THE VARIABLE STARS AND BLUE HORIZONTAL BRANCH OF THE METAL-RICH GLOBULAR CLUSTER NGC 6441

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ABSTRACT

We present time-series $VI$ photometry of the metal-rich ([Fe/H] = $-0.53$) globular cluster NGC 6441. Our color-magnitude diagram shows that the extended blue horizontal branch seen in Hubble Space Telescope data exists in the outermost reaches of the cluster. About 17% of the horizontal-branch stars lie blueward and brightward of the red clump. The red clump itself slopes nearly parallel to the reddening vector. A component of this slope is due to differential reddening, but part is intrinsic. The blue horizontal-branch stars are more centrally concentrated than the red clump stars, suggesting mass segregation and a possible binary origin for the blue horizontal-branch stars. We have discovered $\sim 50$ new variable stars near NGC 6441, among them eight or more RR Lyrae stars that are highly probable cluster members. Comprehensive period searches over the range 0.2–1.0 days yielded unusually long periods (0.5–0.9 days) for the fundamental pulsators compared with field RR Lyrae of the same metallicity. Three similar long-period RR Lyrae are known in other metal-rich globular clusters. With over 10 examples in hand, it seems that a distinct subclass of long-period, metal-rich RR Lyrae stars is emerging. It appears that these stars have the same intrinsic colors as normal RR Lyrae. Using the minimum-light color of the RR Lyrae, we determine the mean cluster reddening to be $E(B-V) = 0.45 \pm 0.03$ mag, with a significant variation in reddening across the face of the cluster. The observed properties of the horizontal-branch stars are in reasonable agreement with recent models that invoke deep mixing to enhance the atmospheric helium abundance, while they conflict with models that assume high initial helium abundance. The light curves of the c-type RR Lyrae seem to have unusually long rise times and sharp minima. Reproducing these light curves in stellar pulsation models may provide another means of constraining the physical variables responsible for the anomalous blue horizontal-branch extension and sloped red clump observed in NGC 6441.

Key words: color-magnitude diagrams — globular clusters: individual (NGC 6441) — RR Lyrae variable — stars: horizontal-branch — stars: variables: general

1. INTRODUCTION

The canonical metal-rich globular cluster ([Fe/H] > $-0.8$) has a horizontal branch (helium core burning phase of stellar evolution) that is compressed against the red giant branch to form a "red clump" (e.g., 47 Tuc: Carney, Storm, & Williams 1993; M71: Hodder et al. 1992). Standard stellar evolution theory and synthetic horizontal branches confirm this morphology (see, e.g., Lee, Demarque, & Zinn 1990; Dorman 1992). However, it is becoming clear that the situation is more complicated than this canonical picture would have us believe.

First, it is evident that a significant fraction of the RR Lyrae variable stars (horizontal-branch stars lying in the pulsation instability strip, hereafter RRL) in the field near the Sun are metal-rich. Preston (1959) first recognized this fact, and the recent metallicity distribution of Layden (1994) shows that 22% of the field RR Lyrae within 2 kpc of the Sun have [Fe/H] > $-1.0$ and 9% have [Fe/H] > $-0.5$ dex. Furthermore, the kinematics of these stars identify them with the Galaxy's thick disk population, and a few RRL with abundances approaching solar may be produced by the thin disk (Layden 1995a). The standard horizontal-branch star picture does not explain the presence of stars hot enough to lie in the instability strip at these ages and metallicities.

In addition, several metal-rich globular clusters contain one or more RRL candidates (cf. Suntzeff, Kinman, & Kraft 1991). Note, however, that the often-quoted example, V9 in 47 Tucanae, has an anomalously high luminosity and long period compared with field RRL of similar abundance (Carney et al. 1993). Nevertheless, Layden (1995b) showed that the number of RRL per unit progenitor luminosity was roughly equal between the metal-rich thick disk field and globular cluster populations. This comparison was hampered by the incomplete search for RRL among the population of metal-rich globular clusters.

A second important complication to the canonical picture of metal-rich globular cluster horizontal branches (HBs) is the recent observation of blue HBs in the cores of two globular clusters and in several open clusters. Hubble
Space Telescope (HST) observations by Rich et al. (1997) showed the globular clusters NGC 6388 and 6441 ([Fe/H] \(= -0.60\) and \(-0.53\): Armandroff & Zinn 1988) to have long blueward extensions to their otherwise red HBs. They initially suggested that age or dynamical effects could be responsible for the blue HBs. However, no deep photometry has been published for these clusters to constrain their ages, and calculations by Rich et al. (1997) indicated that stellar interactions are too infrequent to be the culprit. They left open the question of the physical cause of the phenomenon. Blue HB stars in younger, more metal rich open clusters have also been observed (e.g., NGC 6791: Kaluzny & Udalski 1992).

Theoretical studies are also focusing on the blue HB star problem. Sweigart & Catelan (1998) presented three scenarios involving enhanced helium abundance and/or stellar rotation designed to explain the blue HB observations of Rich et al. (1997). They emphasized that observational tests including the existence and periods of RR Lyrae variables, and the relative numbers of HB and red giant branch stars (the \(R\) ratio), could discriminate between their scenarios. They suggest that the blue HB extensions seen by Rich et al. (1997) are extreme cases of the "second parameter effect," in which the color distribution of stars along globular cluster HBs is seen to depend on metallicity and a second parameter, possibly age, helium or CNO abundances, or core rotation.

Thus, ample motivation exists to study the horizontal branches and RR Lyrae content of metal-rich globular clusters. With this in mind, we have undertaken a variable star survey of 12 of the metal-rich globular clusters listed by Suntzeff et al. (1991) as having poor or no variable star branches and RR Lyrae content of metal-rich globular clusters which the color distribution of stars along globular cluster HBs is seen to depend on metallicity and a second parameter, possibly age, helium or CNO abundances, or core rotation.

In § 2 of this paper, we describe the observation and data reduction procedures we employed. In § 3 we present color-magnitude diagrams of the cluster and nearby field. In § 4 we identify ~50 variable stars in the cluster, derive their photometric properties, and for some present their mean light curves. In § 5 we derive the foreground reddening of NGC 6441 and discuss in detail the properties of the cluster’s RR Lyrae variables and compare them to the predictions of the Sweigart & Catelan (1998) models. We present our conclusions in § 6, and in the Appendix we note details on some of the variable stars.

2. OBSERVATIONS AND REDUCTIONS

We obtained time-series images of NGC 6441 using the direct CCD camera on the 0.9 m telescope at Cerro Tololo Inter-American Observatory during two runs in 1996 May and June (three and eight usable nights, respectively). The Tek No. 3 2048 CCD provided a 13.5 field of view with 0.4 pixels. We used filters matched to the CCD to reproduce the Johnson \(V\) and Kron-Cousins \(I\) bandpasses. We processed the raw images by following the usual procedure for over-scan subtraction and bias correction, and we used twilight sky frames to flat-field the data.

In each pointing toward the cluster, we obtained a short-exposure (30–100 s) \(VI\) frame pair and a long-exposure (250–300 s) \(VI\) pair. This provided two independent magnitude estimates of the HB stars at each observational epoch and extended the dynamical range of the observations. Such pointings were obtained 0–3 times each night. The time interval between pointings was at least 2 hours, so a typical RR Lyrae (0.3–0.8 day periods) would undergo a significant magnitude change. In total, we obtained 15 pointings toward NGC 6441. The seeing varied between 1’2 and 3’0 (1’7 median). Figure 1 shows a short-exposure \(V\)-band image of the cluster. The bright star to the west of the cluster was masked out in all the frames.

On a photometric night in 1996 May, we obtained a \(VI\) image pair of NGC 6441, together with a large number of Landolt (1992) photometric standards. We also secured an off-cluster \(VI\) pair centered 13.3 north of the cluster center, outside the tidal radius (7.8; Harris 1996) designed to determine the photometric properties of the fore/background starfield. The standards covered a large range in color \((-0.3 < V - I < 4.0\) and air mass \((1.08 < X < 1.74)\) and were obtained at roughly hourly intervals throughout the night. This time \((T)\) coverage confirmed that the entire night was photometric and enabled us to seek and correct for small, slow variations in extinction. In total, 63 individual standards were observed at 13 independent epochs. The instrumental aperture magnitudes of these stars \((A_b)\), in bandpasses \(b = V\) or \(I\), were fitted with the equation

\[
A_b - S_b = c_{1,b} + c_{2,b} X + c_{3,b} (V - I) + c_{4,b} T + c_{5,b} T^2 ,
\]

where \(S_b\) is the standard magnitude and \(c_{i,b}\) \((i = 1, 5)\) are the fitted coefficients. The time-dependent terms produced corrections of 0.01 mag or less. The rms scatter about the adopted fits were 0.010 and 0.013 mag in \(V\) and \(I\), respectively.

