RR Lyrae Stars in the Boötes dSph

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ABSTRACT

We present a catalog of 15 RR Lyrae variable stars in the recently discovered Boötes dSph galaxy – the most metal-poor simple stellar population with measured RR Lyrae stars. The pulsational properties of the RR Lyrae conform closely to period-abundance trends extrapolated from more metal-rich populations and we estimate the distance of Boötes to be $(m - M)_0 = 18.96 \pm 0.12$. The average period (0.69 days), the ratio of type c to type ab pulsators (0.53) and the RRab period shift (-0.07) indicate an Oosterhoff II classification for Boötes, a marked contrast to the other dSph galaxies, which are Oosterhoff intermediate. This supports the contention that the Oosterhoff dichotomy is a continuum – that RR Lyrae properties, to first order, vary smoothly with abundance. The dSph galaxies are not distinct from the Galactic globular clusters, but bridge the Oosterhoff gap. The absence of any anomalous Cepheids in Boötes could indicate the lack of an intermediate age population.

Subject headings: stars:variables:RR Lyrae – galaxies: dwarf – galaxies: individual (Boötes)

1. Introduction

Belokurov et al. (2006, hereafter B06) have reported the discovery of a new dSph galaxy in the constellation of Boötes. This galaxy, claimed to be faintest known Local Group galaxy, is very sparse and apparently metal-poor, with a color-magnitude diagram consistent with an abundance near $[Fe/H] \sim 2.3$. Munoz et al. (2006, hereafter M06) have presented spectra of Boötes stars, revealing the dSph to be extremely metal-poor ($[Fe/H] \sim -2.5$) with a high apparent M/L ratio ($\sim 130 – 680$).

Studies of variable stars in dSph galaxies (Siegel & Majewski 2000, hereafter SM00, and references therein) have found rich populations of RR Lyrae variable stars as well as anomalous Cepheids. The variable stars are useful not only for constraining the distance modulus to the dwarfs but for confirming gross properties of the stellar populations. The
presence of anomalous Cepheids and RR Lyrae stars indicate intermediate and old stellar populations, respectively, and the pulsational properties of the latter are heavily dependent upon the abundance – and perhaps evolution – of the horizontal branch (HB) stars. Inversely, the RR Lyrae in dSph galaxies may probe regions of parameter space unoccupied by Galactic RR Lyrae. Boötes is a perfect example of this – it appears to be one of the most metal-poor simple stellar populations near the Galaxy. In this Letter, we present a survey of variable stars in Boötes, identify 15 RR Lyrae variable stars and show that their pulsational properties are consistent with trends extrapolated from more metal-rich populations. We also comment on the impact this study has on the Oosterhoff “dichotomy”.

2. Observations and Reduction

We observed the Boötes dSph with the 0.8-meter telescope at McDonald Observatory on UT April 30 to May 3 2006 and June 23-26 2006. Images were obtained with the Prime Focus Corrector (PFC) in the $B$, Washington $M$, $T_2 (= I)$ and narrow-band DDO51 filters. The PFC has a field of view of 46′0 and although this should presumably be large enough to observe the entirety of Boötes, a slight offset in the 0.8-m setting circles displaced our pointing slightly southwest of the dSph center. Boötes subtends a large angle on the sky (M06 estimate $r_h \sim 13′$) and there is some indication that it extends off the eastern end of our survey field.

Data were reduced with the IRAF CCDPROC package. Although the 0.8-m telescope is unguided, the tracking is stable enough – and the pixel scale coarse enough – to allow 600s integrations without significant image ellipticity. Only the first two nights of the April run were photometric.

The data were photometered using the DAOPHOT and ALLFRAME packages (Stetson 1987, 1994). Despite the coarse pixel scale of the PFC (1″35 per pixel), we derived excellent PSFs with precise photometry down to Boötes’ HB. Photometric errors are approximately $\sigma_B = 0.08$ at $B = 20$ for individual images and $\sigma_B = .01$ at $B = 20$ in the combined image created for ALLFRAME.

Standard stars were measured using multi-aperture photometry and DAOGROW (Stetson, 1990) to extract total magnitudes. The total magnitudes were then calibrated to the standards of Landolt (1992) and Geisler (1990,1996) using the matrix inversion methods outlined in Siegel et al. (2002). Individual images were calibrated using the iterative technique described in Siegel et al. with apertures corrected to the total magnitudes of the PSF stars as calculated by DAOGROW. The $B$ zero point of the photometric frames showed variation
consistent with that of the standard stars (.01 mag).

