

# 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 Lyrae 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 Lyrae variables is derived to map extinction throughout the bulge. The reddening inferred from RR Lyrae variables in the Galactic bulge, LMC, SMC, and IC 1613 match that established from OGLE red clump giants and classical Cepheids. RR Lyrae variables obey a period-colour ( $VI$ ) relation that is relatively insensitive to metallicity. Edge-on and face-on illustrations of the Milky Way are constructed by mapping the bulge RR Lyrae 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 Lyrae variables do not trace a prominent Galactic bar or triaxial bulge oriented at  $\phi \simeq 25^\circ$ .

*Subject headings:*

## 1. Introduction

Recent estimates of the distance to the center of Milky Way range from  $R_0 \simeq 7 - 9$  kpc (Groenewegen & Blommaert 2005; Bica et al. 2006; Feast et al. 2008; Groenewegen et al. 2008; Vanhollebeke et al. 2009; Majaess et al. 2009; 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 Lyrae 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 & Distribution

The sample of RR Lyrae variables used here is that compiled by Collinge, Sumi, & 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.

It is instructive to begin by examining the distribution of RR Lyrae variables in position, magnitude, extinction, and distance space. The loca-

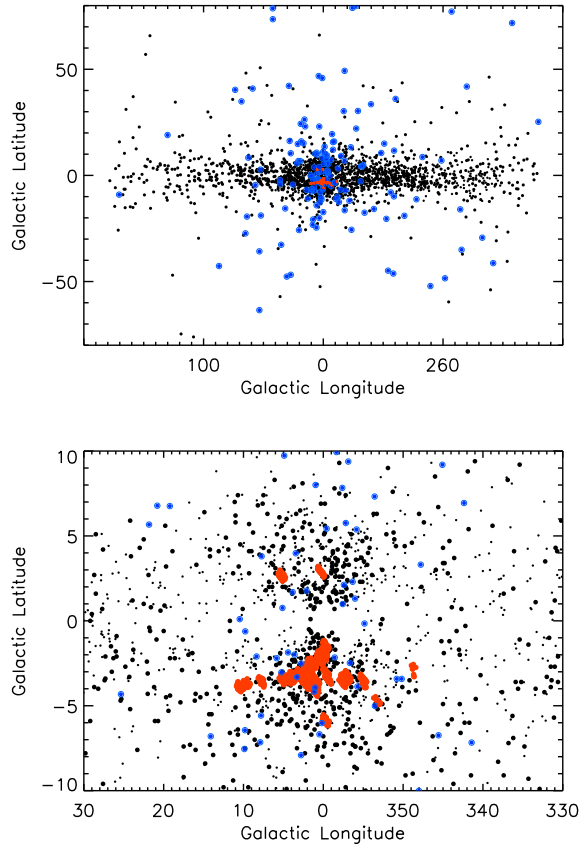


Fig. 1.— Edge-on view of the Milky Way as delineated by OGLE bulge RR Lyrae variables (red dots), planetary nebulae (black dots), and globular clusters (blue dots) in Galactic coordinate space.

tions 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 & 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 Lyrae 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, right).

The distribution of the sample’s mean magnitude as a function of Galactic position indi-

cates 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  $b \simeq -1^\circ$ .

