | $V$ (mag) | $I$ (mag) | $R$ (mag) | Amp$V$ (mag) | Type | Comments
|-----------------------|----------|-----------|-----------|-----------|--------------|------|----------
| Draco 172059.5+575542.7 | 0.36947$^b$ | 20.110    | 19.702    | 20.454    | 0.540        | c    | BS 173   
| Draco 171938.4+574724.7 | 0.37903$^c$ | 20.118    | 19.571    | 20.532    | 0.489        | c    | BS 50    
| Draco 172112.7+580131.2 | 0.38572$^c$ | 20.179    | 19.726    | 20.579    | 0.548        | c    | BS 181   
| Draco 172110.8+574736.2 | 0.39233$^c$ | 20.016    | 19.619    | 20.518    | 0.541        | c    | BS 179   
| Draco 171917.5+580107.5 | 0.39502   | 20.100    | 19.616    | 20.373    | 0.447        | c    |          

**Note.**—Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

$^a$ Names given in Baade & Swope 1961.

$^b$ Notes different period from that found by Baade & Swope 1961.

$^c$ Notes a star with no period in Baade & Swope 1961.

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**Phase**

Fig. 2.—Light curves of selected other periodic variables found in Draco dSph. An eclipsing binary and three anomalous Cepheids are shown, and their periods are given in days.

HJD = 2450000

Fig. 3.—Sample light curves of other variables found in Draco dSph.
our photometry is good, the largest offset being 0.07 mag in magnitude and phase of each harmonic were calculated. We searched parameters such as the amplitude of the variation and amplitude of the Fourier series were fitted to the RR Lyrae light curves phased to the period determined earlier and periodicity. Additionally, Fourier series were fitted to the RR Lyrae light curves phased to the period determined earlier and parameters such as the amplitude of the variation and amplitude of phase of each harmonic were calculated. We searched for multiperiod variables by subtracting the first three harmonics of the Fourier series from the phased light curves and then repeating the period search. We then redetermined secondary periods for the six double-mode (RRab) stars found by Nemec (1985) in the data of Baade & Swope (1961), by searching the periodogram where the second period was expected.

Baade & Swope (1961) do not find any red irregular or long-period variables in their data, with the exception of BS 203, a bright blue variable with a period of ~3 yr. We observed all of their “special variables” except for BS 138. The only significant difference in these is that the period we find for BS 134 is 0.592 days, not 1.458 days, which agrees with Nemec (1985) who realnalyzed the data of Baade & Swope (1961). The periods we calculated for variables also found by Baade & Swope (1961) are very similar in most cases. The cases that differ are labeled in Table 1. As a result some stars are classified differently from Baade & Swope (1961). BS 97, BS 121, BS 173, and BS 145 are all RR Lyrae stars, BS 140, BS 169, BS 143, BS 72, BS 11, and BS 112 are RRd stars. We did not

### Table 2

**Other Variables in Draco Dwarf Galaxy**

| Name | $P$ (days) | $<V>$ (mag) | $<I>$ (mag) | $<B>$ (mag) | Amp$_V$ (mag) | Comments* |
|------|------------|-------------|-------------|-------------|---------------|-----------|
| Draco 172017.3+574817.3...... | 0.068, 0.073, 0.079 | 21.985 | 21.468 | 22.033 | 0.873 | SX Phe |
| Draco 171906.2+574120.9...... | 0.2435 | 19.645 | 18.058 | 20.751 | 0.266 | Ecl. Binary |
| Draco 171906.4+574948.2...... | 0.59229* | 18.846 | 18.368 | 19.267 | 0.877 | Ceph, BS 134 |
| Draco 172017.3+575708.1...... | 0.90085 | 19.204 | 18.573 | 19.640 | 0.679 | Ceph, BS 141 |
| Draco 171934.5+575849.6...... | 0.93644 | 19.043 | 18.439 | 19.597 | 0.888 | Ceph, BS 157 |

Note.—Table 2 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

* Type of variable and name given in Baade & Swope 1961.

