Radial Velocities of RR Lyrae Stars in and around NGC 6441

Andrea Kunder1, Arthur Mills1, Joseph Edgecomb1, Mathew Thomas1, Levi Schilter1, Craig Boyle1, Stephen Parker1, Gordon Bellevue1, R. Michael Rich2, Andreas Koch3, Christian I. Johnson4, and David M. Natar5
1 Saint Martin’s University, 5000 Abbey Way SE, Lacey, WA 98503, USA
2 Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095-1562, USA
3 Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstr. 12–14, D-69120 Heidelberg, Germany
4 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
5 Center for Astrophysical Sciences and Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA

Abstract
Detailed elemental abundance patterns of metal-poor ([Fe/H] ∼ −1 dex) stars in the Galactic bulge indicate that a number of them are consistent with globular cluster (GC) stars and may be former members of dissolved GCs. This would indicate that a few per cent of the Galactic bulge was built up from destruction and/or evaporation of GCs. Here, an attempt is made to identify such presumptive stripped stars originating from the massive, inner Galaxy GC NGC 6441 using its rich RR Lyrae variable star (RRL) population. We present radial velocities of 40 RRLs centered on the GC NGC 6441. All 13 of the RRLs observed within the cluster tidal radius have velocities consistent with cluster membership, with an average radial velocity of 24 ± 5 km s−1 and a star-to-star scatter of 11 km s−1. This includes two new RRLs that were previously not associated with the cluster. Eight RRLs with radial velocities consistent with cluster membership but up to three times the distance from the tidal radius are also reported. These potential extra-tidal RRLs also have exceptionally long periods, which is a curious characteristic of the NGC 6441 RRL population that hosts RRLs with periods longer than seen anywhere else in the Milky Way. As expected of stripped cluster stars, most are inline with the cluster’s orbit. Therefore, either the tidal radius of NGC 6441 is underestimated and/or we are seeing dissolving cluster stars stemming from NGC 6441 that are building up the old spheroidal bulge.

Key words: Galaxy: bulge – Galaxy: formation – Galaxy: kinematics and dynamics – globular clusters: individual (NGC 6441) – stars: horizontal-branch – stars: variables: RR Lyrae

Supporting material: machine-readable table

1. Introduction
Globular clusters (GCs) are relics from the early universe, and as such, play an important role in deciphering the early history of the Galaxy. Their interplay within the Galactic bulge, however, is poorly understood, due in part to several strange bulge GCs that have properties not seen anywhere else in the Milky Way. For example, Terzan 5 is a GC harboring stars of hugely different ages, implying it was previously a massive clump in the early universe (Ferraro et al. 2016). Like Terzan 5, two further GCs in bulge, NGC 6569 and NGC 6440, have double horizontal branches (Mauro et al. 2012), a morphology not seen anywhere else in the Milky Way, and suggestive that there are more of these ancient fossil remnants of massive clumps lurking in the bulge.

NGC 6441 is also one of these curious inner Galaxy GCs. It has a very extended blue horizontal branch (Rich et al. 1997) in spite of its high metallicity of [Fe/H] ∼ −0.41 ± 0.06, rms = 0.36 dex, on the Carretta & Gratton metallicity scales (Clementini et al. 2005; Gratton et al. 2007), and traditional evolutionary scenarios cannot account for this property following the discovery that their RR Lyrae variables (RRLs) have exceptionally long periods (Layden et al. 1998; Pritzl et al. 2001). The rich population of RRLs in NGC 6441 (more than 50; Clement et al. 2001), is further curious given the paucity of RRLs in metal-rich systems. For example, less than 10% of field RRLs within 2 kpc of the Sun have [Fe/H] > −0.5 dex, and this is true also of the preponderance of RRLs within Galactic GCs.

