

Concerning the Distance to the Center of the Milky Way and Its Structure

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ABSTRACT

The distance to the Galactic center inferred from OGLE RR Lyr variables observed in the direction of the bulge is $R_0 = 8.1 \pm 0.6$ kpc. An accurate determination of R_0 is hindered by countless effects that include an ambiguous extinction law, a bias for smaller values of R_0 because of a preferential sampling of variable stars toward the near side of the bulge owing to extinction, and an uncertainty in characterizing how a mean distance to the group of variable stars relates to R_0 . A VI -based period–reddening relation for RR Lyr variables is derived to map extinction throughout the bulge. The reddening inferred from RR Lyr variables in the Galactic bulge, LMC, SMC, and IC 1613 match that established from OGLE red clump giants and classical Cepheids. RR Lyr variables obey a period–color (VI) relation that is relatively insensitive to metallicity. Edge-on and face-on illustrations of the Milky Way are constructed by mapping the bulge RR Lyr variables in tandem with cataloged red clump giants, globular clusters, planetary nebulae, classical Cepheids, young open clusters, HII regions, and molecular clouds. The sample of RR Lyr variables do not trace a prominent Galactic bar or triaxial bulge oriented at $\phi \simeq 25^\circ$.

Key words: *Stars: distances – Galaxy: center – Galaxy: structure*

1. Introduction

Recent estimates of the distance to the center of Milky Way range from $R_0 \simeq 7\text{--}9$ kpc (Groenewegen and Blommaert 2005, Bica *et al.* 2006, Feast *et al.* 2008, Groenewegen *et al.* 2008, Vanhollebeke *et al.* 2009, Majaess *et al.* 2009a, Matsunaga *et al.* 2009). The standard error associated with R_0 as inferred from variable stars is often smallest owing to sizeable statistics ($\leq 5\%$, $se = \sigma/\sqrt{n}$). Yet it remains a challenge to identify and mitigate the dominant source of error, namely the systemic uncertainties. In this study, several effects are discussed that conspire to inhibit an accurate determination of R_0 from the photometry of variable stars. RR Lyr variables detected in the direction of the bulge by OGLE are utilized to estimate the distance to the Galactic center, to map extinction throughout the region surveyed, and to assess the morphology of the Galaxy in harmony with red clump giants and pertinent tracers.

2. Analysis

2.1. Sample and Distribution

The sample of RR Lyr variables used here is that compiled by Collinge, Sumi, and Fabrycky (2006) from the OGLE survey of Galactic bulge fields (Udalski *et al.* 1992, 2002, Sumi 2004). Readers are referred to the comprehensive discussion in Collinge *et al.* (2006) regarding the construction of the database. Stars exhibiting spurious distances were not included in the present analysis.

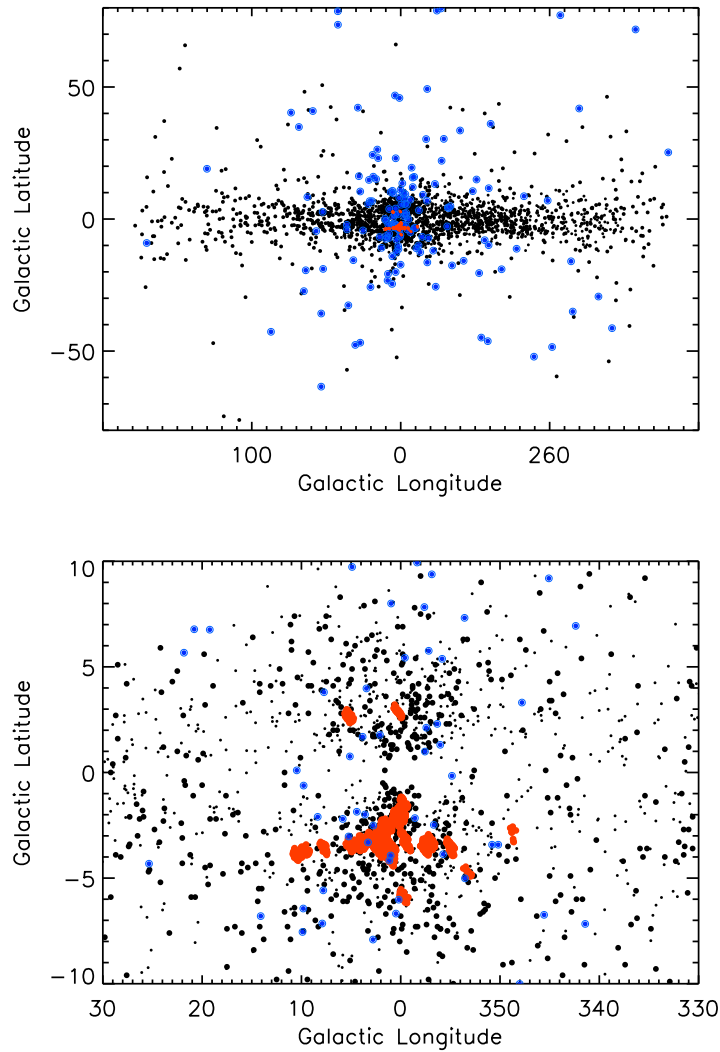


Fig. 1. Edge-on view of the Milky Way as delineated by OGLE bulge RR Lyr variables (red dots), planetary nebulae (black dots), and globular clusters (blue dots) in Galactic coordinate space.

It is instructive to begin by examining the distribution of RR Lyr variables in position, magnitude, extinction, and distance space. The locations of the variables are mapped on an edge-on model of our Galaxy as illustrated by planetary nebulae and globular clusters (Fig. 1). The distribution of planetary nebulae in Galactic coordinate space was compiled from the catalogs of Kohoutek (2001) and MASH I and II (Parker *et al.* 2006, Miszalski *et al.* 2008). Harris (1996) tabulated the relevant data for globular clusters. Planetary nebulae, whose progenitors are primarily old low mass objects, outline the Galactic bulge where their distribution peaks rather clearly (see Fig. 1 of Majaess *et al.* 2007). RR Lyr variables are not sampled in areas tied to anomalous extinction near the plane ($A_V \geq 8$, Fig. 2), and a similar absence is noted for planetary nebulae (Fig. 1, bottom).