The on- and off-cluster \(VI\) pairs obtained on this night were reduced using the DAOPHOT II point-spread function (PSF) fitting photometry package (Stetson 1994). The interactivity of this package enabled us to select ~170 PSF stars well distributed spatially over the frame. This was critical in accurately characterizing the significant radial variation in PSF across the frame. For each frame, the PSF was iteratively improved by fitting and removing faint neighbor stars. The final PSF was applied to the image using ALLSTAR. A second application of ALLSTAR yielded a frame with all the stars subtracted except a set of ~220 bright, isolated stars. This frame was used to derive aperture corrections by subtracting the PSF-fit DAOPHOT magnitudes of the stars from their aperture magnitudes (derived using the same software and parameters as those used in measuring the standard stars). The aperture correction was then applied to all the stars measured in the frame, and the standard star relations were applied, yielding standard \(VI\) magnitudes for thousands of stars on the on- and off-cluster fields. The on-cluster \(VI\) data provides a set of secondary standards for calibrating the other on-cluster images.

The remaining images of NGC 6441 were reduced using a version of the DoPHOT PSF-fitting package (Schechter,
Mateo, & Saha 1993), which allows for spatial variations in the PSF. Instrumental magnitudes were obtained for each frame and combined into instrumental $VI$ pairs, and then transformed to standard $VI$ magnitudes via fits to the secondary standards described above. We grouped the $VI$ frame pairs as follows: good-seeing frames with (a) long and (b) short exposure times, and poor-seeing frames with (c) long and (d) short exposure times. This grouping strategy minimized mismatches due to variable depth and seeing. Within each group, we spatially matched stars from the different frames, and combined the photometry for each star using an error-weighted mean. For the error in each combined stellar magnitude, we adopted the standard error of the mean for the individual measures, which proved to be a more conservative estimate than computing the error directly from the DoPHOT errors.

3. COLOR-MAGNITUDE DIAGRAMS

We combined the mean photometry from groups $a$ and $b$ (the long- and short-exposure frames with good seeing) using an error-weighted mean to produce a single data set with maximum dynamic range. Outside a radius of 1100 pixels (7:33) from the cluster center, elongated star images sometimes registered as multiple stars, compromising the
mean photometry and complicating variable star detection (see § 4). Figure 2a shows the \((V-I, V)\) color-magnitude diagram (CMD) for 22,871 stars on the on-cluster frame lying within 1100 pixels of the cluster center. Only stars detected on four or more frames, and having combined errors in \(V\) and \(V-I\) of \(\sigma_V < 0.050\) mag and \(\sigma_{V-I} < 0.071\) mag, are shown. Table 1 lists the combined photometry for all the bright stars (\(V < 19\) mag) within 1100 pixels of the cluster center.

Figure 2b shows the corresponding CMD for the off-cluster field. This diagram represents data from a single \(VI\) frame pair, so the errors are larger. Poor photometry, galaxies, and cosmic rays were rejected by performing 3 \(\sigma\) cuts on the DAOPHOT values of \(\chi\) and “sharp” as functions of magnitude. Only stars with \(\sigma_V < 0.050\) mag and \(\sigma_{V-I} < 0.071\) mag are shown (DAOPHOT errors).

Several features are apparent in these CMDs. First, both the cluster and field have large numbers of extremely red giant stars. Second, in both CMDs one can detect the red clump stars of the bulge at \(V \approx 16.8\) and \(V-I \approx 1.7\) mag. This agrees well with photometry of the nearby field MM-5B from the OGLE group (Stanek et al. 1994). Note that the red clump in Figure 2a is shifted redward and faintward relative to that in Figure 2a, suggesting a mean reddening difference between the two fields. Third, a prominent feature of the on-cluster CMD is the NGC 6441 red clump, which forms a swath of stars near \(V \approx 17.5\) and \(V-I \approx 1.4\) mag, running parallel to the reddening vector [we adopt \(A_V = 2.6(V-I)\) throughout this paper]. Finally, the on-cluster CMD shows a population of stars bluer and somewhat brighter than the cluster red clump. Such stars are not present on the off-cluster CMD and represent the first ground-based view of the extended blue horizontal branch seen by Rich et al. (1997).

Figures 3a and 3b zoom in on the HB regions of these CMDs. The tight distribution of red clump stars in Figure 2a paralleling the reddening vector suggests that there is significant differential reddening across the face of the cluster. This also explains why a tight red giant branch (RGB) is not seen; differential reddening spreads the RGB stars roughly perpendicular to the unreddened RGB fiducial. We will consider the reddening problem in more detail in § 5.2.

Another important feature is highlighted in Figure 3c, where stars from Figure 3a lying between 40°–160° of the cluster center are displayed. The excess of blue HB (BHB) star candidates seen in Figure 2a is evident, indicating that they too are members of the cluster. The cluster’s red clump and red giant branch are better defined in this panel as well.

Figure 3d shows another effort to isolate NGC 6441 stars from the field. Here we have statistically subtracted the CMD of off-cluster stars located between 40° and 160° of the frame center from the stars in Figure 3c. Before subtracting, we corrected for a 0.11 mag reddening difference between the fields (the off-cluster field has the higher reddening), which we estimated from the shift in color histograms of stars having values of the reddening-independent parameter \(V_{V-I} = V - 2.6(V-I)\) between 12.1 and 13.3 (Stanek et al. 1994). For each star in the off-cluster CMD, we removed from the on-cluster CMD the star nearest in color-magnitude space. Although the subtraction is over-aggressive for the faint stars, the brighter sequences

| ID | \(X_{\text{pix}}\) | \(Y_{\text{pix}}\) | \(V\) | \(\sigma_V\) | \(V-I\) | \(\sigma_{V-I}\) |
|----|--------|--------|-----|--------|-----|--------|
| 1   | 1267.64 | -27.67 | 17.001 | 0.169 | 1.071 | 0.192 |
| 2   | 1336.58 | -25.93 | 18.611 | 0.043 | 1.150 | 0.059 |
| 3   | 949.77  | -25.65 | 17.553 | 0.151 | 1.567 | 0.171 |
| 4   | 1225.50 | -25.00 | 18.059 | 0.021 | 1.206 | 0.030 |
| 5   | 1216.89 | -24.55 | 18.799 | 0.041 | 1.135 | 0.069 |
| 6   | 901.32  | -24.13 | 18.519 | 0.046 | 0.966 | 0.057 |
| 7   | 1327.34 | -23.72 | 18.794 | 0.026 | 1.306 | 0.040 |

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.
Fig. 3.—Color-magnitude diagrams for stars with moderate errors ($\sigma_V < 0.10$ mag and $\sigma_{V-I} < 0.14$ mag) and located (a) within 440" of NGC 6441, (b) within 400" of the center of the adjacent field, and (c) between 40" and 160" of NGC 6441. In (d), the points in (c) are shown after the statistical subtraction of the CMD generated from off-cluster stars located in the same radial zone.

The lack of faint, extremely blue HB stars in Figure 3c, relative to their abundance in the CMD of Rich et al. (1997), comes as a mild surprise. Even in CMDs where we relax the criteria on the photometric errors, these stars do not appear at $V > 18$ mag. This suggests that these stars may be radially concentrated toward the cluster center, but we cannot state this unequivocally without detailed completeness modeling. A simpler, more direct comparison with the Rich et al. (1997) BV data will soon be available from the deep, ground-based $BV$ photometry of the cluster recently obtained by H. Smith et al. (1998, private communication).

Does the prominence of the less extreme BHB (i.e., brighter than $V \approx 18$ mag) vary with radial distance from the cluster center? Rich et al. (1997) found no evidence for a change in the number ratio of BHB to red clump stars with radius over their small $HST$ field of view ($\sim 100''$, with the PC chip centered on the cluster) and interpreted this as evidence against the production of BHB by dynamical effects. We can extend this search to larger radii using our $VI$ photometry. For this purpose, we defined BHB stars as having $16.8 < V < 18.0$ and $0.3 < V - I < 0.8$ mag and red clump stars as having $13.6 < V - I < 13.9$ and $1.30 < V - I < 1.56$ mag. We defined the number fraction

$$F = \frac{(N_{\text{BHB},c} - N_{\text{BHB},f})}{(N_{\text{RC},c} - N_{\text{RC},f})},$$

where the $c$ and $f$ subscripts indicate stars counted from the cluster and field photometry sets, respectively. For stars in the radial annulus $50'' - 100''$, we obtained $F = 0.054 \pm 0.012$, whereas for radii of $100'' - 240''$, we obtained $F = 0.027 \pm 0.008$. The blue HB stars are a factor of 2 more prominent in the inner annulus.