The mix of at least two stellar populations observed in NGC 6441 is thought to be composed of stars with distinct values of helium abundances (Gratton et al. 2007; Bellini et al. 2013). One formation scenario that explains why this GC hosts different stellar populations is that massive and complex clusters such as NGC 6441 may have been former dwarf galaxy cores—remnants of a larger system, such as a dwarf galaxy or star cluster complex that merged with the Milky Way and is currently being pulled apart by the tidal forces of the Milky Way (Bekki & Tsujimoto 2016; Bekki 2017). This would be consistent with its large mass—fifth in rank after clusters ω Cen, M 54 at the center of Sagittarius dwarf galaxy, NGC 6388 and NGC 2419. This would also be consistent with its extended horizontal branch (EHB), as several studies have argued that EHB clusters are of extragalactic origin, formed probably as nuclei in dwarf satellites that were accreted by the Milky Way (Bekki & Norris 2006; Lee et al. 2007). Further evidence that this GC was accreted is that its RRLs have periods that are longer than seen in other Milky Way GCs (Pritzl et al. 2000, 2001).

Because NGC 6441 lies in a field that is very crowded, severe contamination by foreground (mainly bulge) field stars prevents the clear extent of this GC. Its position in the Galaxy is also where the reddening is severe, not only along its line of sight where $E(B-V) = 0.47$ mag (from Harris 1996, 2010 edition), but it also has extreme differential reddening throughout the cluster with $\Delta E(B-V) \sim 0.14$ mag (Law et al. 2003). Therefore, identifying possible tidal tails around NGC 6441 is a challenging task.
However, it is especially intriguing to search for tidally stripped stars, as recent results indicate their are field stars in the inner Galaxy with abundances that are typically found in GC stars (Fernández-Trincado et al. 2017, Schiavon et al. 2017b). These stars appear to be homogeneously distributed with a metallicity distribution peaking at [Fe/H] $\sim$ $-$1. The current best interpretation is that they are members of dissolved GCs (Fernández-Trincado et al. 2017; Schiavon et al. 2017a, 2017b). Because the elemental abundances of these potential GC stripped stars coincide with stars formed in the later stellar generations of the GC, the RRLs in and around NGC 6441, which are also thought to be a third (or later) generation of cluster stars (Jang et al. 2014), are particularly good probes for signatures of dissolving GC stars.

From the orbit of NGC 6441, it is known that although often labeled as a bulge cluster (e.g., Origlia et al. 2008; Bellini et al. 2013), and although indeed confined to the inner $\sim$3–4 kpc of the Galaxy, its velocity components are not consistent with it being a member of the central bulge/bar (Casetti-Dinescu et al. 2010; Bica et al. 2015). Instead, this cluster as well as GC NGC 6388 can be thought of as members of a pressure supported-spheroidal bulge with low rotation and high-velocity dispersion, and therefore they would have a different origin than the bulge/bar. Especially in light of the recent finding that the inner Galaxy RR Lyrae stars are also a population of stars consistent with a spheroidal component that formed before the bulge/bar that dominates the mass of the bulge (Kunder et al. 2016), it is important to search for and understand other old systems that may be part of the ancient inner Galaxy.

In this paper, we report on the kinematics of 40 RR Lyrae stars centered on NGC 6441, but extending spatially out to more than half a degree (four times that of the cluster tidal radius). We have taken advantage of the pulsation properties of RRLs to further establish membership of these stars and investigate the connection between the NGC 6441 GC, the underlying RRL field star properties and the build up of the bulge/bar. Lastly, an orbital integration of the cluster is carried out to determine its orbit around the Milky Way and hence the location in the sky where stripped tidal debris is most likely to reside.

2. Observations and Radial Velocity

Observations were carried out using the AAOmega multi-fiber spectrograph on the Anglo-Australian Telescope on three separate nights: 2016 August 09, 2016 August 10, and 2017 June 18 (OPTICON proposal code 17A/051, NOAO PropID: 2017A-195 and NOAO PropID: 2016B-0058 Pf. A. Kunder). The spectrograph was centered on 8600 Å, with the 580V and 1700D gratings to probe the Calcium Triplet, so the wavelength regime of $\sim$8300–8800 Å was covered at a resolution of $R \sim$ 10000. The exposure times ranged from 1800 to 7200 s, and one exposure per night was taken, meaning that we had three epochs for each RRL.