RR Lyrae stars vary in color by 0.2-0.4 mag (Nemec 2004), which could induce offsets in the relative photometry. Although we took four $I$ observations from which stellar colors could be measured, this is inadequate for precise epochal colors for each CCD frame. We therefore transformed the photometry of the RR Lyrae stars using the average RR Lyrae $< B > - < I >$ color. Given that the $B - I$ color term is small (-.059 mag), this reduces the color-induced photometric scatter to $<1-2\%$.

Accurate stellar positions were estimated from the IRAF task TFIN DER and the NOMAD astrometric catalog (Zacharias et al. 2004). The astrometry has a precision of $0''2$ in each coordinate.

3. Light Curve Fitting

Light curves are based on 58 $B$ images obtained with the PFC. A table of Julian dates and $B$ magnitudes for all our RR Lyrae stars is available electronically through the ApJ.

To identify variable stars in our data, we used the variability index produced by DAOMASTER – the ratio of scatter to observational error. We selected stars with variability greater than 2.75 as potential variables. Twenty stars in our sample showed this level of variability. Figure 1 shows the color-magnitude diagram of Boötes with the variable stars marked.

Fifteen of the variables are on the Boötes HB and all of these are RR Lyrae stars (§4). The bright star near $B - I \sim 1.5$ shows 0.1 mag variability with no consistent periodicity on the 1-2 day timescale. Its $M - DDO51$ color is precisely along the field dwarf locus. All three red variables have $M - DDO51$ colors consistent with stars near the tip of the red giant branch (TRGB). One of these has an apparent magnitude ($I = 14.7$) near the Boötes TRGB ($I = 15.2$; Bellazzini et al. 2004). The red stars show variations of 0.1-0.2 mag, but manifested between the two observing runs, not over either individual run. These may be long-period variables near the TRGB. The remaining bright variable is located just above the Boötes HB – a position normally associated with anomalous Cepheid variables. However, this star shows no periodicity on the scale of 1-2 days, only a 0.2 magnitude difference between the observing runs. It could be a foreground quasar or another long-period variable.

The absence of any anomalous Cepheids (AC) could indicate that Boötes lacks an intermediate-age population (see Nemec et al. 1988; Mateo et al. 1995). However, Boötes may have too few stars to produce AC. Our study of Leo II (SM00) identified only four AC
against 148+ RR Lyrae stars.

For the RR Lyrae candidates, periods were fit using methods outlined in SM00. We used Stetson’s (1996) modified version of the Lafler-Kinman index (1965) to identify potential periods and used a Levenberg-Marquardt algorithm to fit the RR Lyrae templates of Layden (1998) to each trial period. With each star, a clear minimum $\chi^2$ was found\(^1\). We should expect 1-3 of Boötes’ RR Lyrae to demonstrate the Blazhko (1907) effect but our data are not extensive enough to detect second-order variation. None of our stars exhibit double-mode pulsation (Cox et al. 1980; Sandage et al. 1981; Cox et al. 1983; Nemec 1985a).

Periods were checked by comparison to the phase dispersion minimization (Stellingwerf 1978) program in IRAF and the STDLC template-fitting program of Layden et al. (1999) and Layden & Sarajedini (2000). Both fit periods within measurement uncertainties of ours.

4. Boötes RR Lyrae Stars

Table I lists ID, coordinates, period, amplitude and Bailey (1902) type (pulsation mode) for the 15 RR Lyrae stars identified in Boötes. We also list intensity-weighted mean magnitudes ($m_B$) calculated by integrating the Layden templates in .02 phase increments at the fit amplitude and period. Light curves of all our variables are shown in figure 2.

Figure 3 shows the period-amplitude distribution of the RR Lyrae stars in Boötes. We note that they follow a period-amplitude relationship similar to that seen in other globular clusters and dSph galaxies, but offset to longer periods – a result consistent with a very low abundance for Boötes. The c variables are of nearly constant amplitude but show a hint of the parabola shape predicted by Bono et al. (1997).