## 2.2. Extinction

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

$$E_{B-V} \simeq \alpha \log P + \beta(m_{\lambda 1} - m_{\lambda 2}) + \phi$$

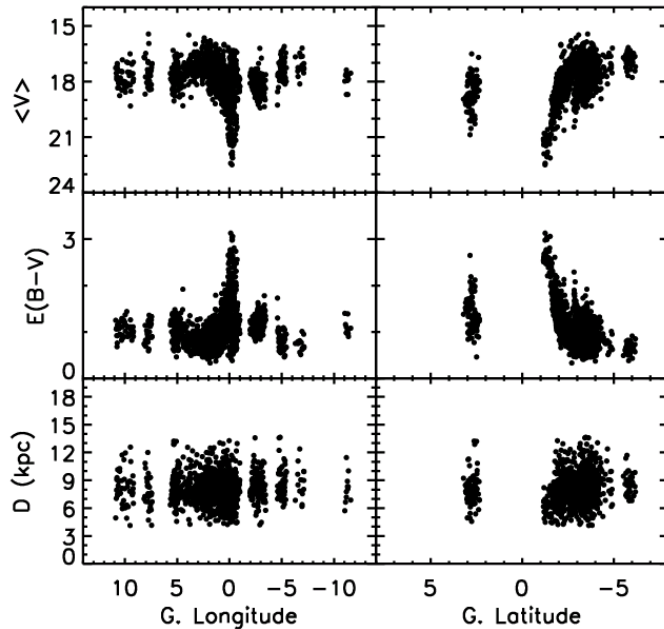


Fig. 2.— The mean visual magnitude, colour-excess, and distance associated with the RR Lyrae variables as a function of Galactic longitude and latitude.

where  $\alpha$ ,  $\beta$ , and  $\phi$  are coefficients that can be derived by minimizing the  $\chi^2$  statistic for a calibrating data set, and  $m_{\lambda 1}$  and  $m_{\lambda 2}$  are mean photometric magnitudes in different passbands. The calibrators are RR Lyrae variables in the globular clusters M3 (Hartman et al. 2005), M54 (Layden & 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  $\pm 0.03$  magnitude. The true scatter applying to use of the relationship for individual RR Lyrae 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 & Caldwell 2007; Turner 2010). RR Lyrae 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 & Nemeč 1996; Soszynski et al. 2003; Gruberbauer et al.

2007; Hurdis 2009). Alternatively, M3 offers a unique opportunity to infer the intrinsic  $VI$  colours of RR Lyrae variables directly since foreground extinction along the globular cluster’s line of sight is negligible (McClure & Racine 1969). Thus a formal fit to  $VI$  photometry of RR Lyrae 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 colour-excess is in satisfactory agreement with that inferred by Sumi (2004) from adjacent OGLE red clump giants (Fig. 4).

The robustness of equation 1 may be further evaluated. Drawing upon photometry for RR

TABLE 1  
MEAN REDDENINGS FOR THE GALAXIES ( $E_{B-V}$ )

Object	Classical Cepheids	RR Lyrae Var.	Red Clump Giants (Udalski et al. 1999)	Zaritsky et al. 2004 (Ngeow et al. 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)

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

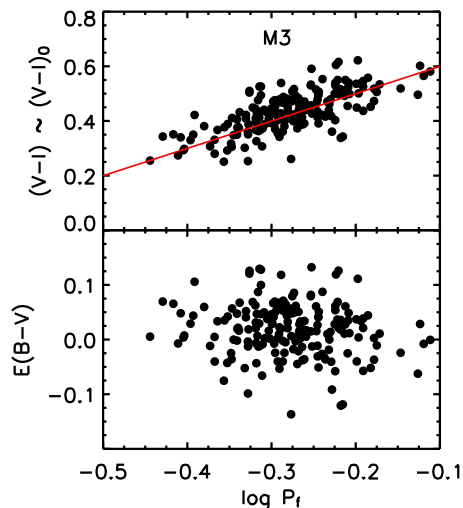


Fig. 3.— Top,  $VI$  colours for RR Lyrae variables in M3 exhibit a period dependence (photometry from Benkő, Bakos, & Nuspl 2006). The overplotted relation is Eqn. 1 (red line) or  $(V - I) \simeq (V - I)_0 \simeq 0.7 + \log P_f$ . Bottom, the computed colour-excess using Eqn. 1.

Lyrae variables in the LMC (Udalski et al. 1998; Soszynski et al. 2003, 2009), SMC (Udalski et al. 1998; Soszynski et al. 2002), and IC 1613 (Dolphin 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 Lyrae variables adhere to a period-colour ( $VI$ ) relation which is relatively insensitive to metallicity. Perhaps an expected result granted the slope of near infrared RR Lyrae variable and Cepheid

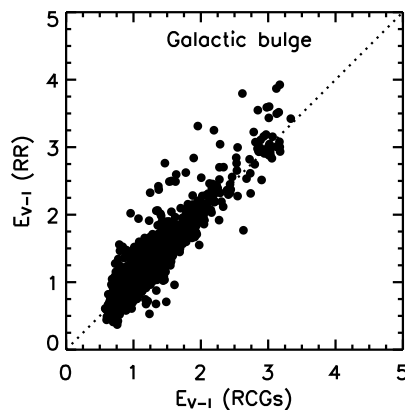


Fig. 4.— The colour-excess inferred from bulge RR Lyrae variables (Eqn. 1) match estimates compiled by Sumi (2004) for adjacent red clump giants.