Targets were selected using the Optical Gravitational Lensing Experiment (OGLE) catalog of RRLs (Pietrukowicz et al. 2012), and we prioritized those stars with existing high-resolution spectroscopy from Clementini et al. (2005) to test the CaT metallicity relation. Unfortunately, the poor weather conditions did not allow for high enough signal-to-noise ratios (S/Ns) for robust equivalent width determinations and hence metallicites for the observed stars. The spectra had S/Ns ranging from 7 to 30.

An identical method to determine radial velocities as presented in Kunder et al. (2016) was carried out. Briefly, the observations were first phased by the stars known OGLE period. Then the radial velocity template from Liu (1991) was used to find the center-of-mass radial velocity for each star, upon being scaled to the correct amplitude for each star. Again, the zero-point in phase was fixed using the time of maximum brightness as reported by OGLE-IV (Soszyński et al. 2014) and we verified that all three observations fit the shifted pulseion curve. An example of a typical radial velocity curve presented here, as well as the photometric light curve from OGLE data, is shown in Figure 1.

The only difference employed here from Kunder et al. (2016) is that the zero-point in radial velocity was calculated by finding the observed center of all three Calcium triplet lines and comparing those to the known Calcium triplet lines ($\lambda$4980.03, 8542.09, 8662.14 Å). In contrast, Kunder et al. (2016) cross-correlates a spectra of a giant star (with a well-determined radial velocity) to each RR Lyrae star, and the peak of the cross-correlation peak is what was adopted as the radial velocity measurement. We believe that although more time-consuming, directly measuring the center of the Calcium triplet lines leads to more accurate zero-point determination. This is because the shape and features in the RR Lyrae spectra change over its $\sim$0.5 day pulsation cycle due to the temperature variations of the star, so using just one template to cross-correlate all the RR Lyrae spectra could give rise to uncertainties for pulsation phases that especially are hotter than that of the template, where, e.g., more Hydrogen Paschen lines are present.

Table 1 gives the OGLE-ID (1), the Galactic l (2) and Galactic b (3) as provided by OGLE, the star’s time-average velocity (4), the number of epochs used for the star’s time-average velocity (5), the I-band amplitude (6), the I-band magnitude (7), the V-band magnitude (8) and the period of the star (9) as calculated by OGLE, the distance from the cluster center in arcminutes (10), and lastly any notes (11). In particular, note that the OGLE objects with known NGC 6441 RRLs listed in Clement et al. (2001).

3. Results

3.1. Cluster Membership

The spatial positions of the observed stars are shown in Figure 2 (left panel), and the tidal radius of $\sim$7.7 arcmin (0′′129, 2010 edition of Harris 1996) is shown. None of our observed RRL fall within the core radius or half-light radius. As expected, the density of the observed RRLs is highest closest to the center of the cluster and decreases as the tidal radius of the cluster is approached. All RRLs observed within the tidal radius have velocities consistent with cluster membership. This is true even for V67, which was speculated to be a field star by Pritzl et al. (2001) because of its large distance from the cluster center as well as its uncertain/blended photometry. We have also observed an RRL within the tidal radius of NGC 6441 that is not included in the Clement et al. (2001) catalog of variable stars, but that has a velocity consistent with cluster membership (OGLE-03748).

Also shown in Figure 2 (right panel) is the radial velocity of the stars as a function of the distance from the center of the
cluster. The group of thirteen stars located within the cluster tidal radius (red circles) show similar kinematic properties, clustering around a mean velocity of 24 ± 5 km s⁻¹, with a star-to-star scatter of 11 km s⁻¹. This radial velocity is in excellent agreement found from a sample of 25 NGC 6441 giants that were vetted not only by radial velocity but also by abundance (Gratton et al. 2007). In particular, Gratton et al. (2007) report an average radial velocity of 21 ± 2.5 km s⁻¹, with a star-to-star scatter of 12.5 km s⁻¹. Although the scatter is similar to what is found here, the average velocity reported by Clementini et al. (2005) is considerably lower. However, it is worth noting that Clementini et al. (2005) measured one epoch per RRL, and so their mean radial velocity values included phase-dependent contributions due to the RRL pulsations.