The Fokker-Planck simulations of Rich et al. (1997) indicated that BHB stars produced from dynamically stripped RGB stars should be concentrated within 4 core radii (26"; Harris 1996). The lack of BHB concentration in the Rich et al. (1997) observations and our observed concentration at larger radii do not appear to be consistent with simple pictures of BHB star production through tidal stripping of normal RGB stars by close encounters in the dense cluster core.

$^4$ The star counts are $N_{\text{BHB},c} = 23, N_{\text{BHB},f} = 1, N_{\text{RC},c} = 417, N_{\text{RC},f} = 11$ for the inner annulus. For the outer annulus, they are 21, 7, 598, and 77, respectively.
In many clusters, relative radial population gradients are attributed to the effect of mass segregation. The relaxation time for NGC 6441 at the half-mass radius, ~0.5 Gyr at 38° (Harris 1996), is much longer than the typical lifetime of an HB star (~0.1 Gyr), but mass segregation could be at play if the BHB stars are members of binary systems. Bailyn (1995) reviewed two scenarios for producing extreme BHB stars from binaries: the merger of helium white dwarf binaries, and mass transfer in wide binaries in which the hydrogen envelope of a red giant evolving close to the RGB tip is donated to the secondary star. Bailyn et al. (1992) found the latter scenario to be particularly appealing in explaining the radial distribution of extreme BHB stars in the globular ω Centauri, and the scenario may be relevant to NGC 6441 as well. It explains the radial concentration of BHB far from the cluster center and the broad color distribution of the BHB population (the latter due to a range in mass loss, produced by a range in orbital separations). On the negative side, the scenario does require NGC 6441 to have a much larger population of binaries with the appropriate orbital periods (a few hundred days) than metal-rich clusters with “normal” red clump HBs. Observationally, there are few constraints on the distribution of binary periods in globular clusters. Theoretically, the primordial period distribution of a cluster’s binary stars could be linked to the angular momentum of the gas cloud that formed the cluster. Also, dynamical evolution of the binary populations will vary from cluster to cluster (see, e.g., Bailyn et al. 1992).

Thus there seems to be no argument against the existence of large variations in the binary period distribution from one cluster to another. Finally, the wide-binary scenario makes a prediction: most BHB stars should be members of a binary system, with radial velocity variations of a few tens of km s⁻¹. Such observations should be obtainable using multifiber spectrographs on the new generation of large telescopes.

4. VARIABLE STARS

We used the Welch & Stetson (1993) variability index, \( I_{ws} \), to characterize the likelihood that a given star is a variable. The value of \( I_{ws} \) is computed for each star from the individual \( V \) and \( I \) magnitudes and their errors. For a nonvariable star, \( I_{ws} \) approaches zero as the number of observations becomes large, whereas for a variable, \( I_{ws} \) approaches a constant value. To minimize the effects of seeing and exposure depth (i.e., the blending of two nearby stars into a single measurable image as the seeing and/or signal-to-noise conditions worsen), we employed the frame groupings described in §2 and computed \( I_{ws} \) for each star detected more than 4 times in each group. Groups \( a \) and \( b \) were useful in detecting variable stars near the cluster (\( R < 1100 \) pixels), and groups \( c \) and \( d \) were useful outside \( R \approx 600 \) pixels.⁵

The morphology of the points in the \( (I_{ws}, V) \)-plane led us to classify stars as probable variables (\( I_{ws} > 170 \)) and possible variables (\( 50 < I_{ws} < 170 \)). When plotted on the cluster CMD, it became clear that three classes of variables are present: extremely red variables (Mira, semiregular, and irregular variables, hereafter LPVs), blue variables (possible RR Lyrae stars), and a few other variables scattered around the CMD. We focused on these stars as follows: all stars with \( V-I > 2.4 \) mag and \( I_{ws} > 50 \) (LPV candidates), all stars with \( V-I < 1.4 \) mag and \( I_{ws} > 50 \) (RR candidates), and all other stars with \( I_{ws} > 120 \). We enhanced our search for cluster RRL stars by supplementing the RRL candidates with stars in the subset \( V-I < 1.5 \) mag, \( 16.8 < V < 17.8 \), and \( 30 < I_{ws} < 50 \). We produced analogous lists from the data in groups \( b \), \( c \), and \( d \) and merged them into a final list of 115 variable star candidates.

We then plotted the \( V \) and \( I \) magnitudes as a function of time for each candidate. The LPV candidates were characterized by constant or slowly varying \( V \) and \( I \) magnitudes, with distinct jumps between the May and June data. Two candidates near the cluster center were sufficiently crowded, and their light curves (LCs) scattered, that we could not unambiguously characterize them as LPVs; their positions and magnitudes are recorded in Table 5 (stars SV6 and SV7). The remaining LPV stars are considered in §4.2.

Among the 56 RRL candidates, 33 had time-magnitude plots that suggested that a close pair of nonvariable stars in some frames had been resolved and in others was detected as a single star; when the photometry from the various frames was matched (based on position), the blended photometry was systematically brighter than the resolved photometry, and a large value of \( I_{ws} \) resulted. Inspection of the images almost always confirmed the blended-neighbor hypothesis. We discuss the remaining 23 candidates in detail in §4.3.

Of the 16 variable star candidates scattered over the CMD, all but one were found to be false detections of critically resolved, nonvariable pairs. The single true variable has a color \( (V-I \approx 2.1) \) consistent with an LPV near maximum light, so we have grouped it with the other LPV stars in Table 2 (V35). Clearly, the large number of critically resolved stars in this dense stellar field presents a complication to the identification of variable stars, but one that is surmountable given careful attention.

4.1. Previous Studies of Stellar Variability

The Catalogue of Variable Stars in Globular Clusters (Hogg 1973), as updated by C. Clement,⁶ lists 12 variable stars in NGC 6441. No photometric or variable-type information is given. Stars V7 and V8 lie outside our field of view. Only variables V1, V6, and V9 were detected as variables in our study. Examination of the remaining stars’ photometry showed that V2, V3, V5, and V10 are all LPVs but were absent from enough frames due to saturation and other effects to sidestep detection. V4 showed no sign of variability in our observations, but at \( V-I = 2.84 \) it is red enough to be an LPV (see §4.2). V11 and V12 are much fainter, bluer stars that Hesser & Hartwick (1976) suspected as being RR Lyrae stars; our photometry shows no sign of variability in these stars (see Table 5 and the Appendix).

4.2. Long-Period Variable Stars

Data for the 31 LPV stars (i.e., stars that varied on timescales longer than a few days) found near NGC 6441 are

⁵ An alternative approach would have been to develop a master list of star positions from the best seeing frames and to measure magnitudes for all the stars in this list on each frame. In practice, the residuals of the fits used to transform the stellar coordinates from one frame to the next were large relative to the tolerance required for accurate PSF fitting using fixed coordinates. However, the residuals were sufficiently small to enable reliable matching of stars from frame to frame.

⁶ The updated electronic catalog is available on request from C. Clement (cclement@astro.utoronto.ca).
presented in Table 2. The first column gives the variable star designation (in roughly decreasing value of the \( I_{WS} \) variability index). We name our newly discovered variables V13, V14, etc. The second and third columns give the position of the star in the \( X \) and \( Y \) coordinate frame of Figure 1 (in units of pixels). The right ascension and declination offsets from the cluster center (in arcseconds, with positive values indicating east and north) can be computed from the pixel positions as follows:

\[
\Delta \alpha = -0.396(X_{\text{pix}} - 1014), \quad \Delta \delta = -0.396(Y_{\text{pix}} - 1000).
\]

The remaining columns give the magnitude–mean \( I \) magnitude (\( \bar{I} \)), the mean color (\( \bar{V} - \bar{I} \)), and the number of observations (\( N \)) during the May and June observing runs. In \( \sim 40\% \) of the stars, we observed a significant change in brightness or color during one or both observing runs. The previously identified LPVs not detected in our study (see § 4.1) are included at the bottom of this table.