4.1. Boötes Stellar Populations

Sandage (1993, S93) demonstrated that the pulsational properties of RR Lyrae track the abundance of the parent population. This provides a check on abundance that is independent of photometric zero point, reddening or assumptions about standard candles. Boötes would represent the lowest-metallicity population for which these relations have been tested.

\(^1\)Star V3 has two $\chi^2$ minima at .32 and .48 days. We did not capture the star during its rise and both periods fit the descent of the light curve – although with a much larger amplitude for the .48 day fit (both were RRc templates). We selected the 0.32 day fit because the period and amplitude would be more consistent with the other Boötes RRc stars as well as those in other dSph galaxies and globular clusters.
The most reliable diagnostic of S93 is the average period of the RRab stars, which is updated in Sandage (2006) to:

$$\log <P_{ab}> = -0.098 \, [\text{Fe/H}] - 0.416$$

The RRab variables in Boötes have an average period of \(0.691 \pm 0.089\) days, consistent with an abundance of \([\text{Fe/H}]=-2.6\) on the Zinn-West (1984) scale.

The shortest and longest RRab period depends on the location of the blue and red edges, respectively, of the instability strip. S93 showed that these values also depend on the abundance of the parent population. We use the formula for the the shortest period from Sandage (2006) and for the longest period from S93:

$$\log(P_{ab}) = -0.452 + 0.033 \, [\text{Fe/H}]^2$$

$$\log(P_{ab}) = -0.09 \, [\text{Fe/H}] - 0.280$$

Our shortest RRab has a period of 0.576 days, consistent with an abundance of \([\text{Fe/H}]=-2.5\) on the Zinn-West scale. Our longest period variable (0.859 days) would be consistent with an abundance of \([\text{Fe/H}]=-2.4\) on the Butler-Blanco scale (Butler 1975; Blanco 1992), which we correct to a Zinn-West abundance of \([\text{Fe/H}]=-2.6\).

Finally, the average RRc period tracks abundance by the S93 equation:

$$\log <P_c> = -0.119 \, [\text{Fe/H}] - 0.670,$$

which, given the average Boötes RRc period of \(0.364 \pm 0.044\) days, indicates an abundance of \([\text{Fe/H}]=-2.0\). This is more metal-rich than the other measures. We would expect the RRc stars to have an average period of 0.42 days given the S93 formula. If star V3 were to be evaluated at the 0.48 day degeneracy, this would only increase the derived abundance to \([Fe/H] \sim -2.1\). A degeneracy in an RRab star and/or several undiscovered RRc with periods near 0.5 days would be required to move the average period to longer values. The average RRc period is the only measure inconsistent with the measured abundance of Boötes. This may indicate non-linearity in the \([Fe/H] - <P_c>\) relation, similar to the slight non-linearity identified in the relationship between abundance and shortest RRab period.

It should be noted that Boötes subtends a large solid angle – its variables are distributed across the PFC field with 14/15 on the eastern half. A few RR Lyrae stars may have been
missed in our survey. Given the small number of RR Lyrae stars, a missed variable with an extremely long or short period could alter our results, shifting the average period or providing an RRab with a shorter or longer period than the ones we have measured.

Nevertheless, our pulsational diagnostics are consistent with the very low Boötes abundance indicated by B06 and M06. This demonstrates that the connection between RR Lyrae pulsation properties and abundance extends to the extremely metal-poor domain. More variable star surveys of the growing number of newly-discovered metal-poor dwarfs in the Local Group would test this assertion.

We noted above that the period-amplitude relation of Boötes’ RR Lyrae stars is shifted relative to M3. Period shifts are well-established in cluster RR Lyrae (Sandage 1981a; Sandage 1981b; Carney et al. 1992) and are quantitatively defined by comparison to a reference variable star population, M3 being the usual template. SM00 refine the period shift measure to:

\[ \Delta \log P = -[0.129 A_B + 0.112 + \log P] \]

The \( \Delta \log P \) values of Boötes are plotted in Figure 4. The right ordinate has the \( \Delta M_{bol} \) scale derived in SM00 by applying assumptions about period shift (notably constant mass) to the fundamental pulsation equation of van Albada & Baker (1971).