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. 2008, 2009,c; Majaess 2009d). By contrast, readers should exhibit caution when employing  $BV$  relations for Cepheid and RR Lyrae variables of differing abundance (Caldwell & Coulson 1985; Madore & Freedman 1991; Chiosi et al. 1993; Tammann et al. 2003; Di Criscienzo et al. 2007; Majaess et al. 2008, 2009c). The computed colour-excess of the brightest member of the variable class, RR Lyrae, is  $E_{B-V} \simeq 0.01$ . That agrees with both a value cited by Feast et al. (2008) and a field reddening in-

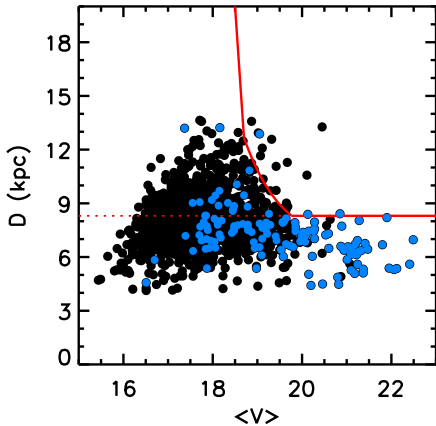


Fig. 5.— OGLE RR Lyrae variables nearest to the Galactic plane ( $b \simeq -1.5^\circ$ ) and fainter than  $V \simeq 19$  are not sampled beyond  $d \simeq 8$  kpc (blue dots).

ferred from 2MASS photometry using methods tested elsewhere (Bonatto et al. 2004, 2006; Majaess et al. 2007, 2008; Bonatto & Bica 2009; Turner et al. 2009b,d; Turner 2010). The implied absolute magnitude for RR Lyrae is  $M_V \simeq 0.55$ , assuming  $E_{B-V} \simeq 0.01$  (eqn. 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 Lyrae was utilized (Droege et al. 2006), although concerns persist regarding the survey’s photometric zeropoint and the star’s modulating amplitude. An ephemeris to phase the  $V$  &  $I$  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 Lyrae variables (Eqn. 2, Majaess et al. 2009). Relying exclusively on the photometric surveys of fellow researchers, Majaess (2009d) reaffirmed that to *first order* SX Phe, RR Lyrae variables, and Type II Cepheids may adhere to a common  $VI$  period-magnitude-colour 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

ing variables 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 Lyrae variables may exhibit a steeper Wesenheit function than Type II Cepheids. However, distances inferred from Eqn. 2 of Majaess et al. (2009) are, however, 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 Lyrae variables are generally consistent with the predictions of Marconi, Di Criscienzo, & 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 & Jurcsik (1997); Kovács & Walker (2001), Di Criscienzo, Marconi, & Caputo (2004), Madore & Freedman (1991, 2009), and Turner (2010) for a broader discussion regarding RR Lyrae and Cepheid Wesenheit relations. The calibrators of the Majaess et al. (2009)  $VI$  distance relation were OGLE LMC Type II Cepheids (Udalski et al. 1999; Soszynski et al. 2008), with an adopted zeropoint to the LMC established from classical Cepheids and other means ( $(m - M)_0 \sim 18.50$ , Laney & Stobie 1994; Gibson 2000; Freedman et al. 2001; Benedict et al. 2002; Majaess et al. 2008; Majaess 2009d). The classical Cepheid zeropoint 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. (2008). That relation is tied to a restricted subsample of Galactic cluster Cepheids (e.g., Turner & Burke 2002) and Cepheids with new HST parallaxes (Benedict et al. 2007).