The distribution of the sample's mean magnitude as a function of Galactic position indicates uneven sampling (Fig. 2). The survey proceeds deeper in tandem with the need to overcome increasing extinction toward the Galactic plane, namely $\langle V \rangle \simeq 17$ at $b \simeq -6^\circ$, $\langle V \rangle \simeq 19$ at $b \simeq 3^\circ$, to $\langle V \rangle \simeq 21$ at $b \simeq -1^\circ$.

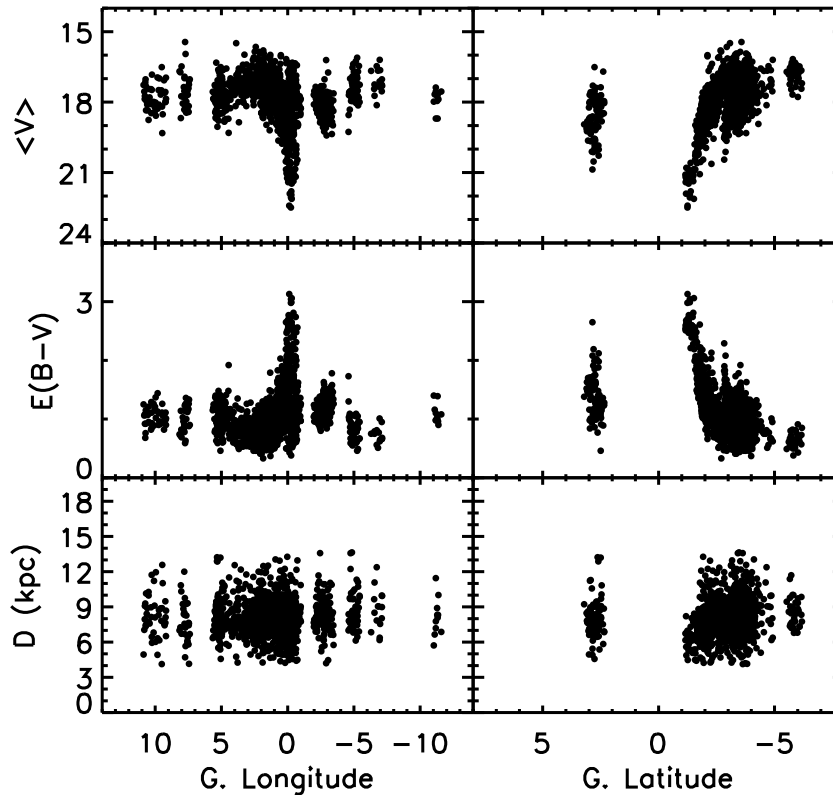


Fig. 2. The mean visual magnitude, color excess, and distance associated with the RR Lyr variables as a function of Galactic longitude and latitude.

2.2. Extinction

Extinction throughout the bulge can be assessed by constructing a period–reddening relation for RR Lyr variables, in similar fashion to classical Cepheids (Majaess *et al.* 2008a, 2009c). That relation shall also facilitate the mapping of interstellar reddening for regions throughout the Milky Way and beyond. An RR Lyr variable’s color excess may be approximated by assuming that:

$$E_{B-V} \simeq \alpha \log P + \beta(m_{\lambda_1} - m_{\lambda_2}) + \phi$$

where α , β , and ϕ are coefficients that can be derived by minimizing the χ^2 statistic for a calibrating data set, and m_{λ_1} and m_{λ_2} are mean photometric magnitudes in different passbands. The calibrators are RR Lyr variables in the globular clusters M3 (Hartman *et al.* 2005), M54 (Layden and Sarajedini 2000), M92 (Kopacki 2001), and NGC 6441 (Pritzl *et al.* 2003). Reddenings for the calibrating globular clusters were acquired from various studies (*e.g.*, Harris 1996, Majaess *et al.* 2009c). The optimum solution is:

$$E_{B-V} \simeq -0.88 \log P_f + 0.87(V - I) - 0.61 \quad (1)$$

which reproduces the calibrating set with an average uncertainty of ± 0.03 magnitude. The true scatter applying to use of the relationship for individual RR Lyr variables may be larger, particularly for stars near the edge of the instability strip. The relation can provide first order estimates to complement space reddenings (Benedict *et al.* 2002, 2007, Laney and Caldwell 2007, Turner 2010). RR Lyr variables pulsating in the overtone were shifted by $\log P_f \simeq \log P_o + 0.13$ to yield the equivalent fundamental mode period (Walker and Nemeč 1996, Soszyński *et al.* 2003, Gruberbauer *et al.* 2007, Hurdis 2009). Alternatively, M3 offers a unique opportunity to infer the intrinsic *VI* colors of RR Lyr variables directly since foreground extinction along the globular cluster’s line of sight is negligible (McClure and Racine 1969). Thus a formal fit to *VI* photometry of RR Lyr variables in M3 may be employed to establish reddenings. An interpretation of Benkó *et al.* (2006) M3 photometry is given in Fig. 3.

Reddenings for locations sampled by the survey are mapped as a function of Galactic position (Fig. 2). The following general trend can be inferred regarding extinction throughout the bulge, namely that it is not symmetric or uniform. For example, across $b \simeq 3^\circ$ the reddening varies from approximately $E_{B-V} \simeq 0.6 \rightarrow 2.3$ (Fig. 2). The reddening throughout the entire sample ranges from $E_{B-V} \simeq 0.4 \rightarrow 3.4$, with extinction increasing to a maximum near the dust ridden Galactic plane (Fig. 2). The estimated color excess is in satisfactory agreement with that inferred by Sumi (2004) from adjacent OGLE red clump giants (Fig. 4).