As with the giant stars observed by Gratton et al. (2007), we find RRLs that have radial velocities consistent with cluster membership but farther than the nominal tidal radius of 0.129 degrees. In fact, eight RRLs outside the tidal radius have radial velocities within 3σ of that of the cluster. Four of these (blue closed triangles in Figure 2) have velocities only ~2σ from the cluster mean, and four (open triangles) have velocities within ~3σ of the cluster mean. We label the stars having a radial velocity within 3σ of the cluster mean as candidate cluster members. Given the large extent of the NGC 6441, and also that radial trends in radial velocity across clusters are expected (e.g., Perryman et al. 1998), at least some of these stars likely have some connection with the cluster.

This is strengthened because they are spatially located along the orbital path of the cluster (see Section 3.4) and as shown in the next section, these stars have especially long periods for their amplitudes, in agreement with the extreme NGC 6441 RRL pulsation properties.

3.2. Period–Amplitude Diagram and Color–Magnitude Diagram

Figure 3 (left panel) shows the periods and amplitudes of our observed stars as well as the colors and magnitudes of the observed RRLs (right panel). It is evident that the NGC 6441 cluster members have considerably longer periods than those in the field. In fact, the NGC 6441 RRLs have periods that are so unusual, that they have been given their own Oosterhoff group (OoIII; Pritzl et al. 2003; Jang & Lee 2015). One popular explanation of their long periods is that these RRLs have helium enhancements of $Y \sim 0.35–0.4$ dex (e.g., Busso et al. 2007; Caloi & D’Antona 2007; Tailo et al. 2017). The potential extra-tidal RRLs have periods that are also separated from the typical bulge field population, in a sense that they are shifted to longer values.
Because the OoI- and OoII-type RRLs are very difficult to disentangle at periods less than 0.5 days, and because here we focus on stars only with periods greater than 0.5 days, we designate an OoII-type RRL as those with an amplitude diagram.

It is interesting to assess how likely it is for random field stars to fall in different parts of the period–amplitude diagram. Because the Ool- and OoII-type RRLs are very difficult to disentangle at periods less than 0.5 days, and because here we are interested in the preponderance of Ool- (or OoIII-type) stars, we focus on stars only with periods greater than 0.5 days. Figure 4 shows the OGLE stars in our observed 0.5 < P < 0.7 field with periods greater than 0.5 day, compared to the OGLE stars in neighboring fields with periods larger than 0.5 day. We designate an OoII-type RRL as those with

\[ A_I > -1.642 - 13.78 \log(P) - 0.03 \]

\[ -19.298 \log(P) - 0.03 \]  

where \( A_I \) is a star’s I-amplitude and \( P \) is the star’s period (see Cacciari et al. 2005). It is immediately apparent that for stars with \( P > 0.5 \) day, NGC 6441 has a larger percentage of OoII-type stars than the field (~81%). In contrast, ~46% of the stars...
RRLs surrounding this cluster with $P > 0.5$ day are OoII-type RRLs. For fields located $\sim 0.5$° away from the cluster, an even smaller percentage, between 23% and 30% of stars, are OoII-type stars (right panel of Figure 4). Therefore, the field RRLs immediately surrounding NGC 6441 have a larger per cent of OoII-type RRLs than fields $0.5^\circ - 2^\circ$ away from the cluster, suggestive that some of our “field” RRLs do belong to NGC 6441.