The mean distance to the sample of RR Lyrae variables observed in the direction of the bulge is  $8.1 \pm 0.6$  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 Lyrae 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 Lyrae 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 Lyrae variables fainter than  $V \simeq 19$  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. (2009) 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).

Establishing the distance to the Galactic center from either bulge Type II Cepheids (Kubiak & Udalski 2003; Majaess et al. 2009) or RR Lyrae 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 & Chaboyer 2008). The Majaess et al. (2009) 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. (2008, 2009) to obtain the coefficients of the Cepheid (Type I & II) distance relations, which includes an estimate for the pseudo extinction law term, should be forgone in favour 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 ( $R_0 \simeq 7.6 - 8.3$  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 the author (Majaess et al. 2009).

## 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  $-10 \leq \ell \leq 10^\circ$ , being nearer to

the Sun for positive  $\ell$ . However, RR Lyrae 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  $5 \leq \ell \leq 10^\circ$  anomalous, as otherwise expected if observing through a dense thick bar (Fig. 2, 6). A formal fit to the variable star sample binned in  $\ell$  yields  $\phi \simeq 77 \pm 15^\circ$ , which is also in agreement with an axisymmetric distribution (Fig. 6, top). 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 Lyrae 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, middle). Indeed, considering the inner region of the galaxy NGC 1672 as a template (Fig. 6, bottom), the Nishiyama et al. 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 Lyrae variables (Fig. 6). RR Lyrae variables may in part sample that region which is nearly axisymmetric. While the pseudo minor spiral arms connect to a primary bar at  $\phi_B \sim 30^\circ$ . The angle  $\phi$  as often cited in the literature may be a mischaracterization or average of two (or multiple) distinct features (Fig. 6, middle). There lacks consensus on defining how that parameter should be ascertained from the data (Fig. 6, middle — e.g., a bulk mean, a mean from tip to tip, a mean for each structure  $\phi_N$  &  $\phi_B$  (preferred), etc.). The observations of Nishiyama et al. are based on high resolution sampling:  $8'$  intervals from  $-10 \geq \ell \geq 10^\circ$  at  $b \simeq 1^\circ$ . By contrast, the data in Fig. 6 (top) consist of an admixture of RR Lyrae variables at differing  $b$  (Fig. 1, 2). That complicates an interpretation of the RR Lyrae 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) is inferred from high latitude bulge variables observed through low extinction ( $b \simeq -5^\circ$ , Fig. 2). Furthermore, Sumi (2004) remarked that the ratio of total to selec-

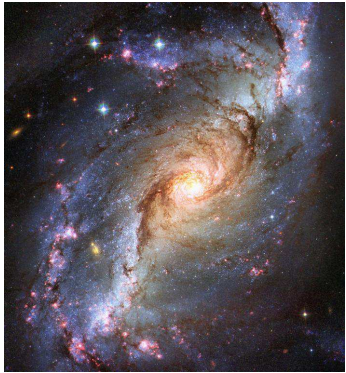
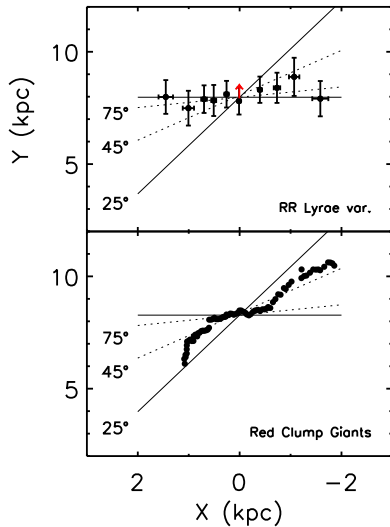


Fig. 6.— Top, an orientation of  $\phi \simeq 25^\circ$  (sun-gal line) is not indicative of RR Lyrae variables detected in the direction of the bulge. Middle, red clump giants may trace a nested nuclear structure within a primary bar (data from Nishiyama et al. 2005, 2006). Bottom, a reprocessed cropped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

tive extinction may vary weakly as a function of galactic longitude, increasing from positive to negative  $\ell$ . The effect on distances becomes magnified granted the reddenings are inherently large toward the Galactic bulge and near the plane. Adopting a mean  $R_\lambda$  may tend to produce nearer distances for objects at positive  $\ell$  relative to objects at negative  $\ell$ . 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