Clearly, the data here do not fully sample the LPVs’ light cycles and thus do not accurately represent the stars’ mean photometric properties. Still, the locations of the stars on the CMD, shown in Figure 4, approximately represent these mean positions. Furthermore, the limited phase coverage leads to LPV detection incompleteness; the observed \( V \) and \( I \) magnitude differences of some true LPVs (e.g., V4) were insufficient to result in \( I_{WS} \) values large enough to

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**TABLE 2**

| Star | \( X_{\text{pix}} \) | \( Y_{\text{pix}} \) | \( T_{\text{May}} \) | \( \bar{V} - \bar{I}_{\text{May}} \) | \( N_{\text{May}} \) | \( T_{\text{Jun}} \) | \( \bar{V} - \bar{I}_{\text{Jun}} \) | \( N_{\text{Jun}} \) |
|------|----------------|----------------|-----------------|-----------------|----------------|----------------|-----------------|----------------|
| V13  | 1005           | 1185           | 12.98           | 3.49            | 5              | 12.59          | 3.05            | 18             |
| V14  | 890            | 1112           | 13.76           | 4.97            | 6              | 12.85          | 4.20            | 17             |
| V15  | 432            | 1183           | 12.89           | 2.70            | 5              | 13.27          | 3.17            | 20             |
| V16  | 1156           | 1609           | 13.03           | 3.85            | 5              | 12.79          | 3.54            | 18             |
| V17  | 1360           | 1147           | 13.16           | 3.65            | 5              | 12.90          | 3.12            | 18             |
| V18  | 1182           | 937            | 13.19           | 2.88            | 5              | 13.43          | 3.05            | 19             |
| V19  | 1463           | 49             | 12.78           | 3.90            | 5              | 13.04          | 4.09            | 19             |
| V20  | 1065           | 1729           | 13.32           | 6.60            | 4              | 12.83          | 6.28            | 13             |
| V21  | 477            | 1510           | 13.03           | 2.70            | 5              | 13.29          | 2.95            | 20             |
| V22  | 1268           | 1076           | 12.95           | 2.95            | 5              | 12.86          | 2.82            | 16             |
| V23  | 979            | 1129           | 13.02           | 3.46            | 5              | 12.68          | 3.29            | 16             |
| V24  | 480            | 962            | 13.07           | 3.06            | 5              | 13.17          | 3.19            | 17             |
| V25  | 1431           | 1347           | 14.68           | 4.10            | 7              | 14.44          | 4.18            | 19             |
| V26  | 1271           | 747            | 12.76           | 3.75            | 5              | 12.67          | 3.54            | 17             |
| V27  | 823            | 396            | 12.98           | 3.02            | 5              | 12.93          | 2.97            | 17             |
| V28  | 1092           | 190            | 14.33           | 2.44            | 7              | 14.29          | 2.37            | 21             |
| V29  | 1073           | 1119           | 12.52           | 2.84            | 3              | 12.23          | 2.53            | 12             |
| V30  | 1486           | 501            | 12.46           | 4.80            | 3              | 12.81          | 4.97            | 17             |
| V31  | 354            | 658            | 12.38           | 3.08            | 3              | 12.26          | 3.92            | 13             |
| V32  | 804            | 1581           | 12.14           | 3.02            | 3              | 12.25          | 3.12            | 12             |
| V33  | 1062           | 1045           | 12.94           | 2.76            | 3              | 12.87          | 2.64            | 12             |
| V34  | 936            | 986            | 13.00           | 2.56            | 5              | 13.15          | 2.70            | 13             |
| V35  | 601            | 1580           | 13.31           | 3.26            | 4              | 13.23          | 3.14            | 19             |
| V36  | 877            | 1017           | 13.52           | 2.19            | 5              | 13.39          | 2.11            | 19             |
| V37  | 933            | 877            | 13.56           | 1.66            | 5              | 12.79          | 1.40            | 18             |
| V38  | 918            | 938            | 12.09           | 2.70            | 3              | 13.32          | 4.25            | 4              |
| V39  | 124            | 1212           | 11.60           | 3.49            | 3              | 12.37          | 4.74            | 12             |
| V40  | 853            | 1440           | 13.00           | 2.88            | 5              | 13.00          | 2.90            | 18             |
| V41  | 504            | 425            | 12.29           | 3.93            | 3              | 11.54          | 2.98            | 4              |
| V42  | 819            | 1149           | 12.72           | 3.03            | 4              | 12.92          | 3.39            | 18             |

* See comment in Appendix.
trigger detections. Finally, saturation and other image complications left some stars with too few observations to fulfill all the variability detection criteria. Thus, it is likely that many more of the stars with $V - I > 2.4$ are LPVs, in particular, faint, red LPVs near the cluster center.

4.3. RR Lyrae Variables and Eclipsing Binaries

In an effort to determine the types of variable stars present among the 23 blue variable star candidates discussed above, we attempted to find the period of each star and create the star’s mean light curve. Classical period-finding techniques such as Fourier transforms or phase dispersion minimization perform poorly, if at all, when the data are sparse and irregularly spaced. We therefore developed the following new method.

In cases where a star’s variable type is suspected (e.g., an RR Lyrae), it is possible to assume a period and fit the folded light curve with an appropriate template light curve. If the assumed period is near the true period, the scatter about the fitted template will be small. By folding the time-magnitude data by a sequence of periods typical of the variable type, and fitting the template and computing the scatter (or $\chi^2$) at each period, one can easily identify $\chi^2$ minima indicative of possible periods. This method is similar to that described by Stetson (1996).

In practice, we used the template-fitting procedure described in Layden (1998). We fitted each star with three templates: $V_3$ and $V_4$ from Layden (1998, his Table 4) are typical of RRa- and RRb-type variables, respectively, whereas a cosine curve was used to represent RRc and contact binary LCs. We fitted the templates over periods ranging from 0.2 to 1.0 days, increasing the period by 0.1% from one step to the next. If no suitable minima were found, we searched on the period interval 1–3 days. Periods longer than 3 days are evident in the time-magnitude plots. Because the templates are seldom a perfect match for the actual LCs, we refined the periods by folding the time-magnitude data by a sequence of periods near the $\chi^2$ minimum, plotting the resulting LCs, and choosing the cleanest LC. This resulted in tighter LCs and improved periods.

We note that this technique should be applicable to any type of variable with a characteristic LC. Indeed, by including template LCs from a large number of variable types, it should be possible to determine both period and variable star type from the template giving the smallest $\chi^2$ value.

Of the 23 blue variable candidates, we were able to determine periods for 11 RR Lyrae stars (V36–V46) and two contact binaries (V48 and V50). Light curves for two detached binaries (V49 and V51) and one long-period star (V6, a Cepheid?) were obtained by examination of the time-magnitude plots. The $V$ and $I$ light curves of these 15 stars are presented in Figure 5. Possible periods were obtained for five additional stars (SV1–SV5; see Table 5). We were unable to determine with certainty whether these stars were low-amplitude RR Lyrae or contact eclipsing binaries (see Fig. 6). We were unable to obtain periods or LCs for the remaining two blue variable candidates, which we list in Table 5 as SV8 and SV9.

Table 3 lists the photometric properties of the 11 RR Lyrae stars. Columns include the location of the stars in the coordinate frame of Figure 1 ($X_{\text{pix}}$ and $Y_{\text{pix}}$), the period in days, the intensity–mean $V$ and $I$ magnitudes ($\langle V \rangle$ and $\langle I \rangle$), the $V$-band amplitude ($\Delta V$), the mean color during the phase interval 0.5–0.8 [(V − $I_{\text{min}}$)], and a brief comment. For several stars, a few discrepant data points were omitted from the computations, (e.g., V37), while for several other stars, only good-seeing data were used (e.g., V42 and V43). These data will prove useful in determining the nature of these unusual stars in the following section.

Table 4 reports the positions of the four eclipsing binaries from Figure 5, along with their periods, $V$- and $I$-band maxima and amplitudes, and a comment. Table 5 lists the positions, magnitude–mean $V$ magnitudes and $V - I$ colors of the uncertain and suspected variables, along with a brief comment.

The time-series photometry for each of the variables is given in Table 6. The columns include the variable star name, the heliocentric Julian date of midobservation (HJD), the $V$-band magnitude and its error ($\sigma_V$), the $I$-band magnitude and its error ($\sigma_I$), and a quality code ($Q$), which corre-

![Image](image.png)

**Fig. 4.**—The NGC 6441 color-magnitude diagram from Fig. 3a with the variable stars marked as follows: long-period variables from Table 2 (filled squares), RR Lyrae stars from Table 3 (filled circles), eclipsing binaries from Table 4 (open triangles), variables of uncertain class (SV1–SV5) from Table 5 (asterisks), and the remaining suspected variables from Table 5 (crosses).

| Star  | $X_{\text{pix}}$ | $Y_{\text{pix}}$ | Period | $V_{\text{max}}$ | $I_{\text{max}}$ | $\Delta V$ | $\Delta I$ | Comment   |
|-------|-----------------|-----------------|--------|-----------------|-----------------|----------|----------|-----------|
| V47... | 836             | 1765            | 0.703  | 16.20           | 15.02           | 1.47     | 1.10     | Detached  |
| V48... | 158             | 1171            | 0.6674 | 15.23           | 14.22           | 0.32     | 0.28     | Contact   |
| V49... | 365             | 768             | 1.010  | 16.52           | 15.45           | 0.36     | 0.20     | Detached? |
| V50... | 838             | 1410            | 0.4335 | 17.85           | 16.55           | 0.55     | 0.55     | Contact?  |

**TABLE 4**

**PHOTOMETRY OF ECLIPSING VARIABLES**
FIG. 5.—Mean light curves for the blue variable candidates that yielded clear periods. Each panel shows the \( V \) (lower curve) and \( I \) (upper curve, in some panels offset vertically by the indicated amount for convenience of display) light curve for the indicated star and period. In all panels, the minor tick marks indicate intervals of 0.2 mag.
Fig. 6.—Mean light curves for the blue variable candidates which yielded two possible periods. In each panel, the leftmost set of light curves (\(V\) below; \(I\) above, possibly shifted vertically) employs the shorter period and has the characteristics of a c-type RR Lyrae, whereas the rightmost set employs the longer period and resembles a contact binary.

