CLUSTERING OF LOCAL GROUP DISTANCES: PUBLICATION BIAS OR CORRELATED MEASUREMENTS?

IV. THE GALACTIC CENTER

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ABSTRACT

Aiming at deriving a statistically well-justified Galactic Center distance, $R_0$, and reducing any occurrence of publication bias, we compiled the most comprehensive and most complete database of Galactic Center distances available to date, containing 273 new or revised $R_0$ estimates published since records began in 1918 October until 2016 June. We separate our $R_0$ compilation into direct and indirect distance measurements. The latter include a large body of estimates that rely on centroid determinations for a range of tracer populations, as well as measurements based on kinematic observations of objects at the solar circle, combined with a mass and/or rotational model of the Milky Way. Careful assessment of the Galactic Center distances resulting from orbital modeling and statistical parallax measurements in the Galactic nucleus yields our final Galactic Center distance recommendation of $R_0 = 8.3 \pm 0.2$ (statistical) $\pm 0.4$ (systematic) kpc. The centroid-based distances are in good agreement with this recommendation. Neither the direct measurements nor the post-1990 centroid-based distance determinations suggest that publication bias may be important. The kinematics-based distance estimates are affected by significantly larger uncertainties, but they can be used to constrain the Galaxy’s rotation velocity at the solar galactocentric distance, $\Theta_0$. Our results imply that the International-Astronomical-Union-recommended Galactic Center distance ($R_0^{\text{IAU}} = 8.5$ kpc) needs a downward adjustment, while its $\Theta_0$ recommendation ($\Theta_0 = 220$ km s$^{-1}$) requires a substantial upward revision.

Key words: astronomical databases: miscellaneous – distance scale – Galaxy: center – Galaxy: fundamental parameters

1. THE DISTANCE TO THE GALACTIC CENTER

The distance from the Sun to the Galactic Center, $R_0$, provides the basic calibration for a wide range of methods used for distance determination, on both Galactic and extragalactic scales. Calculations of many physical parameters, including the distances, masses, and luminosities of Galactic objects, as well as the Galaxy’s integrated mass and luminosity, depend directly on $R_0$. In fact, most luminosity and a large number of mass estimators scale as distance squared, while masses based on total densities or orbital modeling scale as distance cubed.

This dependence could involve adoption of a Galactic mass and/or rotation model, in which case we also need to know the Sun’s circular velocity accurately. As $R_0$ estimates are refined, so are the estimated distances, masses, and luminosities of numerous Galactic and extragalactic objects, as well as our best estimates of the rate of Galactic rotation and the size of the Milky Way. In addition, a highly accurate direct Galactic Center distance determination would immediately allow reliable recalibration of the zero points of numerous secondary distance calibrators, including Cepheids, RR Lyrae, and Mira variable stars, which would consequently reinforce the validity of the extragalactic distance scale (e.g., Olling 2007). In turn, this would enable better estimates of globular cluster ages, the Hubble constant, and a lower limit to the age of the universe (Monelli et al. 2015), and place tighter constraints on a range of cosmological scenarios (e.g., Reid et al. 2009).

It is no surprise, therefore, that determinations of the Galactic Center distance have been the subject of many studies ever since the first attempt by Harlow Shapley in 1914–1918.

However, the importance of determining an accurate $R_0$ value, combined with the large number of studies undertaken to achieve this goal, has led to speculations that some degree of publication bias (also known as “observation bias” or a “bandwagon effect”) may have affected subsequent Galactic Center distance determinations (e.g., Reid 1989, 1993; Niki-forov 2004; Foster & Cooper 2010; Malkin 2013a, 2013b; Francis & Anderson 2014).