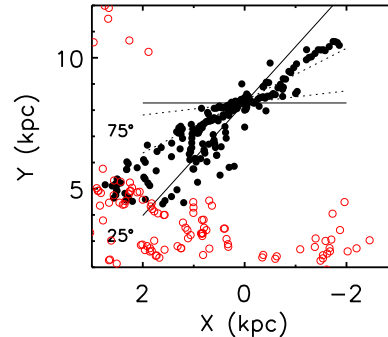


Fig. 7.— A compilation of results from studies of red clump giants exhibits unsatisfactory scatter. At increasing distance from the Galactic center the red clump giants (black dots) may be sampling spiral features in the young disk. HII region are symbolized by red open circles. The upcoming VVV survey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

RR Lyrae variables.

The red clump giant observations of Nishiyama et al. 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 §2.2 & 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 Lyrae 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 & Paunzen 2003), HII regions & molecular clouds (Hou et al. 2009). Classical Cepheids, young open clusters, HII regions, and molecular clouds trace the Milky Way's younger spiral arms

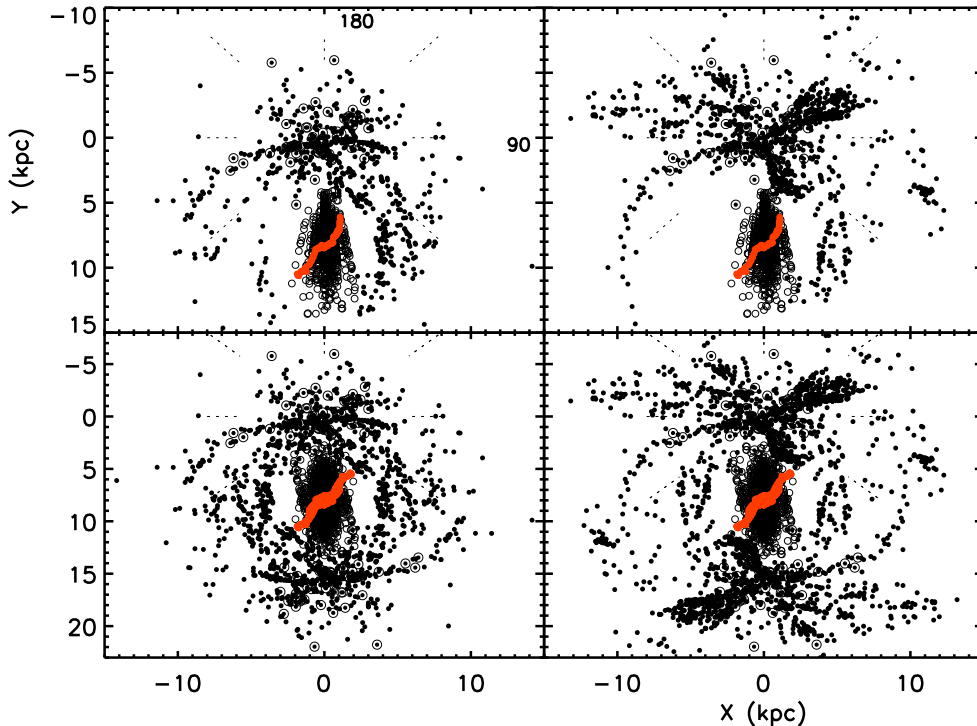


Fig. 8.— Face-on view of the Milky Way as delineated by bulge RR Lyrae variables and red clump giants (red), classical Cepheids, young open clusters, HII regions, and molecular clouds. Left, illustration without molecular clouds. Right, illustration without HII regions. *Bottom, data flipped and mirrored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

(Walraven et al. 1958; Bok 1959; Kraft & Schmidt 1963; Tammann 1970; Opolski 1988; Efremov 1997; Majaess et al. 2009,b). An overdensity of HII regions and molecular clouds is observed near the interaction between the reputed bar and young disk [ $X, Y \simeq 1.5, 4$  kpc] (Fig. 8). Interestingly, the Sagittarius-Carina 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. 2009,b, 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. 2009,b; 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 fea-

tures 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 & 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 Lyrae variable and red clump giant populations into analyses 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. 9, see also Weiland et al. 1994). That profile is argued