Corresponds to the symbols used in the light curves: \(Q = 1\) indicates a long exposure under good seeing conditions (filled circle), \(Q = 2\) indicates a short exposure in good seeing (open circle), \(Q = 3\) indicates a long exposure in poor seeing (filled triangle), and \(Q = 4\) indicates a short exposure in poor seeing (open triangle). Figure 7 shows the finder charts for each variable star.

4.4. Cluster Membership

The positions of the variable stars in the CMD and their radial locations with respect to the centroid of the cluster light provide useful information regarding the stars’ membership in the cluster. Figure 4 shows the variable stars placed in the CMD, whereas Figure 8 shows the cumulative

| Star  | \(X_{\text{pix}}\) | \(Y_{\text{pix}}\) | \(V\) | \(V-I\) | Comment                  |
|-------|-------------------|-------------------|------|--------|-------------------------|
| SV1   | 1364              | 1501              | 15.81| 0.99   | See Appendix            |
| SV2   | 536               | 0.52              | 1.10 |        |                          |
| SV3   | 580               | 1244              | 17.25| 1.07   | See Appendix            |
| SV4   | 1268              | 1129              | 17.24| 0.72   | See Appendix            |
| SV5   | 912               | 796               | 17.37| 0.97   | See Appendix            |
| SV6   | 1062              | 940               | 16.89| 2.59   | Crowded, LPV?           |
| SV7   | 1034              | 969               | 15.13| 2.49   | Crowded, LPV?           |
| SV8   | 643               | 563               | 17.21| 1.18   | Blended image, RR Lyrae?|
| SV9   | 1359              | 93                | 17.10| 1.17   | Blended image, eclipsing binary? |
| V11   | 1120              | 755               | 17.86| 0.48   | Nonvariable, see Appendix|
| V12   | 1123              | 867               | 17.29| 0.69   | Nonvariable, see Appendix|
The radial distributions of the stars in various classes. The squares in Figure 8 give the total sky-subtracted V-band photon counts inside the radius $R$, normalized by the amount at $R = 440\".$ The crosses give the analogous counts expected if a uniform stellar distribution were spread across the usable pixels of the CCD. These curves represent the approximate distributions expected for cluster member and field stars, respectively. The actual observed distribution for a given class of star will deviate from these expectations due to brightness and crowding effects. The lines in Figure 8 are the normalized cumulative radial distributions of the stars in various classes. The radial distributions of the RR Lyrae, red clump, and blue HB stars all resemble that of the cluster light (Fig. 8). Of these three classes of stars, the red clump stars are the least radially concentrated, as expected if a significant number of field red giants contaminate the counting box. The BHB stars are more centrally concentrated, and the RR Lyrae stars seem even more so, although the number of stars involved is small and the expected background contamination varies between the three stellar classes. Note that all three of these distributions drop precipitously within 1’ of the cluster center, indicating that our detection completeness decreases at smaller radii, reaching zero inside $\sim 30\".$ It is highly probable that these eight RR Lyrae belong to the cluster.

Of the other three RR Lyrae from Table 3, V36 is almost certainly a foreground star. Its location 297 from the cluster, its position in the CMD just blueward of the prominent cluster red clump, and just redward of the blue HB stars. The radial distributions of the RR Lyrae, red clump, and blue HB stars all resemble that of the cluster light (Fig. 8). Of these three classes of stars, the red clump stars are the least radially concentrated, as expected if a significant number of field red giants contaminate the counting box. The BHB stars are more centrally concentrated, and the RR Lyrae stars seem even more so, although the number of stars involved is small and the expected background contamination varies between the three stellar classes. Note that all three of these distributions drop precipitously within 1’ of the cluster center, indicating that our detection completeness decreases at smaller radii, reaching zero inside $\sim 30\".$ It is highly probable that these eight RR Lyrae belong to the cluster.

The LPV stars from Table 2 have a distribution in Figure 8 very similar to that of the cluster light between 1’ and 4’. Inside 1’, incompleteness sets in, although not as quickly as.
for the fainter HB stars. Suspected variables SV6 and SV7 are probably cluster LPVs whose photometry has been compromised by stellar crowding. Thus, most of the LPVs in Table 2 probably belong to the cluster. In the CMD, most of the LPVs form a fairly tight, linear sequence running from \((V - I, V) = (2.6, 15.6)\) to \((5.0, 18.0)\). A set of five LPVs appears to parallel this sequence ~0.8 mag brighter. These five stars (V3, V5, V9, V30, and V31) have a cumulative radial distribution consistent with a uniform foreground population. Given that the distance modulus difference between the cluster and the bulge is ~0.8 mag, based on the offset in \(V\) magnitudes of the red clumps and RRL stars, it seems reasonable to conclude that these five bright LPVs belong to the bulge, rather than to the cluster.

The population of the two LPVs ~1.0 mag fainter than the cluster LPV sequence is unclear. Their magnitudes and
and amplitudes from Bookmeyer et al. 1977; metallicities

Figure 9, we show the metal-rich ßeld ab-type RRL (periods
a star's position in this plane depends on its metallicity. In
typical RRL in the ßeld and in metal-poor globular clusters,
independent tool for comparing RR Lyrae variables. For
 normalized to the total number inside 440° radius for red clump stars (solid
line, RC); blue HB stars (dotted line, BHB); RR Lyrae stars (short-dashed
line, RRL); LPV stars (long-dashed line); and eclipsing binaries (dash-dotted
line, ECL). The V-band light distribution (sky subtracted, in intensity
units) indicates the distribution expected for cluster members (open squares,
CL). A uniform illumination over the useable CCD pixels indicates the
distribution expected for a ßeld star population (crosses, FLD). The radial
locations of the suspected variable stars, SV1–SV9, are marked along the
top, with the probable RR Lyrae stars in italics.

large radial distances from the cluster (R = 215° for V25
and 322° for V28) suggest they are members of the background field. It is conceivable that they belong to the Sagit-
tarius dwarf galaxy, but (1) the distance modulus between Sagit-
tarius and the bulge is ~ 2.5 mag (Sarajedini & Layden
1995), 0.7 mag too large for the observed offset, and (2)
NGC 6441 is over 10° from the nearest part of Sagittarius in
the map of Ibata et al. (1997). Complete light-curve cover-
age of these variables would enable estimates of their dis-
tances, whereas spectroscopy would indicate whether their
radial velocities are consistent with an origin in the Galaxy
or in Sagittarius.

Finally, we consider the variables of uncertain type from Table 5. Of these five stars, SV2, SV3, and SV5 lie in the
clump of bona fide cluster RRL in Figure 4, and so we
tentatively consider them to be RRL as well. Their radial
locations (Fig. 8) are consistent with those of the other RRL. Although SV4 has the correct V magnitude, it is 0.3
mag bluer than the other RRL. Whether SV1 is a c-type RR
Lyrae or a contact binary, its location in the CMD clearly
indicates that it belongs to the foreground field.

5. DISCUSSION

5.1. The Period-Amplitude Diagram

The period-amplitude diagram is a useful, reddening-
independent tool for comparing RR Lyrae variables. For
typical RRL in the ßeld and in metal-poor globular clusters,
a star’s position in this plane depends on its metallicity. In
Figure 9, we show the metal-rich ßeld ab-type RRL (periods
and amplitudes from Bookmeyer et al. 1977; metallicities
from Layden 1994). At a given amplitude, the more metal-
rich stars have systematically shorter periods. The ab-type
RRL in the globular cluster NGC 6171 (Dickens 1970;
[Fe/H] = −1.04: Harris 1996) overlie the ßeld RRL of
similar metallicity, while that cluster’s c-type RRL congre-
gate near (log P, ΔV) = (−0.5, 0.5).

The RR Lyrae stars in NGC 6441 are systematically dis-
placed to longer periods and smaller amplitudes. The bulge
RRL V36 is marked by the large asterisk at ΔV ≈ 1.2, a
position suggesting a metallicity of [Fe/H] = −1.0 to
−1.2, consistent with the distribution of metallicities in
bulge RRL (Walker & Terndrup 1991). The large asterisks
at lower amplitude mark the anomalously red variables
V41 and V42. The open circles mark the suspected c-type
RRL SV2, SV3, and SV5. The solid circles mark the remain-
ing RRL in Table 3.