In de Grijs et al. (2014, hereafter Paper I), de Grijs & Bono (2014, hereafter Paper II), and de Grijs & Bono (2015, hereafter Paper III), we embarked on large-scale data mining of the NASA/Astrophysics Data System (ADS) to explore whether distance determinations to the Large Magellanic Cloud (LMC), the M31 group, and the Small Magellanic Cloud, respectively, had been polluted by such bandwagon effects. In this paper, we extend our series of papers by adding a similar analysis of distance estimates to the Galactic Center. Our ultimate aim is to provide a self-consistent distance framework that can serve as a benchmark for the structure of the Local Group of galaxies (see, e.g., Table 4 in Paper II, combined with the recommended distance to the Small Magellanic Cloud from Paper III).

To achieve our aim, in Section 2 we discuss our approach to mining the NASA/ADS database, eventually resulting in the most complete and most comprehensive database of Galactic Center distances published, starting from Shapley’s (1918) distance estimate, published in 1918 October, until early 2016 June. In Section 3, we review three different types of Galactic Center distance indicators, including direct distance measurements and centroid- and kinematics-based Galactic Center...
distance determinations. This is followed in Section 4 by a detailed discussion of the validity of and the uncertainties affecting the “best” measurements, which we also place in the context of the most recent progress in the field. Finally, Section 5 summarizes and concludes the paper.

2. DATA MINING

The distance to the Galactic Center has long been a subject of intense scrutiny. Since the mid-1970s, it has become standard practice in meta-analyses of the Galactic Center distance to publish compilations of previously published values (e.g., Harris 1976; de Vaucouleurs 1983; Kerr & Lynden-Bell 1986; Reid 1993; Nikiforov 2004; Perryman 2009, his Table 9.1; Malkin 2013a, 2013b). Although the latest such compilation dates only from 2013, upon close examination it transpired that Malkin’s (2013a, 2013b) compilation of 53 Galactic Center distance estimates published between 1992 and 2011 is incomplete: our own perusal of the literature from this same period revealed an additional 32 papers with newly derived or updated Galactic Center distance estimates.

Since gaps in the data may mask or, alternatively, artificially suggest the presence of publication bias (for a discussion, see Paper I), we decided to compile our own database of Galactic Center distances that is as complete as possible until the present time. We followed a similar two-pronged approach to that employed in Papers I, II, and III. First, we scanned all 23,516 papers until and including 2016 February tagged with the “Galactic Center” keyword in the NASA/ADS for potential new or rederived Galactic Center distance determinations. At the same time, we carefully followed the reference trail: where a paper referred to the provenance of the Galactic Center distance adopted by its authors, we made a note of the original reference and double-checked that the latter was actually included in our final database.

This approach led to a final database containing a total of 273 Galactic Center distance measurements since Shapley’s (1918) first attempt at determining the centroid of the Galactic globular cluster distribution known at that time. As for Papers I–III, the full database is available at http://astro-expat.info/Data/pubbias.html, where we provide our compilation of Galactic Center distances both as a function of publication date and by tracer, supported by full bibliographic information. We compiled the extinction-corrected distance moduli, as well as their statistical and systematic uncertainties, if available. Only 25 authors published their systematic uncertainties separately; in addition, five papers specified that their published error bars include the systematic uncertainties. For the remaining Galactic Center distance measurements, the uncertainties refer to the statistical errors only. As in Papers I–III, instead of combining individual values based on different assumptions or input parameters, we have included all (final) Galactic Center distance measurements published in a given paper. The range spanned by such alternative values provides a valuable estimate of the systematic uncertainty inherent to the distance determined, although we note that these values are often highly correlated.

Figure 1 shows an overview of the data as published in the original articles, i.e., without having homogenized or recalibrated the various measurements. We show both the full data set in Figure 1(a) and subsets selected according to their provenance, i.e., direct measurements (statistical parallaxes, Galactic Center orbital modeling, Galactic Center Cepheids), centroid determinations (δ Scuti; RR Lyrae, Cepheid, and Mira variables; red clump stars), and determinations involving adoption of a kinematic disk model (Cepheids, RR Lyrae, Miras, open clusters). We have also included the Galactic Center distance values recommended by the International Astronomical Union (IAU). At its XIIth General Assembly held in Hamburg (Germany) in 1964, the IAU released its first formal recommendation for the value of $R_0 = 10$ kpc. This was subsequently amended to $R_0 = 8.5$ kpc (Kerr & Lynden-Bell 1986), a value that has been in force since 1986. Nevertheless, even a casual comparison of the Galactic Center distances in our database (see Figure 1) with the current IAU recommendation reveals that the latter value is well above the mean of most current and recent determinations of $R_0$. As such, the community has called for a further adjustment of the IAU recommendation, but this would need to be done in tandem with adjustments of the Galactic rotation rate at the solar circle, as well as of the Oort constants, which all depend on one another.