The robustness of Eq. (1) may be further evaluated. Drawing upon photometry for RR Lyr variables in the LMC (Udalski *et al.* 1998, Soszyński *et al.* 2003, 2009), SMC (Udalski *et al.* 1998, Soszyński *et al.* 2002), and IC 1613 (Dolphin

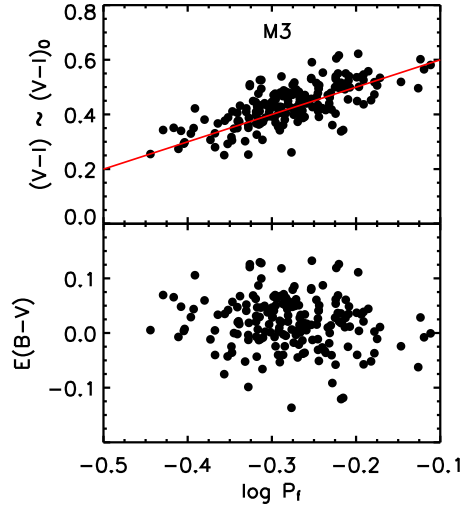


Fig. 3. *Top*, VI colors for RR Lyr variables in M3 exhibit a period dependence (photometry from Benkő, Bakos, and Nuspl 2006). The overplotted relation is Eq. (1) (solid line) or $(V - I) \simeq (V - I)_0 \simeq 0.7 + \log P_f$. *Bottom*, the computed color excess using Eq. (1).

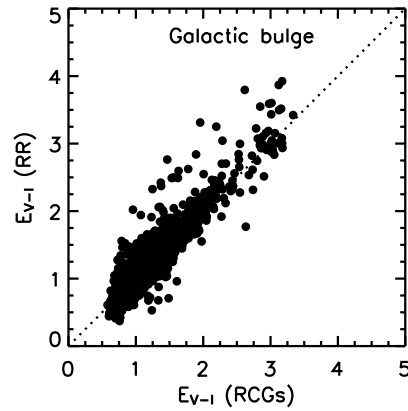


Fig. 4. The color excess inferred from bulge RR Lyr variables (Eq. 1) match estimates compiled by Sumi (2004) for adjacent red clump giants.

et al. 2001), the resulting mean reddenings for the galaxies are consistent with estimates inferred from red clump giants, a Galactic classical Cepheid relation, and other means (Table 1). That indicates RR Lyr variables adhere to a period–color (VI) relation which is relatively insensitive to metallicity. Perhaps an expected result granted the slope of near infrared RR Lyr variable and Cepheid distance relations are comparatively unaffected by chemical composition (Longmore *et al.* 1990, Udalski *et al.* 2001, Bono 2003b, Pietrzyński *et al.* 2004, Persson *et al.* 2004, Sollima *et al.* 2006, Del Principe *et al.* 2006, Benedict *et al.* 2007, van Leeuwen *et al.* 2007, Fouqué *et al.* 2007, Matsunaga *et al.* 2006, Majaess *et al.* 2008a, 2009a,

Table 1
Mean reddenings for the galaxies (E_{B-V})

Galaxy	Cepheids (TI)	RR Lyr	Red Clump Giants (Udalski <i>et al.</i> 1999)	Zaritsky <i>et al.</i> 2004 (Ngeow <i>et al.</i> 2009)	Photometry
LMC	0.14	0.12	0.14	0.13	(1,2,6,7,8)
SMC	0.13	0.10	0.09	–	(1,3)
IC1613	0.05	0.05	–	–	(4,5)

(1) Udalski *et al.* (1999), (2) Soszyński *et al.* (2009), (3) Soszyński *et al.* (2002), (4) Dolphin *et al.* (2001), (5) Udalski *et al.* (2001), (6) Soszyński *et al.* (2008b), (7) Cioni *et al.* (2000), (8) Massey (2002). The classical Cepheid reddenings inferred from the Galactic calibration of Majaess *et al.* (2009c). The color excess varies with position across the Magellanic Clouds and shall be elaborated upon elsewhere.

2009c, Majaess 2009d). By contrast, readers should exhibit caution when employing BV relations for Cepheid and RR Lyr variables of differing abundance (Caldwell and Coulson 1985, Madore and Freedman 1991, Chiosi *et al.* 1993, Tammann *et al.* 2003, Di Criscienzo *et al.* 2007, Majaess *et al.* 2008a, 2009c). The computed color excess for the brightest member of the variable class, RR Lyr, is $E_{B-V} \simeq 0.01$ mag. That agrees with both a value cited by Feast *et al.* (2008) and a field reddening inferred from 2MASS photometry using methods tested elsewhere (Bonatto *et al.* 2004, 2006, Majaess *et al.* 2007, 2008a, Bonatto and Bica 2009, Turner *et al.* 2009b, Turner 2010). The implied absolute magnitude for RR Lyr is $M_V \simeq 0.55$ mag, assuming $E_{B-V} \simeq 0.01$ mag (Eq. 1) and $d \simeq 260$ pc (Benedict *et al.* 2002, Bono *et al.* 2002, Majaess 2009d). To establish the parameters VI photometry from The Amateur Sky Survey for RR Lyr was utilized (Droege *et al.* 2006), although concerns persist regarding the survey’s photometric zero point and the star’s modulating amplitude. An ephemeris to phase the V and I data was adopted from the GEOS RR Lyr database (Boninsegna *et al.* 2002, Le Borgne *et al.* 2004, 2007).