These results are consistent with the positions of the three
previously known long-period, metal-rich RRL: V9 in 47
Tuc (Carney et al. 1993), and V28 (ab-type) and V27 (c-type)
in NGC 6388 (Silbermann et al. 1994). However, our data
have more than tripled the number of members of this inter-
esting subclass of variable. Also, the positions of SV3, SV5,
and perhaps SV2 support our interpretation that these stars
are c-type RRL in NGC 6441.

5.2. Reddening

Using a variety of methods, Hesser & Hartwick (1976)
estimated the interstellar reddening toward NGC 6441 to
be E(B − V) = 0.46 ± 0.15 mag. They noted that, based on
the appearance of the Palomar Sky Survey prints, “The
obscuration in the immediate vicinity of NGC 6441 is approximately uniform” (p. 107). However, the large uncertainty they quote reflects the large range of solutions produced by the different techniques, 0.23 ≤ E(B − V) ≤ 0.7. Furthermore, the large angular extent over which some of their estimates were obtained may produce deceptive results if significant patchiness exists on scales of several arcminutes or less. Zinn (1980) and Reed, Hesser, & Shawl (1988) obtained E(B − V) = 0.47 and 0.49, respectively, from integrated light measurements.

The RR Lyrae variables we have detected toward NGC 6441 provide an excellent opportunity to determine the reddening in a small region around the cluster. Mateo et al. (1995b) showed that the dereddened V − I colors of typical RR Lyrae near minimum light (phases 0.5–0.8) is roughly constant. We determine (V − I)₀ = 0.57 ± 0.02 for the eight stars with [Fe/H] > −1.3 listed by Mateo et al. (1995b). We use the apparent minimum-light colors of the 11 RRL in Table 3, (V − I)₀, to determine the reddening, E(V − I), along each line of sight (see Table 7). These values are converted into E(B − V) and Aᵥ using the relations of Dean, Warren, & Cousins (1978).

Of these stars, only V36 is a “typical” RRL, judging from its position in the period-amplitude diagram and its expected location in the Galactic bulge. Indeed, one could question whether the (V − I)₀ colors of bulge RRL are the same as the local stars used to calibrate the relation. It is reassuring that V36 gives E(B − V) = 0.46 ± 0.03 mag, in excellent agreement with the existing reddening values.

Does the relationship work for the atypical, long-period variables in NGC 6441? Unfortunately, V − I colors do not exist for the two other known members of this class, V9 in 47 Tuc and V28 in NGC 6388. However, the data from Carney et al. (1993) on V9 indicates that the analogous relation employing (B − V)₀, period, and metallicity (Blanco 1992 and references therein) does work, yielding E(B − V) = 0.03. For comparison, Harris’s (1996) compilation lists E(B − V) = 0.05. With this encouragement, and excluding the two anomalously red and bright stars V41 and V44, we find the mean E(B − V) of the nine RRL toward NGC 6441 to be 0.45 mag (0.05 mag rms). Again, our reddening estimate is in excellent agreement with the existing estimates.

The rms value is somewhat larger than expected from the estimated uncertainties (~0.03 mag for a single star). This suggests there may be some differential reddening across the face of the cluster. The extension of the cluster red clump along the reddening vector and the absence of a well-defined red giant branch provide similar evidence (see § 3).

To search for further evidence of spatially variable reddening, we considered individually the CMDs of stars lying in eight equal-sized sectors of an annulus with radius 40°–100° centered on the cluster (the angles α₁ and α₂ in Table 7 defined the bounds of each sector and are measured counterclockwise from the line radiating in the +x-direction from the cluster center in Fig. 1). For each CMD, we isolated the red clump stars using and 13.6 < Vᵥ − I < 13.9 and produced their generalized color histogram (see Fig. 10). Several curves are substantially displaced toward redder colors, indicating the presence of differential reddening. Sector 4 is particularly noticeable. The median V − I color of each histogram [med(V − I)]₀, and the number of stars involved (Nsec), are shown in Table 7. The widths of the individual histograms are not drastically larger than the color width of the red clump in 47 Tuc (~0.2 mag: Armandroff 1988), suggesting that the effects of differential reddening within a given sector are small, although red giant branches in the CMDs are still noticeably broadened (especially in sector 4). The small-scale peaks in the Figure 10 histograms are due to shot noise, indicating that further spatial segregation of the cluster is not warranted.

In an effort to recover the dereddened CMD of the cluster, we corrected the differential reddening in the individual sectors to a representative mean [med(V − I)]₀, and then corrected the entire data set for the average RRL reddening [E(V − I)]₀, based on the RRL stars in or near those sectors. We assumed Aᵥ = 2.6E(V − I). The dereddened CMD is shown in Figure 11. The principal sequences seem to have tightened up somewhat, compared with Figure 3c. However, the slope of the red clump stars persists, confirming the Rich et al. (1997) HST photometry. Sweigart & Catelan (1998) note that this intrinsic slope rules out older cluster age or extreme mass loss on the giant branch as causes of the extended blue HB seen in NGC 6441.

| Sector | α₁ (°) | α₂ (°) | med(V − I)₁₅₉ | Nsec | RR Lyr | E(V − I) | E(B − V) |
|--------|-------|-------|----------------|------|--------|---------|---------|
| 1 ......| 0     | 45    | 1.391          | 64   | V36ᵇ   | 0.588   | 0.456   |
|        |       |       |                |      | V46ᵇ   | 0.612   | 0.474   |
| 2 ......| 45    | 90    | 1.429          | 63   | V40    | 0.604   | 0.468   |
|        |       |       |                |      | V45    | 0.516   | 0.400   |
| 3 ......| 90    | 135   | 1.472          | 59   | V41    | 0.884   | 0.683   |
|        |       |       |                |      | V44    | 0.874   | 0.676   |
| 4 ......| 135   | 180   | 1.524          | 95   | V39    | 0.707   | 0.548   |
| 5 ......| 180   | 225   | 1.460          | 82   | V37    | 0.529   | 0.410   |
| 6 ......| 225   | 270   | 1.401          | 79   | V38    | 0.531   | 0.412   |
|        |       |       |                |      | V42    | 0.572   | 0.444   |
| 7 ......| 270   | 315   | 1.409          | 92   | V43    | 0.532   | 0.413   |
| 8 ......| 315   | 360   | 1.393          | 90   |        |         |         |

ᵇ These angles (in degrees) define the sector boundaries, see § 5.2.

b V36 and V46 lie outside sector 1, at radii of 300° and 165°, respectively.
In the eight sectors numbered in the figure (see Table 7). Each histogram is a sum of unit-area Gaussian curves placed at the $V - I$ color of each star and having a width equal to the color error of the star. The shifts between sectors indicate the presence and degree of differential reddening.

5.3. V41 and V44

The nature of the variables V41 and V44 is unclear. Their LCs suggest they are RR Lyrae stars, or possibly another class of pulsating variable. They are both $\sim 0.7$ mag brighter, and $\sim 0.3$ mag redder, than the other eight cluster RR Lyrae. Both are located close to the cluster center ($63^\circ$ and $57^\circ$, respectively), so are likely to be members.

One possibility is that they are type II Cepheids belonging to the cluster. However, we searched for periods between 1 and 5 days and found no reasonable minima, and the time-magnitude plots indicate shorter period variations. Anomalous Cepheids have periods between 0.36 and 1.6 days, absolute magnitudes between 0.5 and 2 mag brighter than RRL, and colors comparable to RRL (Nemec et al. 1994). Based on the first two criteria, V41 and V44 could be anomalous Cepheids. However, both stars are significantly redder than the RRL in NGC 6441. Furthermore, most anomalous Cepheids are found in dwarf spheroidal galaxies, metal-poor systems with a component of younger stars ($\leq 5$–10 Gyr: Mateo et al. 1995a). Bono et al. (1997b) confirm theoretically that the minimum mass for the formation of anomalous Cepheids is $\sim 1.8 M_\odot$ at $[\text{Fe/H}] = -1.7$, and this minimum increases quickly with increasing metal abundance. It seems unlikely that NGC 6441 possesses a population of stars young enough to produce HB stars of this mass. It may also be possible to produce anomalous Cepheids through binary star coalescence, but at the metallicity of NGC 6441, the mass limit appears incompatible with turnoff stars of globular cluster age ($M \approx 0.8 M_\odot$). Given these complications, and that we are not aware of the existence of any metal-rich examples of this type of variable, it seems unlikely that V41 and V44 are anomalous Cepheids.

Another possibility is that V41 and V44 are RR Lyrae stars in the foreground bulge. The similarity of their $V$ magnitudes to that of V36 supports this idea, but their much redder $V - I$ colors would require a large amount of differential reddening. The two stars do lie near each other, $21^\prime$ apart in sector 3; perhaps they lie behind a small, dense foreground dust cloud. To test this, we extracted a subset of the stars in Table 1 that lie within $20^\prime$ of the stars' centroid and plotted their CMD. It shows no displacement relative to the CMD of the other stars in sector 3, nor to Figure 3c, indicating that heavy differential obscuration is not responsible for the anomalous colors of these stars. Furthermore, the central location of V41 and V44 argues strongly for cluster membership. If they belong to the field, the probability of both variables lying inside $63^\circ$ radius is $4 \times 10^{-4}$.