Because of the unusual RRL properties of the NGC 6441 stars, their absolute magnitudes are thought to be brighter than normal, making it difficult to know what absolute magnitude to use for distance determinations (this is true also for the red giant branch bump, as shown by, e.g., Nataf et al. 2013b). Varying and patchy reddening in the $0.5^\circ$ field studies is also a cause for concern when interpreting the color–magnitude diagram (CMD). Both the reddening maps from OGLE (Nataf et al. 2013a) as well as those from minimum-light colors of the RRLs (Kunder et al. 2010), show that the RRLs surrounding NGC 6441 are more extincted than those within the cluster tidal radius by $\sim 0.2$ mag in $I$.

Finally, the differing periods of the central NGC 6441 RRLs with those on the outskirts suggest that the stars within the tidal radius of NGC 6441 are $\sim 0.2$ mag brighter than those on the outskirts. A range of absolute magnitudes of RRLs in and around this cluster is also expected from [Fe/H] variations seen in the cluster RRLs (Clementini et al. 2005). We therefore use the CMD as only a rough guide for evaluating cluster membership.

The known cluster members have magnitudes that make their identification with NGC 6441 straight-forward—they are fainter and located at a distance of $\sim 11.6$ kpc, whereas the distance of the bulge peaks at $\sim 8$ kpc. Indeed, it was photometrically that Layden et al. (1998) associated these RRLs with NGC 6441. Only one extra-tidal candidate has a magnitude consistent with that of the cluster. The majority of extra-tidal candidates have magnitudes that are $\sim 1$ mag brighter than expected—they have magnitudes similar to V67, a star spectroscopically studied here with a velocity consistent with cluster membership, but initially thought to be too bright to be a cluster member (Pritzl et al. 2001). Note that when using the Hubble Space Telescope, Pritzl et al. (2003) found that previous ground-based photometry of the NGC 6441 RRLs was largely affected by blends, resulting in photometry errors of up to 1.5 mag in the $V$ band.

### 3.3. The field RRLs around NGC 6441

The 27 field RRLs (including the extra-tidal candidates) have a mean heliocentric velocity of $-15$ km s$^{-1}$ (galactocentric velocity of $-32$ km s$^{-1}$) with a star-to-star scatter of $117$ km s$^{-1}$. Removing the eight potential extra-tidal candidates, the field RRLs have a mean velocity of $-30$ km s$^{-1}$ (galactocentric velocity of $-48$ km s$^{-1}$) with a star-to-star scatter of $137$ km s$^{-1}$. This large velocity dispersion is in stark contrast to what is seen for the giants and red clump stars in the bulge that trace out the Galactic bulge/bar (e.g., Kunder et al. 2012; Ness et al. 2013; Zoccali et al. 2014). It is also in contrast to the velocity dispersion of the Schiavon et al. (2017b) sample of 59 N-rich stars, which are those linked to GC stars. Despite the fact that the N-rich stars in Schiavon et al. (2017b) are located within $|b| < 5^\circ$, the location in the bulge where the largest dispersion in velocities is observed ($\sim 100$ km s$^{-1}$, e.g., Kunder et al. 2012), these stars have a velocity dispersion of only $86$ km s$^{-1}$.

Instead, the velocity dispersion is consistent with the hot population identified by Kunder et al. (2016) and also seen in targeted metal-poor star studies of the bulge (e.g., García Pérez et al. 2013; Howes et al. 2014, 2015, 2016; Schlaufman & Casey 2014; Schultheis et al. 2015; Koch et al. 2016). Note, however, that as Walker & Terndrup (1991) show, the metallicity distribution of the bulge RRLs may not necessarily be as low as the metallicities probed by the cited studies. The bulge RRLs stand out as a different population within the inner...
Galaxy because of their old age, predating the stars that dominate the mass of the inner Galaxy. It is likely that the similarities in radial velocities and dispersions of the extremely metal-poor stars being currently discovered means that these stars have similar ages as the RRL population.