2.3. Distance

A type II Cepheid VI reddening-free relation is employed to provide distances for the sample of RR Lyr variables (Eq. 2, Majaess *et al.* 2009a). Relying exclusively on the photometric surveys of fellow researchers, Majaess (2009d) reaffirmed that to first order SX Phe, RR Lyr variables, and type II Cepheids may adhere to a common VI period–magnitude–color relation (see also the interesting JHK_s results of Matsunaga *et al.* 2006). A VI Wesenheit diagram and function illustrate the underlying period–magnitude continuity unifying variable stars of the population II instability strip (Majaess 2009d), although perhaps somewhat imperfectly. Admittedly, small statistics inhibit an elaborate analysis toward the SX Phe

regime and RR Lyr variables may exhibit a steeper Wesenheit function than type II Cepheids. However, distances inferred from Eq. (2) of Majaess *et al.* (2009a) appear largely insensitive to that latter putative difference (Fig. 10, see also Majaess 2009d). The slopes of the Wesenheit functions characterizing shorter-period type II Cepheids and RR Lyr variables are generally consistent with the predictions of Marconi, Di Criscienzo, and collaborators, underscoring the viability of their research team's pulsation models. Readers are referred to studies by van den Bergh (1968), Madore (1982), Opolski (1983), Kovacs and Jurcsik (1997), Kovacs and Walker (2001), Di Criscienzo, Marconi, and Caputo (2004), Madore and Freedman (1991, 2009), and Turner (2010) for a broader discussion regarding RR Lyr and Cepheid Wesenheit relations. The calibrators of the Majaess *et al.* (2009a) VI distance relation were OGLE LMC type II Cepheids (Udalski *et al.* 1999, Soszyński *et al.* 2008a), with an adopted zero point to the LMC established from classical Cepheids and other means ($(m - M)_0 \approx 18.50$ mag, Laney and Stobie 1994, Gibson 2000, Freedman *et al.* 2001, Benedict *et al.* 2002, Majaess *et al.* 2008a, Majaess 2009d). The classical Cepheid zero point to the LMC was inferred from the photometry of Udalski *et al.* (1999) and Sebo *et al.* (2002), using the reddening-free distance relation of Majaess *et al.* (2008a). That relation is tied to a restricted subsample of Galactic cluster Cepheids (*e.g.*, Turner and Burke 2002) and Cepheids with new HST parallaxes (Benedict *et al.* 2007).

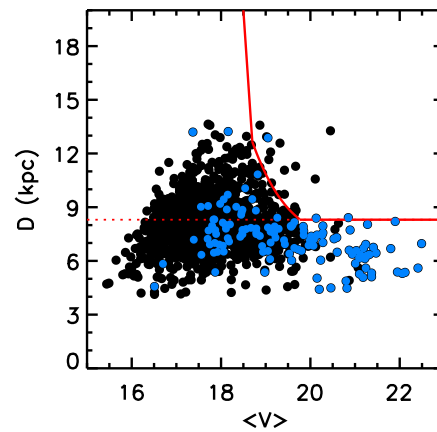


Fig. 5. OGLE RR Lyr variables nearest to the Galactic plane ($b \simeq -1.5^\circ$) and fainter than $V \simeq 19$ mag are not sampled beyond $d \simeq 8$ kpc (blue dots).

The mean distance to the sample of RR Lyr variables observed in the direction of the bulge is 8.1 ± 0.6 kpc ($\sigma/2$). Yet what is the relation to R_0 , the distance to the Galactic center? The mean is R_0 if the sampling were uniform across a symmetric bulge. However, a fraction of RR Lyr variables are not sampled equally at the rear and forefront of the bulge. Indeed, as the survey nears the Galactic plane, the effects of extinction increase the magnitude threshold needed to adequately

sample the bulge beyond the limit of the survey (Fig. 2, 5). The mean distance inferred from RR Lyr variables near $b \simeq -1^\circ$ is $d \simeq 7$ kpc, while at larger Galactic latitudes it is approximately a kiloparsec further (Fig. 2, 5). RR Lyr variables fainter than $V \simeq 19$ mag and nearest to the Galactic plane are not observed beyond $\simeq 8$ kpc (Fig. 5). Establishing R_0 from that limited subsample shall yield a result systemically too close. The data were therefore excluded from the derivation of R_0 . Majaess *et al.* (2009a) suggested the impact of the bias may be assessed by ascertaining R_0 *via* an alternative approach, namely by adding an estimate for the radius of the bulge to the distance to its near side. Admittedly, that approach introduces new uncertainties and is idealistic granted the bulge may be triaxial (Fig. 6).

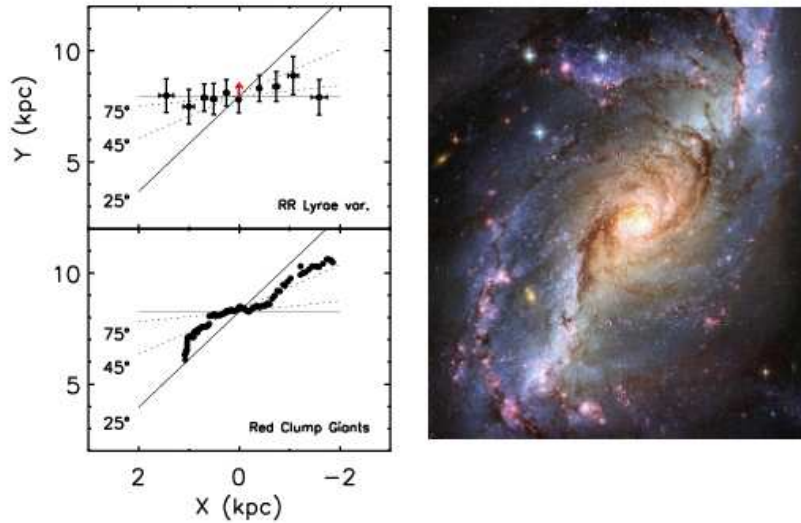


Fig. 6. *Top left*, an orientation of $\phi \simeq 25^\circ$ (sun-gc line) is not indicative of RR Lyr variables detected in the direction of the bulge. *Bottom left*, red clump giants may trace a nested nuclear structure within a primary bar (data from Nishiyama *et al.* 2005, 2006). *Right*, a reprocessed cropped portion of the HST image of NGC 1672.