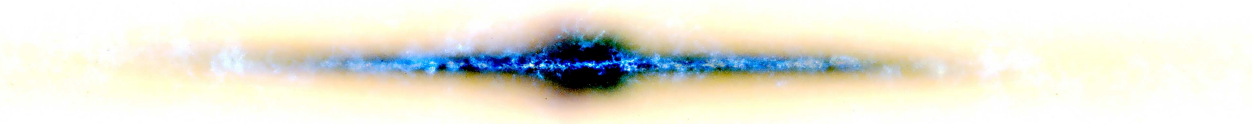


Fig. 9.— A reprocessed cropped portion of the 2MASS mosaic of the Milky Way (Cutri et al. 2003). The Galactic bulge exhibits a peanut-like morphology.

by fellow researchers to indicate a bar seen edge-on (Chung & Bureau 2004, and references therein). Conversely, the morphology of the Galactic bulge appears somewhat spherical in optical images (Gaposckin 1960; Brunier & Tapissier 2009; Mellinger 2009). However, the bulge assumes a peanut-like geometry once anomalous extinction across the Aquila Rift is accounted for (Straizys 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).

### 3. Summary & Future Research

In this study, RR Lyrae variables cataloged by Collinge, Sumi, & 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 Lyrae 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  $\ell$  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 & Chaboyer 2008), an uncertainty in the LMC’s zeropoint 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 Lyrae variables (Udalski et al. 2001; Freedman et al. 2001; Feast 2003; Smith 2004; Mottini 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. 2008; Catelan 2009; Majaess et al. 2009,c; Majaess 2009d), the effects of photometric contamination (e.g., blending & crowding) on distances computed to variable stars (Stanek & 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 zeropoints owing to the difficulties in achieving standardization, particularly across a range in colour (e.g., Turner 1990; Stetson et al. 2004; Saha et al. 2006; Joner et al. 2008). The author suggests the evidence indicates that  $VI$ -based RR Lyrae and Cepheid distance and period-colour 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 Lyrae variables, Type II Cepheids, and classical Cepheids at a common and comparatively nearby zeropoint (e.g., SMC, IC 1613).

The sample of RR Lyrae 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 Lyrae 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 ( $\phi_B \sim 30^\circ$ ). Yet there are pertinent concerns with the aforementioned interpretation, and that found in the literature (§2.4, Fig. 6 & 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,  $\phi$  as currently cited in the literature may be a mischaracterization or average of two (or multiple) distinct features (e.g.,  $\phi_N$  &  $\phi_B$ , Fig. 6). The structure of the Galaxy’s inner region may be too complex to be ascribed a single linear term or angle  $\phi$  (Fig. 6). Lastly, curiously, extinction in the region of  $5 \leq \ell \leq 10^\circ$  as inferred from RR Lyrae 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 Lyrae 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

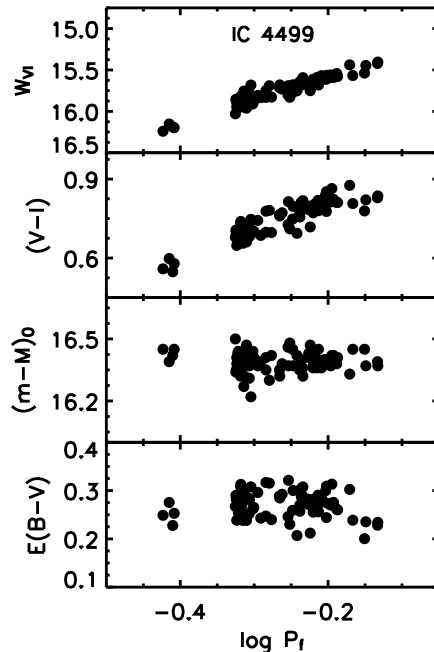


Fig. 10.— RR Lyrae variables follow  $VI$  period-colour and Wesenheit period-magnitude-colour relations (e.g.,  $RRe \rightarrow RRab$  variables in the globular cluster IC 4499, photometry from Walker & Nemec 1996). The cluster’s distance and mean colour-excess are  $(m - M)_0 = 16.40 \pm 0.04$  (sd)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

spiral arm may in part originally stem or branch from near that region (Fig. 8).