Our final database is significantly more comprehensive than any previously published compilation of Galactic Center distance estimates. We will demonstrate this by comparison of our data set with those of three benchmark papers, Kerr & Lynden-Bell (1986), Reid (1993), and Malkin (2013a). The last paper was selected for this comparison since it is the most recent large compilation. As already addressed earlier in this section, we added 32 papers (containing 42 new Galactic Center distance estimates) to Malkin’s (2013a) compilation of 53 articles published between 1992 May and 2011 July. The review by Reid (1993) has long been used as the “gold standard” in the field of Galactic Center distance determinations. It includes 37 $R_0$ values published between 1972 June and 1992 April, taken from 38 articles. Our compilation, by contrast, includes 20 additional Galactic Center distance estimates, found in 17 papers not included by Reid (1993). Finally, the current IAU recommendation for the value of $R_0$ is based on the compilation of 26 estimates by Kerr & Lynden-Bell (1986). Again, our own perusal of the literature published in the period spanning from 1973 August to 1986 May revealed nine additional Galactic Center distance determinations.

3. DISTANCES BY TRACER

Based on observations taken since 1914, Shapley (1918) used the light curves and, hence, the period–luminosity relation of Cepheid variables in 69 Galactic globular clusters to visualize the spatial distribution of the Galactic globular cluster system. He eventually extended his analysis to include all 93 Galactic globular clusters known at that time. He subsequently determined the centroid of the three-dimensional globular cluster distribution to determine the first ever distance to the Galactic Center, $13 \text{ kpc} \leq R_0 \leq 25 \text{ kpc}$.

Armed with our current understanding of the structure of the Milky Way, it is clear that this distance estimate was considerably too large. In fact, the period–luminosity relation he applied was $\approx 1$ mag too faint, while he used Population II Cepheids (W Virginis stars)—combined with the 25 brightest stars in his seven sample clusters (since Population II Cepheids were only known in a limited number of clusters)—instead of
the Population I Cepheids he thought he had observed. Population II Cepheids are some 2 mag fainter than their Population I counterparts, while it appears that Shapley (1918) may also have made calibration errors regarding the absolute magnitudes of the brightest stars and the associated reddening corrections (Sandage 2004, pp. 301–2), thus offsetting the error introduced by his use of an incorrect period–luminosity relation to some extent. As a consequence, Shapley’s (1918) distance scale was off by ∼1 mag, corresponding to a factor of ∼1.6. Note that the implications of Shapley’s (1918) results based on his approach of using both Population II Cepheids and his clusters’ brightest stars may suggest that the difference between classical and Population II Cepheids only applies to a limited number of clusters.

While Shapley’s (1918) Galactic Center distance determination now seems a mere historical curiosity, the fact remains that this was the first viable “centroid” approach to estimate the Galactic Center’s distance. Nevertheless, it is instructive to compare Shapley’s (1918) result with the most recent $R_0$ determination based on the globular cluster centroid. Nikiforov & Smirnova (2013) found that the globular clusters composing the Galaxy’s metal-rich and metal-poor subsystems separately form bar-like structures that closely resemble the Galactic bar as a whole. They conclude that only nonaxisymmetric models can provide sufficiently strong constraints on $R_0$. In addition, these authors found evidence for an extinction component associated with the Galactic bar that affects the observational incompleteness of globular clusters on the far side of the

Figure 1. Galactic Center distance determinations from the literature since records began. (a) All measurements. (b)–(g) Measurements as a function of tracer used. The horizontal blue dashed lines indicate the IAU-recommended values for $R_0$ at the relevant publication dates.
Galactic Center, a selection effect that must be considered seriously in determining \( R_0 \).