** Fig. 4.—Period distribution of 146 RR Lyrae in Draco. The median period for RRab stars is 0.617 and for RRc stars 0.392. Both components of the double-mode stars are also plotted in black.**
find variables BS 10, BS 31, BS 111, and BS 195 due to the proximity of highly saturated stars.

We present a histogram of the 139 RR\textsubscript{ab} and RR\textsubscript{c} Lyrae in Draco, with 0.02 day bins in Figure 4. Both components of the double-mode stars are also plotted (in black). The median period for RR\textsubscript{ab} stars is 0.617 days and for RR\textsubscript{c} stars is 0.392 days, which places the Draco dSph between Oosterhoff type I (~0.55 days) and type II (~0.65 days) clusters, similarly to other dSph (Dall’Ora et al. 2003). In Figure 5, we present a CMD of stars in Draco. Circles represent RR Lyrae, squares are anomalous Cepheids and triangles are other variables. Among these other variables is the long-period blue variable BS 203, a foreground 0.24 day eclipsing binary, and a multimode SX Phe star that is pulsating in three modes, with periods 0.068, 0.073, and 0.079 days. The period-amplitude diagram for the 146 RR Lyrae in Draco is shown in Figure 6. Circles represent RR\textsubscript{ab} stars, triangles RR\textsubscript{c} stars, and squares RR\textsubscript{d} stars, for which both periods are plotted.

5. DISTANCE TO DRACO dSph

The distance to the Draco dSph galaxy has been estimated by several authors. Baade & Swope (1961) obtained a distance of \( d = 99 \) kpc assuming an absolute magnitude of \( M_B = 0.5 \) mag for RR Lyrae; Nemec (1985) obtained \( d = 84 \pm 12 \) kpc using RR\textsubscript{d} stars found by reanalyzing the data of Baade & Swope (1961); Aparicio, Carrera, & Martinez-Delgado (2001) obtained \( d = 80 \pm 7 \) kpc by the magnitude of the horizontal branch at the RR Lyrae instability strip; and Bellazzini et al. (2002) obtained \( d = 92.9 \pm 6 \) kpc by fitting template cluster horizontal branches.

We use the short distance scale statistical parallax calibration of Gould & Popowski (1998), which is a robust method of measuring the absolute magnitude of RR Lyrae stars. They find

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M_V = 0.77 \pm 0.13,
\]
at $\langle[Fe/H]\rangle = -1.60$, for a sample of 147 halo RR Lyrae stars with high-quality proper motions from the Hipparcos (ESA 1997) and Lick NPM1 (Klemola, Hanson, & Jones 1993) surveys. Shetrone, Côte, & Sargent (2001) find $\langle[Fe/H]\rangle = -2.00 \pm 0.21$ in Draco dSph from high-resolution spectroscopy of six red giants in the galaxy. Lehner et al. (1992) also found a metallicity of $\langle[Fe/H]\rangle = -1.9$, $\sigma = 0.4$, from spectra of 14 giants. The abundances seem to fall into two groups, one with an average [Ca, Mg/H] near $-1.6 \pm 0.2$ and the other $-2.3 \pm 0.2$. We adopt the value $\langle[Fe/H]\rangle = -2.00$ (also quoted in Mateo 1998) for our distance determination. The metallicity correction is derived from the slope of the luminosity-metallicity relation for RR Lyrae, which lies between 0.2 (Chaboyer 1999) and 0.3 (Sandage 1993). Using 0.2 for the slope of the slope and 0.4 dex for the difference in metallicity of Draco dSph from galactic RR Lyrae, we find $M_V = 0.69$ for the RR Lyrae in Draco dSph.

Draco dSph is located at Galactic coordinates $l = 86^{\circ}37$, $b = 34^{\circ}72$. To remove the effects of the Galactic interstellar extinction, we used the reddening map of Schlegel, Finkbeiner, & Davis (1998), which yields $E(B-V) = 0.027$ mag. This corresponds to expected values of Galactic extinction of $A_I = 0.053$, $A_V = 0.091$, and $A_B = 0.118$ mag, using the extinction corrections of Cardelli, Clayton, & Mathis (1989) as prescribed in Schlegel et al. (1998).