A  $VI$ -based RR Lyrae period-reddening relation derived here reaffirms that extinction throughout the bulge is highly inhomogeneous, varying from  $E_{B-V} \simeq 0.4 \rightarrow 3.4$  (Eqn. 1 & Fig. 2). RR Lyrae variables, red clump giants, and classical Cepheids provide consistent reddenings for the Galactic bulge, LMC, SMC, and IC 1613 (Table 1). The  $VI$ -based RR Lyrae colour-excess relation appears relatively insensitive to metallicity and may be further refined by obtaining multiband photometry for variables in globular clusters (e.g., Sawyer 1939; Demers & Wehlau 1977; Layden et al. 1999; Clement et al. 2001; Pritzl et al. 2003; Horne 2005; Benkó et al. 2006; Samus et al. 2009). A sizeable portion of the observing program at the Abbey Ridge Observatory (Lane 2007; Majaess et al. 2008b; Turner et al.

2009a) shall be dedicated to such an endeavour. 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 Lyrae variables follow  $VI$  period-colour and scatter-reduced Wesenheit period-magnitude-colour relations as demonstrated here and elsewhere (Kovacs & Jurcsik 1997; Kovács & Walker 2001; Soszynski et al. 2003; Di Criscienzo, Marconi, & Caputo 2004; Benkó, Bakos, & Nuspl 2006; Di Criscienzo et al. 2007; Soszynski et al. 2009; Majaess 2009d). A pertinent example is the RR Lyrae demographic in the globular cluster IC 4499 (Fig. 10, photometry from Walker & Nemec 1996). The Wesenheit function may be inferred without *a priori* knowledge of the colour-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 Lyrae 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  $[\text{Fe}/\text{H}]-M_v$  correlation to infer the distance to individual RR Lyrae variables with differing periods may yield inaccurate results. The  $[\text{Fe}/\text{H}]-M_v$  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 & NGC 6388 Pritzl et al. 2000; Bono 2003b; Catelan 2009). Applying a strict  $[\text{Fe}/\text{H}]-M_v$  relation to RR Lyrae variables with differing periods at a common zeropoint may yield an acceptable mean distance pending a series of ideal circumstances, including where the over-estimated distances for shorter-period variables perfectly balance the underestimated distances of longer period variables (e.g., Majaess et al. 2009c, although remedied in Majaess 2009d via a reddening-free period-magnitude-colour 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 Lyrae 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 variables (Benedict et al. 2002, 2007; van Leeuwen et al. 2007), open clusters (e.g., Turner & Burke 2002; Soderblom et al. 2005; van Leeuwen 2009), globular clusters (e.g.,  $\omega$  Cen, van de Ven et al. 2006), and the galaxies M33 & 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 Lyrae variables (Macri et al. 2006; Sarajedini et al. 2006; Majaess et al. 2008; Feast et al. 2008; Feast 2008; Groenewegen et al. 2008; Scowcroft et al. 2009; Majaess et al. 2009,c; Majaess 2009d; Turner 2010). Yet a significant challenge remains to identify and then mitigate the uncertainties beyond the 7 – 10% threshold, beyond first order.

## acknowledgements

I am grateful to fellow researchers M. Collinge, T. Sumi, S. Nishiyama, L. Hou, J. Benkó, A. Walker, J. Nemec, F. Benedict, G. Kopacki, B. Pritzl, A. Layden, A. Dolphin, A. Sarajedini, J. Hartman, I. Soszyński & the OGLE team, whose comprehensive surveys were the foundation of the study, to the AAVSO (M. Saladyga & A. Henden), CDS, arXiv, NASA ADS, 2MASS, Hubble Heritage, and the RASC. The following works facilitated the preparation of the research: Elmegreen (1985), Alcock et al. (1998), Bono (2003b), Smith (2004), Di Criscienzo et al. (2004), Feast (2008), Cabrera-Lavers et al. (2008), and Marconi (2009).

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