In this section, we will focus on the “modern” period since 1990 to distinguish among three different types of Galactic Center distance determinations in order of decreasing accuracy, i.e., direct (geometric) methods, centroid-based methods, and distance determinations based on observations of tracer objects at some distance from the Galactic Center, combined with a kinematic model of the Galactic disk. We will also address the uncertainties inherent to each of the methods applied.

3.1. Direct Measurements

The current best, “direct” (geometric) estimates of \( R_0 \) are based on astrometric orbit determinations of the so-called S stars in the Galactic Center region. Two competing groups are leading efforts in this field, i.e., Genzel et al. versus Ghez and collaborators; see Table 1. Figure 1(b) shows the run of these determinations as a function of publication date (black points). The latest result from the Genzel group is \( R_0 = 8.2 \pm 0.34 \text{kpc} \) (Gillessen et al. 2013), while the Ghez group published \( R_0 = 8.0 \pm 0.3 \text{kpc} \) (Yelda et al. 2011; but see Morris et al. 2012 for a rather surprising downgrade). We will return to a discussion of these direct measurements in Section 4.

The next best direct Galactic Center estimates come from statistical parallax measurements of the nuclear star cluster. These measurements are also included in Table 1. Taking the straight mean and standard deviation of all such measurements gives \( R_0 = 8.16 \pm 0.40 \text{kpc} \). However, this approach does not do full justice to the published results. Systematic uncertainties related to the dynamical cluster models affect the resulting distance determinations. Assuming uniform, isotropic, and fully phase-mixed systems (e.g., Eisenhauer et al. 2003; Do et al. 2013) seems to yield systematically smaller \( R_0 \) values than adopting anisotropic, spherical Jeans models (e.g., Do et al. 2013). The current best results are based on joined-up analyses of both the nuclear star cluster’s stellar velocity dispersions and S-star orbital modeling. The latter lead to \( R_0 = 8.46^{+0.42}_{-0.42} \text{kpc} \) (Do et al. 2013, combined with Ghez et al. 2008) and \( R_0 = 8.33 \pm 0.11 \text{kpc} \) (Chatzopoulos et al. 2015, combined with Gillessen et al. 2009a).

3.2. Galactic Center Cepheids in Context

Matsunaga et al. (2011) used the near-infrared period–luminosity relation of van Leeuwen et al. (2007), adopting solar metallicity, calibrated on the basis of Cepheids with parallax-based distances, to determine the distance modulus to three classical Cepheids in the Galactic nucleus. These three objects were found within 40 pc (projected distance) of the central black hole, leading the authors to conclude that \( R_0 = 7.9^{+0.1}_{-0.2} \text{kpc} \) (see also Bonatto et al. 2013; Matsunaga 2013). The latter value was scaled based on adoption of \((m-M)_0 = 18.50 \text{mag}\) for the distance modulus to the LMC. Although this is not strictly speaking a “direct” Galactic Center distance measurement, we include it here in a separate subsection rather than in the section where we discuss the
Cepheid centroid given the close proximity of these nuclear Cepheids to the actual Galactic Center. The direct measurements discussed in Section 3.1 and the nuclear Cepheid distance of Matsunaga et al. (2011) are indeed fully consistent with one another, with the Cepheid distance somewhat on the short side.

On the other hand, a comparison of Matsunaga et al. (2011) do not claim precise coincidence with the Galactic Center, but merely that their projected positions are consistent with their presence in the thin-disk-like structure of the nuclear bulge. These authors point out that their mean distance estimate suffers from an additional, systematic uncertainty of approximately 0.3 kpc, which is predominantly driven by the uncertainties inherent to the extinction law applied (i.e., the total-to-selective extinction ratio) and by scatter among the prevailing period–luminosity relations, both corresponding to uncertainties of 0.09 mag in distance modulus. Matsunaga et al. (2015) added a fourth nuclear Cepheid to their sample and obtained their kinematics. They concluded that the velocities of these Cepheids suggest that the stars orbit within the nuclear stellar disk, i.e., within ~200 pc of the Galactic Center. This is indeed consistent with their earlier suggestion.