Establishing the distance to the Galactic center from either bulge type II Cepheids (Kubiak and Udalski 2003, Majaess *et al.* 2009a) or RR Lyr variables yields an analogous result ($R_0 \simeq 8$ kpc). However, that result depends rather sensitively on the extinction law adopted, particularly since the reddenings are inherently large (Fig. 2). The nature of the extinction law toward the bulge is actively debated and is thus a primary source of uncertainty in the determination of R_0 (Gould *et al.* 2001, Udalski 2003, Ruffle *et al.* 2004, Sumi 2004, Kunder and Chaboyer 2008). The Majaess *et al.* (2009a) distance relation employed here assumes an extinction law similar to that cited for bulge stars by Udalski (2003). In hindsight, however, perhaps the least squares approach adopted by Majaess *et al.* (2008a, 2009a) to obtain the coefficients of the Cepheid (Type I and II) distance relations, which includes an estimate for the pseudo extinction law term, should be forgone in favor

of relations derived assuming an extinction law *a priori*. The matter shall be elaborated upon in a separate study. Nevertheless, the distance derived here to the center of the Milky Way agrees with that inferred by geometric means ($R_0 \simeq 7.6\text{--}8.3$ kpc, Vanhollebeke *et al.* 2009, Table 1). Note, however, that geometric-based estimates of R_0 exhibit scatter and non-zero uncertainties, important details which are often overlooked including previously by this author (Majaess *et al.* 2009a).

2.4. Galactic Structure

One commonly proposed scenario has the Milky Way exhibiting a bar oriented at $\phi \simeq 25^\circ$ along the sun-Galactic center line. The reputed bar typically extends from $-10^\circ \leq \ell \leq 10^\circ$, being nearer to the Sun for positive ℓ . However, RR Lyr variables do not appear to delineate a prominent bar or triaxial bulge at $\phi \simeq 25^\circ$ (Fig. 2, 6). Incidentally, nor is extinction in the region of $5^\circ \leq \ell \leq 10^\circ$ anomalous, as otherwise expected if observing through a dense thick bar (Fig. 2, 6). A formal fit to the variable star sample binned in ℓ yields $\phi \simeq 77^\circ \pm 15^\circ$, which is also in agreement with an axisymmetric distribution (Fig. 6, top left). Alcock *et al.* (1998) and Kunder *et al.* (2008) likewise note that there is marginal evidence for a bar in the distribution of bulge RR Lyr variables. Readers are referred to their studies for a comprehensive discussion of the proposed rationale.

Nishiyama *et al.* (2005, 2006) infrared survey of red clump giants put forth detailed evidence that the Milky Way exhibits a distinct nuclear structure nested within a primary bar (Fig. 6, bottom left). Indeed, considering the inner region of the galaxy NGC 1672 as a template (Fig. 6, right), the Nishiyama *et al.* (2005, 2006) data may imply the presence of two minor pseudo spiral arms or spurs (note the dust lanes) that emanate from a nuclear structure and then reconnect to an underlying primary bar. The nested feature is oriented at an angle ($\phi_N \simeq 70^\circ$) consistent with the distribution of most RR Lyr variables (Fig. 6). RR Lyr variables may in part sample that region which is nearly axisymmetric while the pseudo minor spiral arms connect to a primary bar at $\phi_B \approx 30^\circ$. The angle ϕ as often cited in the literature may be a mischaracterization or average of two (or multiple) distinct features (Fig. 6, bottom left). There lacks consensus on defining how that parameter should be ascertained from the data (Fig. 6, bottom left – *e.g.*, a bulk mean, a mean from tip to tip, a mean for each structure ϕ_N and ϕ_B – preferred, etc). The observations of Nishiyama *et al.* (2005, 2006) are based on high resolution sampling: $8'$ intervals from $-10^\circ \geq \ell \geq 10^\circ$ at $b \simeq 1^\circ$. By contrast, the data in Fig. 6 (top left) consist of an admixture of RR Lyr variables at differing b (Fig. 1, 2). That complicates an interpretation of the RR Lyr distribution since a degeneracy emerges owing to a correlation between distance and Galactic latitude (b , Fig. 2). For example, the most distant and deviant point in Fig. 6 (top left) is inferred from high latitude bulge variable stars observed through low extinction ($b \simeq -5^\circ$, Fig. 2). Furthermore, Sumi (2004) remarked that the ratio of total to selective extinction may vary weakly as a function of galactic longitude, increasing from positive to negative ℓ .

The effect on distances becomes magnified granted the reddenings are inherently large toward the Galactic bulge and near the plane. Adopting a mean R_λ may tend to produce nearer distances for objects at positive ℓ relative to objects at negative ℓ . That follows the orientation of the proposed bar. Admittedly, if that bias is real it affects the results derived here for the distribution of bulge RR Lyr variables.

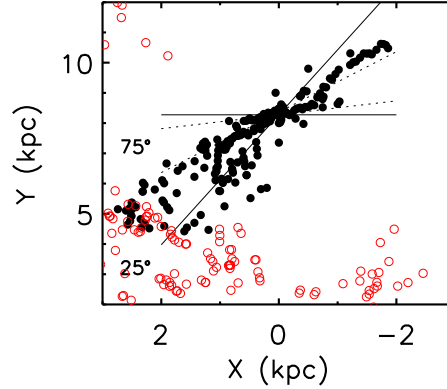


Fig. 7. A compilation of results from studies of red clump giants exhibits unsatisfactory scatter. At increasing distance from the Galactic center the red clump giants (black dots) may be sampling spiral features in the young disk. HII regions are symbolized by red open circles. The upcoming VVV survey shall bolster statistics in the under-sampled fourth quadrant (Minniti *et al.* 2010).

The red clump giant observations of Nishiyama *et al.* (2005, 2006) were adopted verbatim and yet the seminal nature of the implied result demands rigorous scrutiny. Indeed, the reader should know there are countless concerns, as with all distance candles. For example, a compilation of results for red clump giants observed toward the Galactic bulge exhibits unsatisfactory scatter (Fig. 7). The scatter at increasing distance from the Galactic center is exacerbated from sampling spiral features in the young disk (Fig. 7). A separate overview of the conclusions from various red clump giant studies is given in Section 2.2 and Table 1 of Vanhollebeke *et al.* (2009). The interpretation and evidence presented by Stanek *et al.* (1994), Rattenbury *et al.* (2007), and Cabrera-Lavers *et al.* (2008) should likewise be considered.