For the distance determination, we only used the RRab stars found in chips 3 and 4, which are normalized to the photometry of Stetson (2000). There are 94 such stars in our data. The remaining RRab stars from chip 1 and 2 are not included in this list. We fitted a Gaussian to a histogram of these 94 stars, using 0.03 mag bins and found $\langle m_V\rangle = 20.18 \pm 0.02$, $\sigma = 0.08$, as shown in Figure 7. This value is in agreement with the value of Aparicio et al. (2001) for the horizontal branch at the RR Lyrae instability strip, 20.2 $\pm$ 0.1 mag, and with the value of Bellazzini et al. (2002) of 20.30 $\pm$ 0.12 mag, obtained by fitting to the template cluster M68. Our measurement implies a distance modulus of $m_V - M_V = 19.49$ mag. Correcting for extinction gives a true distance modulus of $(m - M)_0 = 19.40$ mag and a distance of 75.8 kpc to Draco dSph.

The systematic errors are 0.06 mag in $A_V$, 0.03 mag in photometry, 0.13 mag in the calibration method, and 0.04 mag in metallicity. The error in the reddening from Schlegel et al. (1998) is 0.02 mag, which corresponds to 0.06 mag in $A_V$, and the error in metallicity is calculated from a conservative error of 0.4 dex, the metallicity difference. Adding the systematic errors in quadrature gives a conservative total estimate of 0.15 mag, which is dominated by the calibration error. We consider the effects of internal extinction to be negligible from a comparison of the spread in magnitudes of RRab stars in different filters. Similar to Figure 7 for $V$ with $\sigma = 0.08$, the spread in magnitudes of RRab stars in $B$ and $I$ are $\sigma = 0.10$ and 0.12, respectively. Thus we find no evidence for internal dust in the Draco dSph galaxy.

The statistical error is 0.02 mag, which leads to a true distance modulus of $(m - M)_0 = 19.40 \pm 0.02$ (stat) $\pm 0.15$ (syst) mag, corresponding to a distance of 75.8 $\pm$ 0.7 (stat) $\pm$ 5.4 (syst) kpc.

6. CONCLUSIONS

We have presented the results of the first CCD variability study in the Draco dSph galaxy since Baade & Swope (1961). Our search produced 163 variable stars, 146 of which are RR Lyrae, four are anomalous Cepheids, one is a field eclipsing binary, one a SX Phe star, and 11 are other types of variables. We have used the short distance scale statistical parallax calibration of Gould & Popowski (1998) for 94 RRab in our field and obtained a distance modulus of $(m - M)_0 = 19.40 \pm 0.02$ (stat) $\pm 0.15$ (syst) mag. By comparing the spread in magnitudes of RRab stars in different filters, we find no evidence for internal dust in the Draco dSph galaxy.

The catalog of all variables, as well as their photometry and finding charts, is available electronically via anonymous ftp and the World Wide Web. The complete set of the CCD frames is available upon request.
We thank Grzegorz Pojmański and Wojtek Pych for their LC and Fourier series programs and Barbara Mochejska for her help. We also thank Janusz Kaluzny, Piotr Popowski, John Huchra, and the referee for their careful reading of and comments on the manuscript. We finally thank Mike Pahre, Emilio Falco, Lucas Macri, and Saurabh Jha for helping obtain the observations. Guest User, Canadian Astronomy Data Centre, which is operated by the Dominion Astrophysical Observatory for the National Research Council of Canada’s Herzberg Institute of Astrophysics.

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The photometry in the printed version of Table 1 was incorrect. Corrected values in the table below match the correct values in the online version of Table 1 in the original paper. These corrections are only typographical in nature, and none of the results or conclusions of the paper are affected. We are grateful to A. Sandage for detecting this error.