Finally, we note that some authors have suggested that the distances to different Galactic Center tracers affected by significant extinction should be adjusted upward, for instance, by adopting a nonstandard or variable extinction law toward the Galactic Center (e.g., Collinge et al. 2006; Vanhollebeke et al. 2009; Pietrukowicz et al. 2012; Nataf et al. 2013, 2016; but see Francis & Anderson 2014). In addition, the effects of population differences (ages and metallicities) may cause certain tracer objects—such as red clump stars—to be redder in the Galactic bulge than their solar neighborhood equivalents (e.g., Girardi & Salaris 2001), which thus implies that significant systematic uncertainties likely remain in the zero-point calibrations of many “standard” secondary distance tracers.

3.3. Centroids

Since the pioneering effort by Shapley (1918), many authors have attempted to determine \( R_0 \) based on the centroids of the distributions of a variety of tracers, including globular clusters; Cepheid; RR Lyrae, and Mira variables; red clumps stars; and even delta Scuti stars and planetary nebulae.

While Figures 1(c)–(e) showed the “raw,” uncorrected centroid data collected in our database, Figure 2 includes the most recent (post-1990) Galactic Center measurements based on different centroid tracers as a function of publication date. We have attempted to homogenize the distance calibration where appropriate: the original data points as listed in the online database are shown as black open circles; the corrected measurements are shown as red bullets with error bars.

The calibrations applied are included in the individual panels. We used a common horizontal branch magnitude of \( M_V(\text{HB}) = 0.60 \) mag for globular clusters, \( M_V(\text{RR}) = 0.72 \) mag for RR Lyrae stars, and \( I \)- and \( K \)-band red clump absolute magnitudes from Hipparcos (Stanek & Garnavich 1998; see also Laney et al. 2012) for the red clump stars, i.e., \( M_I^{\text{RC}} = -0.23 \) mag and \( M_K^{\text{RC}} = -1.57 \) mag, with \( M_K^{\text{RC}} = M_K + 0.044 \) mag (Grocholski & Sarajedini 2002). In addition, we adopted a homogenized distance scale based on \( (m-M_0) = 18.50 \) mag, thus also ensuring internal consistency with the recommended distance benchmarks derived in Papers I–III.

The left-hand side of Table 2 provides an overview of the mean Galactic Center distances and their standard deviations based on published centroid determinations since 1990. It is readily apparent that the RR Lyrae and Mira centroids yield systematically larger distances than the other tracers. We checked whether this might be a signature of publication bias by recalculating the RR Lyrae statistics for Galactic Center distances published since 2000. Their (mean, \( \sigma \)) combinations are (8.21, 0.31) kpc and (8.31, 0.39) kpc before and after correction, respectively.

Determination of \( R_0 \) based on the centroid approach is significantly more uncertain than using direct geometry. Uncertainties hindering accurate Galactic Center distance estimation include ambiguities associated with the prevailing extinction law, a preference for smaller values of \( R_0 \) because of sampling biases (where extinction causes tracers on the near side of the bulge to have a greater chance of inclusion than their counterparts on the far side), and difficulties in converting the mean distance to one’s tracer sample into a value of \( R_0 \).