A face-on perspective of the Milky Way (Fig. 8) is now assembled from cataloged RR Lyr variables (Collinge *et al.* 2006), red clump giants (Nishiyama *et al.* 2005, 2006), classical Cepheids (*e.g.*, Szabados 1977, 1980, 1981, Berdnikov *et al.* 2000), young open clusters (Dias *et al.* 2002, Mermilliod and Paunzen 2003), HII regions and molecular clouds (Hou *et al.* 2009). Classical Cepheids, young open clusters, HII regions, and molecular clouds trace the Milky Way's younger spiral arms (Walraven *et al.* 1958, Bok 1959, Kraft and Schmidt 1963, Tammann 1970, Opolski 1988, Efremov 1997, Majaess *et al.* 2009a, 2009b). An over-density of HII regions and molecular clouds are observed near the interaction between the reputed bar and young disk [$X, Y \simeq 1.5, 4$ kpc] (Fig. 7). Interestingly, the Sagittarius-Carina

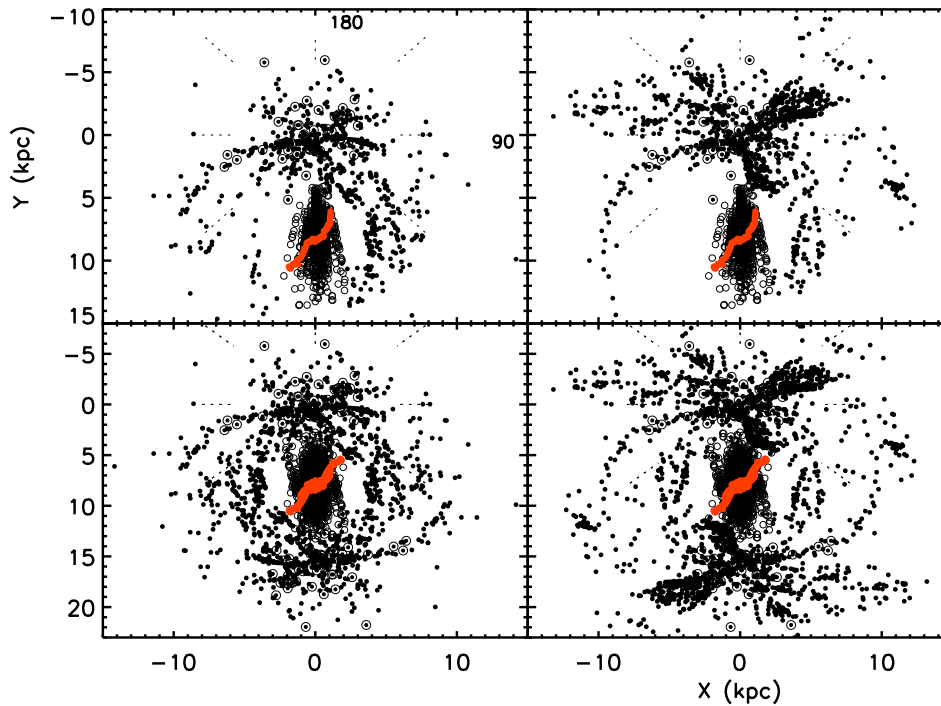


Fig. 8. Face-on view of the Milky Way as delineated by bulge RR Lyr variables and red clump giants (red), classical Cepheids, young open clusters, HII regions, and molecular clouds. *Left*, illustration without molecular clouds. *Right*, illustration without HII regions. *Bottom*, data flipped and mirrored to provide perspective.

arm may emanate from that region since it in part stems or branches from $\ell \leq 35^\circ$ rather than $\ell \simeq 50^\circ$ (Majaess *et al.* 2009a, 2009b, see also Fig. 5 in Russeil 2003). Superposed logarithmic spiral patterns ineptly characterize distinct features near the Sun, particularly segments of the putative Orion spur or Local and Sagittarius-Carina arms (Russeil 2003, Majaess *et al.* 2009a, 2009b, Hou *et al.* 2009). Added flexibility is needed to consider spurs, and spiral arms that merge, branch, twist unexpectedly, and exhibit a degree of flocculence. Such features are common amongst a sizeable fraction of the Universe's galaxies, while perfect grand-design spiral patterns are less prevalent (browse the Atlas of Galaxies or Galaxy Zoo Project, Sandage and Bedke 1988, Raddick *et al.* 2009). Indeed, the commonly espoused scenario of the Sun within a spur indicates that such features are likely not unique, and exist elsewhere throughout the Galaxy. More work is needed here, and a holistic approach that integrates RR Lyr and red clump giant populations into analyzes of the Galaxy's overall structure may facilitate an interpretation.

Complementing the edge-on illustration of the Milky Way displayed earlier (Fig. 1), 2MASS IR observations imply that the Milky Way exhibits a peanut

shaped bulge (Fig. 6, see also Weiland *et al.* 1994). That profile is argued by fellow researchers to indicate a bar seen edge-on (Chung and Bureau 2004, and references therein). Conversely, the morphology of the Galactic bulge appears somewhat spherical in optical images (Gaposkin 1960, Brunier and Tapissier 2009, Mellinger 2009). However, the bulge assumes a peanut-like geometry once anomalous extinction across the Aquila Rift is accounted for (Straižys *et al.* 2003, Majaess *et al.* 2009b, and references therein). Readers are encouraged to correlate CO markers tied to molecular complexes in Aquila and Lupus with the corresponding dark rifts in A. Mellinger’s photographic mosaic of the Galaxy (see Fig. 6 of Dame *et al.* 2001).

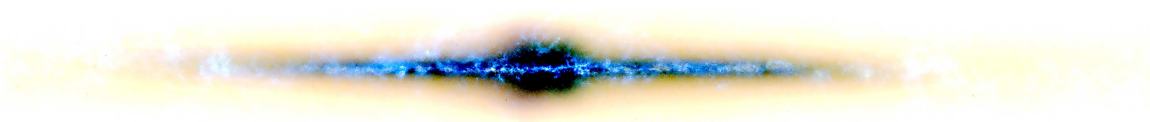


Fig. 9. A reprocessed cropped portion of the 2MASS mosaic of the Milky Way (Cutri *et al.* 2003). The Galactic bulge exhibits a peanut-like morphology.