Figure 5 shows the bulge/bar rotation curve traced out by the bulge giants from the Bulge Radial Velocity Assay (BRAVA) survey (Kunder et al. 2012) compared with both the metal-poor field bulge stars and the field RRLs surrounding NGC 6441. The average velocities and dispersions of \( \sim 100 \) stars with \( \text{Fe}/\text{H} < -1 \) dex from the ARGOS survey (Ness et al. 2013) are also over-plotted. It is not clear how metal-poor these stars reach or where exactly they are located because we do not have access to individual measurements; unlike the bulge surveys mentioned previously, the ARGOS data is not-public. The field RRLs around NGC 6441 are slower-rotating compared with the giants, as seen also for the inner Galaxy RRLs in Kunder et al. (2016). However, this field extends further in longitude than probed in Kunder et al. (2016). A more extensive investigation of the bulge field RRLs covering a larger spatial across the bulge is being carried out and will be the subject of a separate paper (A. M. Kunder et al. 2018, in preparation).

3.4. Orbit

Material lost by accreted dwarf galaxies is predicted to form pronounced tidal tails on both sides of the dwarf: the leading tail, traveling faster than the dwarf, and the trailing tail, which moves slower, and for circular orbits (like NGC 6441) the tails are tracers of the cluster path (e.g., Jordi & Grebel 2010; Kazantzidis et al. 2011; Lokas et al. 2011). The strong tidal tails of the GCs, Palomar 5 and NGC 5466, for example, roughly follow the orbit of the cluster (Belokurov et al. 2006; Grillmair & Dionatos 2006) with some (expected) misalignment.

To gain insight into where expected tidal debris would lie, an orbital integration of NGC 6441 is carried out. We adopt the radial velocity of the cluster presented here, along with its distance of 11.6 kpc from (from Harris 1996, 2010 edition) and proper motion from Casetti-Dinescu et al. (2010). Using the galpy Python package\(^6\) and the recommended MWPotential2014 potential with the default parameters (Bovy 2015), we integrated the orbit in time for 150 Myr. The orbital path is shown by the dotted line in Figure 2 (left panel). The correlation between the orbit of NGC 6441 orbit and the candidate extra-tidal stars is suggestive and indicates a low probability that all of these stars are due to random fluctuations in the field.

Calculating the orbit of NGC 6441 also gives information as to where this cluster may have originated. As we have integrated forward in time by 150 Myr, the trailing arm will lie almost directly behind the leading arm. If the orbital path of NGC 6441 is tracing out the leading arm, most of our 3\(\sigma\) candidates are located along the trailing arm, as is expected for tidal debris. From observations of known streams in the Milky Way, “narrow” streams have widths of \( \sim 0.25 \) (Koposov et al. 2014) and prominent streams stemming from GCs (like Pal 5) have widths of \( \sim 0.75 \). NGC 6441 is more massive than most GCs and also has a relatively large radial velocity dispersion, so it would not be surprising if the tidal debris has a width of at least \( \sim 0.75 \) along its orbit. Careful N-body modeling of this cluster could yield more details as to the expected width and density of tidally stripped stars.

4. Discussion

RRLs are not nearly as ubiquitous throughout the bulge as compared to bulge red clump stars and red giants. They are therefore much less likely to be field star contaminants if they are located around stellar systems, such as GCs, with rich populations of RRLs. RRLs have also been shown to be particularly useful in finding streams in the inner Galaxy, even with the lack of kinematical information, shedding important detections on dissolving GCs in the inner Galaxy (Mateu et al. 2018).

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\(^6\) http://github.com/jobovy/galpy, version 1.2.
suggesting they are different from the bulge giants, although the sample size is small (~50). It has been put forward that these metal-poor stars are actually halo interlopers (e.g., Howes et al. 2014; Kunder et al. 2015; Koch et al. 2016).

Here, we present radial velocities of 40 RRLs around the massive, complex, and peculiar GC NGC 6441 to investigate this cluster’s spatial extent and its connections to the bulge field RRLs. In particular, we try to find candidate dissolved cluster members stemming directly from NGC 6441, a cluster in which the RRLs are a second- or third-generation population (Jang et al. 2014), similar to the field stars in the inner Galaxy with abundances that are typically found in GC stars presented in Schiavon et al. (2017b), Fernández-Trincado et al. (2017).