3.4. Kinematic Tracers

A large number of Galactic Center distance determinations base their estimates on the distances to a variety of tracer
Table 2
Mean Original and Homogenized Galactic Center Distances and Their Standard Deviations ($\sigma$) Based on Published Post-1990 Estimates

| Centroids | Before Correction | After Correction |
|-----------|------------------|-----------------|
| Tracer    | Mean $\pm \sigma$ | Mean $\pm \sigma$ |
| Globular clusters | 7.65 $\pm$ 0.66 | 7.60 $\pm$ 0.56 |
| Cepheids  | 8.02 $\pm$ 0.32  | 7.88 $\pm$ 0.19  |
| RR Lyrae  | 8.15 $\pm$ 0.34  | 8.45 $\pm$ 0.39  |
| Miras     | 8.57 $\pm$ 0.35  | 8.58 $\pm$ 0.27  |
| Red clump stars | 7.91 $\pm$ 0.53 | 7.96 $\pm$ 0.42 |

| Kinematics | Before Correction | After Correction |
|------------|------------------|-----------------|
| Tracer     | Mean $\pm \sigma$ | Mean $\pm \sigma$ |
| Cepheids+RR Lyrae | 7.88 $\pm$ 0.44 | 8.15 $\pm$ 0.43 |
| Open clusters | 7.73 $\pm$ 0.98 | 7.76 $\pm$ 1.07 |
| Disk tracers | 7.68 $\pm$ 0.49 | … $\pm$ … |
| Masers     | 8.01 $\pm$ 0.53  | … $\pm$ …      |
| …          | …                | …               |

Note. All values are expressed in units of kpc; note that the numbers of data points contributing to the “before” and “after” values for a given tracer are not necessarily the same.

Figure 3. Post-1990 Galactic Center distance estimates based on kinematic disk models for a variety of tracers, as indicated in the individual panels. Where possible, we have homogenized the Galactic Center distances based on RR Lyrae and Cepheid variables, as well as those based on open cluster distances. The original data points are shown in black, with their homogenized counterparts represented in color and slightly offset along the horizontal axis. In the top panel, the Cepheid-based original values are indicated by open circles; those based on RR Lyrae distances are shown as crosses. The horizontal dashed lines represent the IAU-recommended Galactic Center distance.

Note, however, that this method of Galactic Center distance determination suffers from larger uncertainties than the centroid approach, given the larger number of assumptions one has to make. In addition to the need for an accurate Milky Way mass model (e.g., Reid et al. 2009; McMillan 2011), the basic, underlying assumption on which the accuracy of this methodology hinges is that the tracers are stationary with respect to the local standard of rest (at the solar position) and in circular motion at the solar circle. Since both of these assumptions are usually imprecise, good results cannot be expected from individual objects.

It is not obvious how one could self-consistently homogenize the Galactic Center distance estimates based on other kinematic disk tracers. We considered using the ratio of the rotational velocities at the solar circle, $\Theta_0$, and $R_0$ to transfer all these measurements onto a common scale. McMillan & Binney (2010) carefully reevaluated a number of current models describing solar rotation about the Galactic Center. Using data of 18 masers in high-mass star-forming regions at the solar circle from Reid et al. (2009), they found that the best-fitting models yield Galactic Center distances in the range from $R_0 = 6.7 \pm 0.5$ kpc to $R_0 = 8.9 \pm 0.9$ kpc, and $\Theta_0$ from 200 $\pm$ 20 km s$^{-1}$ to 279 $\pm$ 33 km s$^{-1}$. Despite these large ranges in $R_0$ and $\Theta_0$, which are largely driven by one’s choice of Galactic rotation curve, these authors found that— with one exception—the $\Theta_0/R_0$ ratio should be narrowly constrained between $\Theta_0/R_0 = 29.9$ km s$^{-1}$ kpc$^{-1}$ and $\Theta_0/R_0 = 31.6$ km s$^{-1}$ kpc$^{-1}$ (see also Reid et al. 2009).

However, Figure 4 shows that, in practice, the $\Theta_0/R_0$ ratios adopted by different authors are significantly smaller than the range proposed by McMillan & Binney (2010; see the horizontal dashed lines in the figure). The red data points are 3 yr averages, aimed at showing the general trend, where the horizontal “error bars” indicate the relevant time period sampled and the vertical error bars represent the corresponding standard deviations. Between 1990 and 2007, the majority of $\Theta_0/R_0$ ratios adopted by authors who recently determined $R_0$ are found near $\langle \Theta_0/R_0 \rangle = 28$ km s$^{-1}$ kpc$^{-1}$; since then, the ratio has slowly increased to $\langle \Theta_0/R_0 \rangle \approx 32$ km s$^{-1}$ kpc$^{-1}$ (2013–2015).