The RR Lyrae stars in Boötes have a mean period shift of -.07. There is some scatter in the period shifts which may indicate scatter in the fundamental properties of Boötes’ RR Lyrae – either age, abundance or evolution. The period shifts of Boötes’ RR Lyrae are consistent with bolometric luminosities several tenths of a magnitude brighter than the RR Lyrae of M3, as expected for a very metal-poor population. We tested this hypothesis by comparing \( m_B \) against \( \Delta \log P \). We found that a linear correlation with a slope of 0.7 mag. This would be consistent with the variable stars of Boötes being 0.05 mag brighter than those of M3, a luminosity difference four times smaller than that predicted by the magnitude-abundance relations in the literature (see §5). This indicates either that the assumption of constant mass in the SM00 derivation is erroneous or that there is too much scatter in the period shift for an internal check on the \( m_B - \Delta \log P \) relation.

4.2. Boötes and the Oosterhoff Continuum

Oosterhoff (1939) established that Galactic globular clusters can be divided into two categories based on the average RRab period and RRab to RRc ratio (see review in Catelan
The dSph galaxies, LMC and Fornax globular clusters, and M31 have average $< P_{ab} >$ and $N_{ab}/N_{RRab}$ measures intermediate between OoI and OoII (SM00; Catelan 2005 and references therein), filling the Oosterhoff gap and providing a continuous trend of pulsation properties with abundance (see Figure 6 in SM00). Nevertheless, some studies of RR Lyrae stars continue to differentiate stars based on their Oosterhoff type.

It could be argued that the dSph RR Lyrae are different from the globular cluster RR Lyrae by virtue of the second-parameter effect. However, Boötes breaks this trend. It is very metal-poor – the most metal-poor object known to have RR Lyrae stars. The average period of Boötes RRab stars (0.69 days) and the ratio of RRc to RRab (0.53) place Boötes in the OoII category. The Oosterhoff dichotomy also manifests in period shift – both cluster and field stars avoid $\Delta \log P$ values between -0.01 and -0.05 (Suntzeff et al. 1991, marked in Figure 4). The stars in Boötes have OoII period shifts.

This means that the dSph galaxies not only fill the Oosterhoff gap in the Peterson diagram, but bridge the gap, providing a continuum of behavior from OoI to OoII. This reinforces the contention of Renzinini (1983), Castellani (1983) and S93 that the Oosterhoff gap only exists because of blueward shift in the HBs of intermediate-abundance Galactic globular clusters.

Of course, as SM00 note, there are many parameters that affect RR Lyrae pulsational properties besides abundance – notably evolution from the zero-age HB (Lee, Demarque & Zinn 1990; Lee & Carney 1999; Demarque et al. 2000). Nevertheless, the presence of Boötes in the OoII part of the Peterson diagram shows that the dSph galaxies follow the same abundance-pulsation relations as the globular clusters. It is clear that when all groups of RR Lyrae stars are considered, metallicity is the “first parameter” of RR Lyrae pulsational properties. The data require no fundamental difference between OoI and OoII RR Lyrae stars because no dichotomy exists in the observational plane.

5. Distance and $M_V$ of Boötes

RR Lyrae stars are excellent standard candles. The average $m_B$ of Boötes’ RR Lyrae variables is $B = 19.81 \pm 0.05$. Sandage (2006) estimates that the typical RR Lyrae at the abundance of Boötes have a $(B - V)_0$ color of $0.331 \pm 0.025$. Piersimoni et al. (2002) provide an empirical calibration of RR color from period, $A_B$ and [Fe/H], from which we calculate $(B - V)_0 = 0.332 \pm 0.03$ for our stars. This places the RR Lyrae locus of Boötes at

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2The RRc variables are .05 mag brighter than the RRab variables.
An analysis of the literature (Fernley et al. 1998; Gratton et al. 2004; Sandage 2006) indicates that stars at \([Fe/H] = -2.5\) should have an absolute magnitude of \(M_V = 0.35 \pm 0.10\), resulting in a Boötes distance modulus of \((m - M) = 19.13 \pm 0.12\). B06 estimate an \(A'_V\) extinction value for Boötes of 0.06 mag. We find, from the maps of Schlegel et al. (1998), a reddening of \(E_{B-V} = .056\); \(A'_V = 0.17\). This produces an absolute distance modulus of \((m - M)_0 = 18.96 \pm .12\) for a distance of 62 \pm 4 kpc.