As was also seen by Gratton et al. (2007) who identified NGC 6441 members from high-resolution abundances, we find evidence that the tidal radius of NGC 6441 is underestimated by a factor of at least two (Figure 2, right panel). We also identify RRL candidates that may be part of tidal tails originating from the cluster, or horizontal-branch stars being dynamically evaporated (e.g., Krogsrud et al. 2013), or part of a large diffuse stellar envelope, such as seen surrounding the halo GCs NGC 1851, NGC 5824, M2, and NGC 1261 (Olszewski et al. 2009; Kuzma et al. 2016, 2018). These stars have periods, amplitudes, and magnitudes that are similar to what is seen within the bona fide NGC 6441 stars. Proper motions of these stars from Gaia as well as follow-up high-resolution spectroscopy will be invaluable to confirm their membership. In particular, it would be of interest to see if these stars are N-rich, as is found in the population of stars by Schiavon et al. (2017b).

If it is confirmed that NGC 6441 has dissolving RRLs, which could make it similar to Terzan 5, a cluster that was much more massive in the past and likely formed at the epoch of the Milky Way bulge formation. This could indicate that although most of the bulge is not “classical” and made by previous major mergers (e.g., Shen et al. 2010), there could be a part of the inner Galaxy where repeated mergers at high redshift contributed to the build up of the bulge (e.g., Hopkins et al. 2010).
The RRL field stars surrounding NGC 6441 have velocities indicating they are rotating slower than the younger giants confined to the bulge/bar. Their velocity dispersion is indicative of a hot population residing in the inner Galaxy, with properties similar to the most metal-poor stars currently observed in the bulge. Both the RRLs in the field of the inner Galaxy as well as those in the GC NGC 6441 suggest a connection with an earlier epoch of bulge formation than the bulge/bar.

Lastly, we note that the frequency of RRLs in a cluster is significantly lower than the frequency of main-sequence stars in a cluster, and tidal tails of GCs are primarily formed by the significantly lower than the frequency of main-sequence stars in a cluster, and tidal tails of GCs are primarily formed by the significant lower than the frequency of main-sequence stars in a cluster, and tidal tails of GCs are primarily formed by the

Due to the dearth of spectroscopic observations of RRLs in the inner Galaxy, identifying RR Lyrae stars in moving groups in the bulge is a field largely unexplored. However, the results presented here argue that detailed elemental abundance patterns of the inner galaxy RRLs could establish the link between the old, spheroidal Galactic bulge and its possible build up from the destruction and/or evaporation of GCs.

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Software: Galpy (v1.2; Bovy 2015).

Appendix

Here, we provide notes on individual stars in our sample. OGLE-BUL-RRLyr-03748: This RRL was not previously listed in the Clement et al. (2001) catalog as being an NGC 6441 member. However, it is within the tidal radius of NGC 6441 and our well-phased RV curve indicates it has a velocity well within the RV distribution of the cluster. We note that our RV curve appears clean, despite the ~0.3 mag scatter in the OGLE optical light curve, which suggests its light curve instabilities such as the Blazhko effect. From its OGLE photometry, we see it also has a long period and large I-amplitude (indicative of an OoII- or OoIII-type star), and it has a de-reddened magnitude and color very similar to the bona fide NGC 6441 RRLs.

OGLE-BUL-RRLyr-04288: This RRL was previously listed in the Clement et al. (2001) catalog as V67 and as being a field star. It has a magnitude that is brighter than the majority of the NGC 6441 stars. It lies just within the tidal radius of NGC 6441 and our RV observations indicate it has a velocity well within the RV distribution of the cluster. We note that there is some scatter in our RV curve, although the OGLE I-band light curve appears to be rather stable, with only small (~0.05) magnitude variations.