3. Summary and Future Research

In this study, RR Lyr variables cataloged by Collinge, Sumi, and Fabrycky (2006) from the OGLE survey were used to determine the distance to the Galactic center, to map extinction throughout the sample, and to facilitate an interpretation of the Milky Way’s structure.

The implied distance to the center of the Galaxy is $R_0 = 8.1 \pm 0.6$ kpc. An accurate determination of R_0 is hindered by countless sources. It is insightful to examine a sample’s distribution in position, magnitude, and extinction space, to assess how the mean distance to a group of variable stars detected in the direction of the Galactic bulge relates to R_0 (Fig. 1, 2, 5). Extinction imposes a preferential sampling of stars toward the near side of the bulge. Consequently, a mean distance inferred from that restricted subsample shall promote smaller values of R_0 . The effect is particularly acute for RR Lyr variables near the Galactic plane ($b \simeq 0^\circ$, Fig. 2), where excessive extinction increases the magnitude threshold needed to adequately sample the bulge beyond the limit of the survey (Fig. 2, 5). Furthermore, the supposed presence of a Galactic bar may bias estimates of R_0 depending on which bulge region(s) are sampled. R_0 shall be systemically too large if inferred solely from bulge stars at negative ℓ that may outline the far side of the reputed Galactic bar (Fig. 6). Caution is warranted when ascertaining R_0 from groups of stars exhibiting poor statistics and sampling limited regions of the bulge. Additional concerns persist regarding an ambiguous extinction law for bulge stars (important, Gould *et al.* 2001, Udalski 2003, Ruffle *et al.* 2004, Sumi 2004, Kunder and Chaboyer 2008), an uncertainty in the LMC’s zero point which is implicitly

tied to the VI -based reddening-free distance relations employed here (Gibson 2000, Freedman *et al.* 2001, Benedict *et al.* 2002, Tammann *et al.* 2003), an ongoing debate surrounding the contested effects of metallicity for Cepheid and RR Lyr variables (Udalski *et al.* 2001, Freedman *et al.* 2001, Feast 2003, Smith 2004, Motini *et al.* 2004, Pietrzyński *et al.* 2004, Romaniello *et al.* 2005, Sollima *et al.* 2006, Macri *et al.* 2006, Bono *et al.* 2008, Scowcroft *et al.* 2009, Romaniello *et al.* 2008, Majaess *et al.* 2008a, Catelan 2009, Majaess *et al.* 2009a, 2009c, Majaess 2009d), the effects of photometric contamination (*e.g.*, blending and crowding) on distances computed to variable stars (Stanek and Udalski 1999, Mochejska *et al.* 2000, 2001, 2002, Macri 2001, Freedman *et al.* 2001, Vilardell *et al.* 2007, Smith *et al.* 2007, Majaess *et al.* 2009c), and floating photometric zero points owing to the difficulties in achieving standardization, particularly across a range in color (*e.g.*, Turner 1990, Stetson *et al.* 2004, Saha *et al.* 2006, Jonek *et al.* 2008). The author suggests the evidence indicates that VI -based RR Lyr and Cepheid distance and period–color relations are relatively insensitive to metallicity, and thus by consequence, that the distance offset observed between metal-rich and metal-poor classical Cepheids occupying the inner and less crowded outer regions of remote galaxies arises primarily from other source(s) (Majaess *et al.* 2009c, Majaess 2009d, see also Udalski *et al.* 2001, Pietrzyński *et al.* 2004, Bono *et al.* 2008). Readers are encouraged to also consider the dissenting views and varied interpretations presented in the works cited earlier. Firm constraints on the effects of metallicity, and hence crowding and blending, may arise from a direct comparison of RR Lyr variables, type II Cepheids, and classical Cepheids at a common and comparatively nearby zero point (*e.g.*, SMC, IC 1613).

The sample of RR Lyr variables do not trace the signatures of a prominent bar or triaxial bulge oriented at $\phi \simeq 25^\circ$ (Fig. 2, 6), as noted previously (Alcock *et al.* 1998, and references therein). The stars exhibit a more axisymmetric distribution and may outline, in part, a nuclear structure (Fig. 6). A confident interpretation is complicated by the admixture of RR Lyr variables at varying galactic positions. By contrast, younger red clump giants may delineate a nearly axisymmetric nuclear structure ($\phi_N \simeq 70^\circ$, Fig. 6) nested within a primary Galactic bar ($\phi_B \approx 30^\circ$). Yet there are pertinent concerns with the aforementioned interpretation, and that found in the literature (Section 2.4, Fig. 6 and 7). First, a compilation of results from several studies on red clump giants exhibits considerable scatter (Fig. 7). The scatter at increasing distance from the center of the Milky Way arises partly from sampling spiral features in the young disk (Fig. 7). Third, ϕ as currently cited in the literature may be a mischaracterization or average of two (or multiple) distinct features (*e.g.*, ϕ_N and ϕ_B , Fig. 6). The structure of the Galaxy’s inner region may be too complex to be ascribed a single linear term or angle ϕ (Fig. 6). Lastly, curiously, extinction in the region of $5^\circ \leq \ell \leq 10^\circ$ as inferred from RR Lyr variables is not anomalous, as otherwise expected if observing through a dense thick bar delineated by red clump giants (Fig. 2, 6).

Edge-on and face-on illustrations of the Milky Way are constructed by mapping the OGLE RR Lyr variable sample in tandem with cataloged red clump giants, planetary nebulae, globular clusters, classical Cepheids, young open clusters, HII regions, and molecular clouds (Fig. 1, 8). An abundance of HII regions and molecular clouds are observed near the boundary between the reputed Galactic bar and young disk [$X, Y \simeq 1.5, 4$ kpc] (Fig. 8). Moreover, the Sagittarius-Carina spiral arm may in part originally stem or branch from near that region (Fig. 8).