A third possibility is that V41 and V44 are cluster RRL whose photometry has been contaminated by another star. If the RRL components are typical of the other eight cluster RRL, then the contaminating stars must have $V \approx 17.4$ and $V - I \approx 1.6$, roughly like those of cluster red clump stars. The positions of V41 and V44 in the period-amplitude diagram (Fig. 9) are consistent with this interpretation. The observed amplitudes are small compared with the other RRL in NGC 6441 with the same period, but the amplitudes become consistent with these stars when corrected for the effect of the photometric companion just described: the $V$-band amplitude of V41 becomes $\sim 0.7$ mag, and that of V44 becomes $\sim 1.2$ mag. Finally, the values of the “sharp” parameters produced by DAOPHOT are typical of stars of their brightness, indicating that the angular separations of the contaminating stars are small compared with the seeing disk. Perhaps V41 and V44 are members of physical binaries with red clump stars. This would be compatible with the wide-binary hypothesis for BHB star formation discussed in § 3. In the case of V41 and V44, the mass-
enhanced secondary has evolved onto the red HB, whereas for the other RRL and BHB stars, the secondary is still on the main sequence and contributes little to the combined light (≤ 0.1 mag).

We conclude that V41 and V44 are probably RR Lyrae members of NGC 6441, but appear brighter and redder than the other cluster RRL because their photometry has been contaminated by the light of unresolved red clump companions. Images with higher spatial resolution and detailed spectroscopy may confirm this conclusion (unfortunately, V41 and V44 were just off the HST images of Rich et al. 1997).

5.4. Light-Curve Shapes

The light curves of “normal” c-type RR Lyrae in clusters and the field have a characteristic shape, roughly sinusoidal, but with the region of maximum brightness skewed toward smaller phases. That is, the phase interval of “rising light” between minimum and maximum brightness is shortened, ΔΦ < 0.5. Among the 31 c-type RRL in the General Catalog of Variable Stars (Kholopov 1985) with V-band photometry, ΔΦ ranges between 0.32 and 0.46, with a mean of 0.39 and rms of 0.04.

Figure 6 shows that the LC shapes of the c-type RRL in NGC 6441 depart somewhat from this norm. Their maxima appear skewed to longer periods, and ΔΦ > ~0.5. The minima may be uncharacteristically sharp as well, especially in the case of SV3. Clearly, better LCs (more observations with smaller errors) for more stars are required to verify this phenomenon. When the observations are confronted with stellar pulsation models (e.g., Bono et al. 1997a), this effect may prove to be a valuable tool for constraining the parameters responsible for bright, blue HB extensions in NGC 6441 and NGC 6388 (e.g., Sweigart & Catelan 1998). The light-curve shapes of the ab-type RRL in NGC 6441 appear to fall within the range of shapes exhibited by “normal” ab-type RRL.

5.5. Comparison with Extended BHB Models

Rich et al. (1997) concluded that neither age nor dynamical effects, individually, could account for the extended blue HB in NGC 6441, though they could not rule out a combination of the two. Sweigart & Catelan (1998) used synthetic HB models to explore the effects of changing parameters that may produce blue HB extensions. They concur that neither age nor enhanced RGB mass loss can produce the sloped HB, and hence luminous BHB extension, seen in NGC 6441. They considered three additional scenarios, (1) high initial helium abundance; (2) core rotation, which at the RGB tip allows both enhanced mass loss and formation of an overmassive core; and (3) envelope helium abundance enhancement from deep mixing during the RGB phase.

In their brief report, Sweigart & Catelan (1998) could not present detailed results of their models. They employ three means of comparing their models and BV synthetic CMDs with our VI photometry: (1) the general distribution of stars in color and magnitude on the HB, (2) the number ratio of HB stars to RGB stars brighter than the mean RRL luminosity, R, and (3) the pulsation characteristics of the RRL.

First, we compare the overall appearance of our observed CMD with the synthetic CMDs of Sweigart & Catelan (1998, their Fig. 2) for their various scenarios. The steep slope of our red clump and its relation to the gentler sloping

BHB are best matched by the scenarios with core rotation and helium mixing and moderate mass loss on the RGB (see their Figs. 2c and 2e). Given the uncertainties introduced by differential reddening, foreground confusion, and by comparing the observed VI CMD with the synthetic BV CMD, we cannot make a more quantitative statement at this time.

Measuring the R-ratio in our photometry is complicated by the high degree of contamination by stars in the foreground and by stars on the cluster asymptotic giant branch (AGB). Using as a guide a field-subtracted version of Figure 11, we defined regions in which to count the number of BHB, red clump, and red giant stars. These regions are shown in Figure 11. We counted the number of stars in each region on the unsubtracted, dereddened cluster CMD (Fig. 11) and the equivalent dereddened field CMD. The counts are given in Table 8. We add nine RRL to the BHB counts and 10 LPV stars to the RGB counts. We used the luminosity functions of Bertelli et al. (1994; Z = 0.008, Y = 0.25, age = 14 Gyr) to estimate that 64% of the stars in the RGB region are first-ascent red giants (36% are AGB stars). Combining the BHB and red clump counts, we obtain R = N_{HB}/N_{RGB} = 1.60 ± 0.14, where the error is due solely to Poisson statistics. Systematic errors incurred by inappropriately defined counting regions are surely higher. If the counts in each region are uncertain by 25%, the systematic error on our estimate of R is 0.66. Even with this level of uncertainty, our counts strongly disfavor the high initial helium abundance scenarios of Sweigart & Catelan (1998).

Their simulations with main-sequence helium abundances of 0.38 and 0.43 produce sloping BHB extensions, but have R = 3.4 and 3.9, respectively, about 3 σ from our observed value. Using the relations of Buzzoni et al. (1983), our value of R implies a helium abundance of Y = 0.25±0.03, where the errors are based on the larger, systematic errors quoted in R. Using their R′ parameter, we obtain Y = 0.21±0.05. We caution that stellar interactions may alter the relative numbers of HB and RGB stars, and thus affect the estimate of Y.

The pulsation properties of the cluster RRL stars provide other constraints on the Sweigart & Catelan (1998) models. Their Figure 3 shows the positions of their model BHB

### Table 8

| Region | Cluster | Field |
|--------|---------|-------|
| BHB....| 175     | 83    |
| RRL....| 9       | 0     |
| RC......| 642     | 41    |
| RGB.....| 918     | 238   |
| LPV.....| 10      | 0     |
| RHB^b  | 107     | 60    |

^a CMD regions for BHB, RC, and RGB counts are defined in Fig. 11.
^b Red HB region is the BHB region redward of (V − I)_0 = 0.49 mag.

7 In fact, we have underestimated the RGB counts in this analysis. The faint boundary of the RGB region is usually defined as the bolometric magnitude equal to that of the RR Lyrae stars. However, this limit passes through the red clump stars. To avoid miscounts, we raised the faint boundary to that shown in Fig. 11. Underestimating N_{RGB} results in overestimating R. The true value of R is therefore less than 1.60, and the disagreement with the model with high initial helium abundance is stronger.
stars (helium mixing scenario with intermediate mass loss) in the temperature-period diagram. The dotted region in our Figure 9 encloses those models. We transposed the region from the \((\log T_{\text{eff}}, \log P)\) plane to the \((\log P, \Delta V)\) plane using equation (1) of Catelan (1998), which relates \(T_{\text{eff}}\) with \([\text{Fe/H}]\) and the \(B\)-band amplitude, \(\Delta B\). We converted from \(B\) to \(V\) amplitudes using the RRL in NGC 6171 (Dickens 1970): \(\Delta V = 0.72 \Delta B + 0.03\) (rms = 0.04) mag, and we assumed \([\text{Fe/H}] = -0.53\) dex. Clearly, the model provides a reasonable, though not perfect, match to the RRL stars in NGC 6441, NGC 6388, and 47 Tuc. It will be interesting to compare the observations with the temperature-period predictions of the other scenarios.