OGLE-BUL-RRLyr-03934: This star is well within the tidal radius of the cluster, and has been studied previously by Clementini et al. (2005), who determined an [Fe/H] ~1 dex for this star. Similar to the RV reported by Clementini et al. (2005), this star has an RV 2-3σ lower than the cluster mean. We note that our three radial velocities have a ~15 km s^{-1} scatter around the radial velocity template. A consistent ~0.05 mag scatter is also seen in the phased OGLE I-band light curve.

OGLE-BUL-RRLyr-03774: This star is the closest RRL in our sample that is outside the nominal tidal radius of NGC 6441 (r ~ 8 arcmin). Its radial velocity is on the high end of the velocity distribution, but well within 2σ of the cluster velocity. It has a well-phased RV curve, and from the OGLE photometry, we see it has a large I-amplitude (indicative of an OoII- or OoIII-type star).

OGLE-BUL-RRLyr-03613: This star has a well-phased RV curve, and a velocity placing it well within what the RV distribution for NGC 6441. However, it is outside of the cluster’s tidal radius (r ~ 13 arcmin). Its pulsation properties indicate it is an OoII or OoIII-type star, as it has a long period and large I-amplitude.

OGLE-BUL-RRLyr-31080: This star has a well-phased RV curve, and a velocity placing it well within what the RV distribution for NGC 6441. However, it is well outside the cluster’s tidal radius (r ~ 24 arcmin). It is spatially located along the leading arm of the cluster and has a large I-amplitude.

OGLE-BUL-RRLyr-30928: We have two noisy measurements at φ ~ 0.0, and one clean one at φ ~ 0.8. Using all three measurements, the radial velocity template fits best at a velocity of ~50 km s^{-1}. Anchoring the radial velocity template to our best measurement, a velocity of ~30 km s^{-1} is found. Therefore, this star could also be a 2σ cluster candidate. It has pulsation properties indicative of an OoII or OoIII-type RRL, and is spatially located along the leading arm of the cluster.

OGLE-BUL-RRLyr-30792: This star has a velocity on the low end of the NGC 6441 RV distribution, but still within 3σ of the cluster velocity. It is spatially located on the leading end of the cluster orbit, ~16 arcmin away from the cluster center. Both its period and amplitude are consistent with an OoII or OoIII-type RRL. It has a magnitude and color consistent with what is expected for RRLs residing in NGC 6441.

OGLE-BUL-RRLyr-30603 and OGLE-BUL-RRLyr-30513: These two stars have RV curves with observations well-spaced along the full pulsation curve and following the RV template well. Both of their RVs are on the low end of the NGC 6441 RV distribution, but within 3σ of the cluster velocity. They are relatively close to the tidal radius of NGC 6441, with distances of ~11 arcmin from the cluster center. Both follow the leading arm of the clusters orbit and have very similar periods and small I-amplitudes.

OGLE-BUL-RRLyr-03311: This RRL is interesting because it lies on the leading arm of NGC 6441 and is relatively close the the tidal radius (~14 arcmin from cluster center). Although we have three reliable radial velocity observations for this star, two are both at φ ~ 0.81, so our spatial coverage is limited. We find a mean velocity is ~21 ± 5 km s^{-1}. It has a large I-amplitude.

OGLE-BUL-RRLyr-03708: This star is interesting because it has velocity close to the edge of the 3σ RV distribution of NGC 6441. Unfortunately, we have two noisy measurements at φ ~ 0.95 and 0.15, and one clean one at φ ~ 0.3. Using all three measurements, the radial velocity template fits best at a velocity of ~9 km s^{-1}. Anchoring the radial velocity template to our best measurement, a velocity of ~21 km s^{-1} is found.

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This star is interesting because it has a relatively long period (~0.68 day) and large amplitude (~0.58 mag), lying between the OoII and OoIII locus in the PA diagram. However, our three radial velocity measurements all indicate it has a velocity of ~−60 km s\(^{-1}\).

ORCID iDs
Andrea Kunder @ https://orcid.org/0000-0002-2808-1370
Christian I. Johnson @ https://orcid.org/0000-0002-8878-3315

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