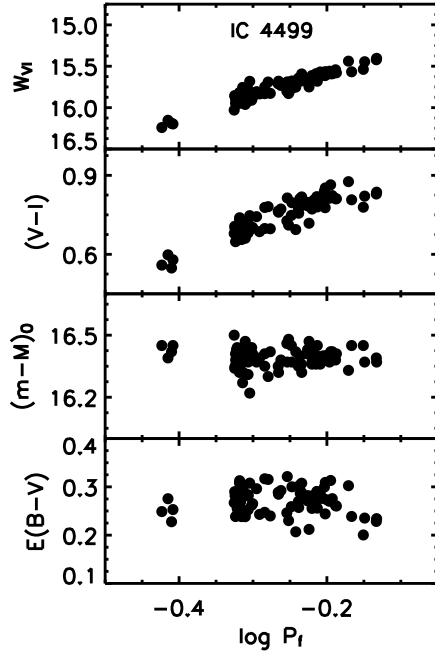


Fig. 10. RR Lyr variables follow VI period–color and Wesenheit period–magnitude–color relations (e.g., $RRe \rightarrow RRab$ variables in the globular cluster IC 4499, photometry from Walker and Nemeč 1996). The cluster’s distance and mean color-excess are $(m - M)_0 = 16.40 \pm 0.04$ mag (sd) and $E_{B-V} = 0.27 \pm 0.03$ mag (sd). Note the minimal internal scatter.

A VI -based RR Lyr period–reddening relation derived here reaffirms that extinction throughout the bulge is highly inhomogeneous, varying from $E_{B-V} \simeq 0.4 \rightarrow 3.4$ mag (Eq. 1 and Fig. 2). RR Lyr variables, red clump giants, and classical Cepheids provide consistent reddenings for the Galactic bulge, LMC, SMC, and IC 1613 (Table 1). The VI RR Lyr color excess relation appears relatively insensitive to metallicity and may be further refined by obtaining multi-band photometry for variable stars in globular clusters (e.g., Sawyer 1939, Demers and Wehlau 1977, Layden *et al.* 1999, Celment *et al.* 2001, Pritzl *et al.* 2003, Horne 2005, Benkő *et al.* 2006, Samus *et al.* 2009). A sizeable portion of the observing program at the Abbey Ridge Observatory (Majaess *et al.* 2008b, Turner *et al.* 2009c) shall be dedicated to such an endeavor. Modest telescopes may serve a pertinent role in such

research (Percy 1980, 1986, Szabados 2003, Paczyński 2006, Genet *et al.* 2009, Turner *et al.* 2009a).

RR Lyr variables follow VI period–color and scatter reduced Wesenheit period–magnitude–color relations as demonstrated here and elsewhere (Kovacs and Jurcsik 1997, Kovacs and Walker 2001, Soszyński *et al.* 2003, Di Criscienzo, Marconi, and Caputo 2004, Benkő Bakos, and Nuspl 2006, Di Criscienzo *et al.* 2007, Soszyński *et al.* 2009, Majaess 2009d). A pertinent example is the RR Lyr demographic in the globular cluster IC 4499 (Fig. 10, photometry from Walker and Nemeč 1996). The Wesenheit function may be inferred without *a priori* knowledge of the color excess, and the distances ensue. Indeed, the Wesenheit function shall be readily employed upon the release of data from the upcoming Gaia survey since the relation may be calibrated directly *via* parallax and apparent magnitudes, mitigating the propagation of uncertainties tied to extinction corrections (Gaia: Bono 2003a, Eyer 2006, Eyer *et al.* 2009). In the interim, however, further work is needed to scrutinize the Wesenheit approach to investigating RR Lyr variables, and to shift from a broad outlook to assessing finer details (*e.g.*, is the relation marginally non-linear, particularly toward the RRe regime, etc). Applying a strict $[Fe/H]–M_v$ correlation to infer the distance to individual RR Lyr variables with differing periods may yield inaccurate results. The $[Fe/H]–M_v$ relation displays considerable spread at a given metallicity (Fig. 1, Pritzl *et al.* 2000). Abundance estimates often exhibit sizeable random and systemic uncertainties, in contrast to individual pulsation periods. Moreover, the correlation is neither linear or universal (*e.g.*, NGC 6441 and NGC 6388, Pritzl *et al.* 2000, Bono 2003b, Catelan 2009). Applying a strict $[Fe/H]–M_v$ relation to RR Lyr variables with differing periods at a common zero point may yield an acceptable mean distance pending a series of ideal circumstances, including where the overestimated distances for shorter period variable stars perfectly balance the underestimated distances of longer period variable stars (*e.g.*, Majaess *et al.* 2009c, although remedied in Majaess 2009d *via* a reddening-free period–magnitude–color treatment). Admittedly, the aforementioned relation is invaluable in assessing the abundance of a target population to first order, etc. Yet there are also innumerable advantages to employing Wesenheit and period–magnitude relations to characterize RR Lyr variables (see also Bono 2003b, Dall’Ora *et al.* 2004, 2006, 2008, Catelan 2009).

Lastly, geometric-based distances to the Galactic center (Eisenhauer *et al.* 2005, Reid *et al.* 2009), nearby variable stars (Benedict *et al.* 2002, 2007, van Leeuwen 2007), open clusters (*e.g.*, Turner and Burke 2002, Soderblom *et al.* 2005, van Leeuwen 2009), globular clusters (*e.g.*, ω Cen, van de Ven *et al.* 2006), and the galaxies M33 and M106 (Argon *et al.* 1998, Brunthaler *et al.* 2005, Herrnstein *et al.* 2005): appear to in sum bolster and consolidate the scale established by Cepheids and RR Lyr variables (Macri *et al.* 2006, Sarajedini *et al.* 2006, Majaess *et al.* 2008a, Feast *et al.* 2008, Feast 2008, Groenewegen *et al.* 2008, Scowcroft *et al.* 2009, Majaess *et al.* 2009a, 2009c, Majaess 2009d, Turner 2010). Yet a signif-

icant challenge remains to identify and then mitigate the uncertainties beyond the 7–10% threshold, beyond first order.

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