We can provide a measurement of the distribution of stars along the HB that may prove useful in constraining future synthetic HB models and in comparing the HB of NGC 6441 with those of other globular clusters. The usual statistic is \((B - R)/(B + V + R)\), where \(B\) and \(R\) are the numbers of HB stars on the blue and red sides of the instability strip, and \(V\) is the number of RRL variables. We adopt the same CMD regions as above except that the section of the BHB region redder of \((V - I)_{\text{b}} = 0.49\) (the mean dereddened magnitude of the RRL in Table 7, see counts in row labeled “RHB” of Table 8) is now added to the red clump counts to produce \(R\). Subtracting the counts in the off-cluster CMD from those in the on-cluster CMD, we obtain \(B = 45 \pm 10, V = 9 \pm 3,\) and \(R = 648 \pm 29\) stars, so \((B - R)/(B + V + R) = -0.86 \pm 0.03\) (Poisson) \(+0.04\) (systematic). The HB is predominantly red, and only \(\sim 17\%\) of HB stars are in the blue extension.

It is tempting to use our photometry to measure the distance to NGC 6441. However, the long periods observed for its RRL suggest that they are more luminous than typical RRL, so the absolute magnitudes usually assumed for these stars may be inappropriate. Moreover, the different models presented by Sweigart & Catelan (1998, their Fig. 2) have absolute magnitudes near the instability strip that range between 0.35 and 0.75 mag (we have omitted the high initial helium scenarios). The absolute magnitudes of the red clumps present a smaller range of 0.80–0.95 mag. Combined with a dereddened apparent red clump magnitude of \(V_R = 15.94 \pm 0.10\) mag from Figure 11, we find that NGC 6441 lies between 11 and 13 kpc from the Sun, on the far side of the Galactic bulge.

6. SUMMARY AND CONCLUSIONS

We present the first ground-based CCD photometry of the metal-rich globular cluster NGC 6441. Our \(V I\) color-magnitude diagram shows that the extended blue horizontal branch discovered by Rich et al. (1997) using the Hubble Space Telescope exists even at large radii from the cluster center. Such hot HB stars are not expected in a cluster of this metallicity.

Our time-series photometry enabled us to detect a large number of variable stars. We increased the number of red, long-period variables from nine to 32. We argue that five are members of the foreground bulge and that two are members of the background field, or possibly the Sagittarius dwarf galaxy. The remaining 25 are members of NGC 6441. We confirm the variability of V6, which may be a foreground Cepheid. Long-term monitoring of these variables is encouraged.

We also discovered 11 ab-type RR Lyrae variables, along with several probable c-type RRL. Based on their radial distances from the cluster center and positions in the CMD, we argue that eight of the ab-type RRL and two to three of the c-type RRL are members of NGC 6441. One RRL belongs to the foreground bulge, and two appear anomalously bright and red. We suspect the latter are photometric blends between cluster RRL and red clump stars and could be physical binaries. We also discovered four eclipsing binary stars in the foreground field and several stars that we could not classify with certainty.

We present a method for determining variable star periods in which the data are folded by a sequence of periods and, at each period, are fitted with a set of light-curve templates. The \(\chi^2\) of the fits are then plotted as a function of the employed periods. Minima in this plot indicate probable periods.

Using this method, we determined periods for the RRL, and produced mean light curves in \(V\) and \(I\). The eight to 11 RRL in NGC 6441 have periods that are systematically longer than field RRL of comparable metallicity. RRL in the metal-rich globular clusters 47 Tuc (V9) and NGC 6388 (V27 and V28) have similar properties. Thus, a new subclass of RRL appears to be emerging.

Using the observed \(V - I\) colors of the RRL at minimum light, we determined the reddening toward NGC 6441 to be \(E(B - V) = 0.45 \pm 0.03\) mag. Two points suggest that these long-period RRL have the same \((V - I)_R\) colors as the “normal” RRL, (a) we obtain \(E(B - V) = 0.46\) mag from the bulge variable V36, and (b) the analogous relation for \((B - V)_R\) at minimum light works for the long-period RRL V9 in 47 Tuc.

Evidence for small changes in the amount of reddening across the face of the cluster come from the star-to-star dispersion in the RRL \(E(B - V)\) values, and from differential shifts along the reddening vector of CMDs generated from small regions around the cluster. The southeast portion of the cluster has \(E(B - V) \approx 0.06\) mag higher than the rest of the cluster, though there is evidence for patchy reddening on a scale of several arcminutes or less.

We employ a differentially dereddened color-magnitude diagram to count stars in various regions along the horizontal and red giant branches. We find the ratio of HB stars to red giants to be \(R = 1.6 \pm 0.7,\) indicating a normal helium abundance of \(Y = 0.25_{-0.05}^{+0.05}\). About 17% of the HB stars lie blueward of the red clump, and \((B - R) / (B + V + R) = -0.86 \pm 0.04,\) indicating a predominantly red HB. We also find that the BHB stars are more centrally concentrated than the cluster red clump stars. This could result from mass segregation if the BHB stars are members of binary systems. Furthermore, the BHB stars could be produced by mass transfer in wide binary systems, as described by Bailyn (1995). The anomalously bright and red RRL V41 and V44, which we have discovered in NGC 6441, could represent binaries consisting of an RRL and a red clump star. Spectroscopic monitoring of these and the other BHB stars for binary motions would provide stronger evidence for or against the binary hypothesis of BHB star formation.

We also consider a different line of hypotheses, involving variations in the physical properties of single stars, which might explain the presence of the BHB stars’ high surface temperatures. As noted by Sweigart & Catelan (1998), the intrinsic slope of the HB, and in particular of the red clump, cannot be reproduced by standard models invoking extreme cluster age or red giant branch mass loss. Similarly,
our measurement of the HB–giant star ratio, $R$, argues strongly against the Sweigart & Catelan (1998) model predictions for a scenario that involves high initial helium abundance. In contrast, the observed periods and amplitudes of our RRL are in reasonable agreement with their model predictions for a scenario in which the helium abundance in the atmosphere has been enhanced through deep mixing on the RGB. However, the results of the Sweigart & Catelan (1998) models appear to be rather sensitive to the assumed mass-loss parameters (mean and distribution), which are at present poorly constrained by either observation or theory. Thus, it remains unclear whether the existing observations can isolate a unique set of physical parameters that explain the production of the extended blue HB.

We note one additional piece of observational evidence that may be brought to bear on this problem. The shapes of the c-type RRL light curves in NGC 6441 appear to differ significantly from their “normal” counterparts. They have longer phase intervals between minimum and maximum light, and the minima appear to be sharper. Perhaps by adjusting the physical parameters in stellar pulsation models (e.g., Bono et al. 1997a), similar light curves can be produced. If so, the intersection of plausible parameters from evolution and pulsation theory could further isolate the physical differences between “normal” clusters and those like NGC 6441. We encourage additional work on this problem from both the theoretical and observational perspectives.

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APPENDIX

NOTES ON INDIVIDUAL VARIABLE STARS

$V01$–$V12$.—Variable stars listed in the Hogg (1973) catalog (and 1997 updated electronic catalog by C. Clement [see footnote 6]).

$V11$ and $V12$.—Hesser & Hartwick (1976) identified these stars as possible RR Lyrae variables (RRL). We obtained an rms scatter about the mean values in Table 5 of 0.03 mag in $V$ and $0.08$ mag in $I$ for both candidates. Their $I_{WS}$ variability indices are 0.0 and 3.2, respectively. Our data thus show no sign of variability in these stars. Indeed, they are more than 0.2 mag bluer than the bona fide RRL stars we have discovered (see Fig. 4).

$SV1$.—Definitely variable, but the class of variable is uncertain. The data fold with minimal scatter at $P = 0.3239$ days to produce the light curve (LC) of a c-type RRL and at $P = 0.6472$ days to produce the LC of a contact eclipsing binary. The star is $0.8$ mag bluer than the member RRL.

$SV2$.—Definitely variable, but the class of variable is uncertain. The data fold with minimal scatter at $P = 0.5612$ days to produce an RRL LC and at $P = 1.122$ days to produce the LC of a contact eclipsing binary. The RRL LC is too sharp at the extrema for a typical RRc, and the rise time is too long for a typical RRab. However, the star falls among the other cluster RRL in the CMD.

$SV3$.—Definitely variable, but the variability class is uncertain. The data fold well at $P = 0.9016$ days, yielding a contact eclipsing binary. A less convincing fold is achieved with $P = 0.4508$ days to produce an RRc LC, but the minimum is too sharp and the maximum is skewed to late phases. The star’s position in Figure 4 suggests it is an RRL member of NGC 6441.

$SV4$.—Definitely variable, but the variability class is uncertain. The $V$-band data fold well with $P = 0.3167$ days, yielding an RRc LC, although the $I$-band curve has significant scatter. A period of $P = 0.4814$ days yields a contact eclipsing binary with an eccentric orbit. The color is 0.3 mag bluer than the bona fide cluster RRL.

$SV5$.—Definitely variable, but the variability class is uncertain. The data fold well with $P = 0.3615$ days, yielding an RRc LC, although the $I$-band curve has significant scatter. A period of $P = 0.7230$ days yields a contact eclipsing binary with considerable asymmetry. The star’s position in Figure 4 suggests it is an RRL member of NGC 6441.

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