Our survey reveals more variable stars in Boötes than would be expected from such a low luminosity dwarf \((M_V = -5.8; \text{B06})\). By comparison, SM00 detect ten times as many RR Lyrae in Leo II, which is over four magnitudes \((\sim 80\times)\) brighter than Boötes. Our preliminary examination of Ursa Major, which B06 claim is of similar brightness to Boötes, indicates perhaps one RR Lyrae in the field. In fact, Boötes has more RR Lyrae stars within its core radius (12) than Ursa Major has HB stars (9, from figure 1 of Willman et al. 2005). This could indicate that Boötes has a high frequency of RR Lyrae stars -- or it could indicate that B06 underestimate Boötes’ \(M_V\). An absolute magnitude of \(M_V \sim -7\) would be more consistent with the number of RR Lyrae stars in Boötes.

### 6. Conclusions

We identify and fit periods to 15 RR Lyrae variable stars in the Boötes dSph galaxy. While Boötes subtends a large solid angle and may have RR Lyrae outside our survey field, the average, shortest and longest RRab periods are consistent with the very low metallicity derived by B06 and M06. Boötes is the most metal-poor object in which RR Lyrae have been identified. The distance modulus of Boötes is \((m - M)_0 = 18.96 \pm 0.12\).

Boötes is a canonical OoII object, with long RRab periods, a large fraction of RRc variables and large negative RRab period shifts. In combination with the other dSph galaxies, it bridges the Oosterhoff gap, confirming that the the gap is a selection effect peculiar to the Milky Way and not necessarily a fundamental aspect of RR Lyrae variable stars.

This research was supported by NSF grant AST-0306884. Work on this program was performed at the Aspen Center for Physics.
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| Var ID | RA J2000.0 | DEC J2000.0 | Period (Days) | $A_B$ | $m_B$ | Bailey Type |
|--------|------------|-------------|---------------|-------|------|-------------|
| V1     | 13:59:29.36 | 14:10:43.6  | .3037714      | 0.628 | 19.78| c           |
| V2     | 13:59:51.34 | 14:39:06.1  | .3102270      | 0.667 | 19.73| c           |
| V3     | 14:00:26.87 | 14:35:33.3  | .3228953      | 0.638 | 19.79| c           |
| V4     | 14:00:08.90 | 14:34:24.3  | .3832322      | 0.584 | 19.82| c           |
| V5     | 14:00:21.56 | 14:37:29.0  | .3863158      | 0.566 | 19.75| c           |
| V6     | 13:59:45.95 | 14:31:40.8  | .3918305      | 0.607 | 19.86| c           |
| V7     | 13:59:49.37 | 14:10:05.6  | .4011623      | 0.742 | 19.76| c           |
| V8     | 13:59:59.69 | 14:27:34.1  | .4145401      | 0.489 | 19.79| c           |
| V9     | 13:59:47.28 | 14:27:56.4  | .5758855      | 1.279 | 19.84| ab          |
| V10    | 14:00:25.76 | 14:33:08.6  | .6279676      | 1.325 | 19.78| ab          |
| V11    | 13:58:04.38 | 14:13:19.3  | .6617310      | 1.201 | 19.82| ab          |
| V12    | 13:59:56.00 | 14:34:55.1  | .6797488      | 0.544 | 19.90| ab          |
| V13    | 13:59:06.36 | 14:19:00.1  | .7061108      | 0.819 | 19.77| ab          |
| V14    | 13:59:25.75 | 14:23:45.4  | .7244797      | 0.858 | 19.89| ab          |
| V15    | 14:00:11.08 | 14:24:19.7  | .8586484      | 0.481 | 19.83| ab          |
Fig. 1.— $BI$ color-magnitude diagram of the Boötes field. Variable stars are marked with triangles.

Fig. 2.— Light curves for the Boötes RR Lyrae, sorted by increasing period. Template light curves are overlayed for comparison.

Fig. 3.— Period-amplitude distribution of the RR Lyrae stars in Boötes. The dashed line marks the period-amplitude locus of M3, parameterized by SM00.

Fig. 4.— The period shift ($\Delta \log P$) of Boötes’ RR Lyrae stars. The right ordinate shows the corresponding bolometric magnitude shift, under the assumption of constant mass. The dashed lines mark the zone avoided by Galactic field and globular cluster stars. This may be contrasted with a similar diagram for Leo II shown in SM00 and Mateo et al. (1995).