Table 1: RR Lyrae in Draco Dwarf Galaxy

| Name             | P (days) | V (mag) | I (mag) | B (mag) | Amp_V (mag) | Type | Comments |
|------------------|---------|---------|---------|---------|-------------|------|----------|
| Draco 172059.5+575542.7        | 0.36947 | 20.151  | 19.735  | 20.517  | 0.540       | c    | BS 173   |
| Draco 171938.4+574724.7        | 0.37903 | 20.152  | 19.683  | 20.570  | 0.489       | c    | BS 50    |
| Draco 172112.7+580131.2        | 0.38572 | 20.176  | 19.726  | 20.462  | 0.548       | c    | BS 181   |
| Draco 172110.8+574736.2        | 0.39233 | 20.068  | 19.675  | 20.613  | 0.541       | c    | BS 179   |
| Draco 171917.5+580107.5        | 0.39502 | 20.145  | 19.671  | 20.433  | 0.447       | c    | ...      |

* Names given in Baade & Swope (1961).  
* Notes different period from that found by Baade & Swope (1961).  
* Notes a star with no period in Baade & Swope (1961).
ERRATUM: “THE RR LYRAE DISTANCE TO THE DRACO DWARF SPHEROIDAL GALAXY”
(2004, AJ, 127, 861)

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The coordinates (and therefore names) of the 49 variables detected in chip 4 were incorrectly assigned in the original manuscript. Corrected versions of the affected Tables 1 and 2, and Figures 2 and 3 are given in this erratum, superseding the previous erratum. These corrections are only typographical in nature, and none of the results or conclusions of the paper are affected. We are grateful to H. Harris for pointing out this error.

\textit{Key words:} errata, addenda

\textit{Online-only material:} machine-readable and VO tables

\textbf{Figure 1.} Figure 2, with corrected labels for the variable names.

\textbf{Figure 2.} Figure 3, with corrected labels for the variable names.
### Table 1
RR Lyrae in Draco Dwarf Galaxy

| Name               | $P$  | $\langle V \rangle$ | $\langle I \rangle$ | $\langle B \rangle$ | $Amp_V$ | Type | Comments |
|--------------------|------|---------------------|---------------------|---------------------|--------|------|----------|
| Draco172059.5+575542.7 | 0.36947$^b$ | 20.151 | 19.735 | 20.517 | 0.540 | c    | BS-173   |
| Draco171938.4+574724.7 | 0.37903$^c$ | 20.152 | 19.683 | 20.570 | 0.489 | c    | BS-50    |
| Draco172112.7+580131.2 | 0.38572$^c$ | 20.176 | 19.726 | 20.462 | 0.548 | c    | BS-181   |
| Draco172110.8+574736.2 | 0.39233$^c$ | 20.068 | 19.675 | 20.613 | 0.541 | c    | BS-179   |
| Draco171845.3+575222.5 | 0.39502 | 20.145 | 19.671 | 20.433 | 0.447 | c    | ...      |

**Notes.**

$^a$ Names given in Baade & Swope (1961).

$^b$ Different period from that found by Baade & Swope (1961).

$^c$ A star with no period in Baade & Swope (1961).

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 2
Other Variables in Draco Dwarf Galaxy

| Name               | $P$  | $\langle V \rangle$ | $\langle I \rangle$ | $\langle B \rangle$ | $Amp_V$ | Comments |
|--------------------|------|---------------------|---------------------|---------------------|--------|----------|
| Draco172017.3+574817.3 | 0.068,0.073,0.079 | 21.985 | 21.468 | 22.033 | 0.873 | SX Phe |
| Draco171906.2+574120.9 | 0.2435 | 19.645 | 18.058 | 20.751 | 0.266 | Ecl. Binary |
| Draco171906.4+574948.2 | 0.59229$^b$ | 18.846 | 18.368 | 19.267 | 0.877 | Ceph, BS-134 |
| Draco172017.8+575708.1 | 0.90085 | 19.204 | 18.573 | 19.640 | 0.679 | Ceph, BS-141 |
| Draco171908.1+575835.0 | 0.93644 | 19.043 | 18.439 | 19.597 | 0.888 | Ceph, BS-157 |

**Notes.**

$^a$ Type of variable and name given in Baade & Swope (1961).

$^b$ Different period from that found by Baade & Swope (1961).

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