Combined with the current best Galactic Center distance estimates based on S-star orbital modeling or statistical parallaxes, $R_0 = 8.3 \pm 0.2$ kpc, these $\Theta_0/R_0$ ratios imply that the Galactic rotation speed at the solar circle is best constrained to the range from $\Theta_0 = 232$ km s$^{-1}$ (1990–2007) to $\Theta_0 = 266$ km s$^{-1}$ based on our current best understanding of Galactic dynamics, i.e., significantly faster than the IAU-
recommended value of $\Theta_0^{\text{IAU}} = 220 \text{ km s}^{-1}$. In fact, this is confirmed statistically: 33 of the 55 post-1990 values of $\Theta_0$ used in this paper attained values of $\Theta_0 \geq 230 \text{ km s}^{-1}$ (only 17 out of 55 publications derived $\Theta_0 < 220 \text{ km s}^{-1}$). The equivalent numbers for the period since 2000 are 25 out of 39 high values (versus 10 out of 39 low rotation speeds). An increasing body of evidence now suggests that the Galactic rotation speed at the solar circle is indeed well in excess of the IAU recommendation (e.g., Reid et al., 2009), with most authors supporting $\Theta_0 \in [235, 260] \text{ km s}^{-1}$ at the present time (e.g., Shen & Zhu 2007; Boyv et al. 2009; Zhu 2009; McMillan & Binney 2010; Sato et al. 2010; Shen & Zhang 2010; Brunthaler et al., 2007; McMillan 2011; Honma et al. 2012; Schönrich et al.; Dambis et al. 2013; Reid 2013; Zhu & Shen 2013; Reid et al. 2014).

4. DISCUSSION

4.1. Statistical Trends

Since the dual basic premises of science are reproducibility and replicability (e.g., de Grijs 2016, and references therein), as fallible humans scientists may be tempted—most likely unknowingly—to trust results that are in good agreement with previously published values. Such behavior may lead to a “bandwagon effect,” more commonly referred to as publication bias (for background, see Paper I).

In the context of Galactic Center distance determinations, the possible presence of publication bias has been addressed repeatedly (e.g., Reid 1989, 1993; Nikiforov 2004; Foster & Cooper 2010; Malkin 2013a, 2013b; Francis & Anderson 2014), although their conclusions are not in general agreement. Publication bias can be revealed either by a gradual convergence of published values to a generally accepted number (e.g., Malkin 2013a, 2013b; Paper I) or by a sudden shift in preferred values following a landmark publication.

Malkin (2013a, 2013b) explored evidence of the former using his compilation of 53 $R_0$ determinations published over a period of some 20 yr (1992–2011), but he did not find any statistically significant trend. Francis & Anderson (2014) used an unspecified, larger sample of 150 Galactic Center distances, cited as “available online,” of which they deemed 137 values as broadly distinct, for a more detailed analysis of possible publication bias affecting published distance estimates. The latter authors claimed to have uncovered a continuing small but significant trend toward decreasing estimates based on 48 values published between 1980 and 2000. (This encompasses approximately half the number of distance determinations we recorded during the same period, i.e., our database includes 100 Galactic Center distance determinations published between 1980 February and 2000 September.) A Student’s $t$ test implies that this trend’s significance is reduced from 92% prior to 2000 to 73% post-2000 (Francis & Anderson 2014; see also Foster & Cooper 2010).

Note that even if the range of published values becomes narrower over time, this does not necessarily imply that authors (or reviewers) are unconsciously affected by a bandwagon effect. On the contrary, as we already addressed in Paper I in the context of LMC distance determinations, later publications may benefit from having access to larger tracer samples than earlier papers, the calibration relations are likely better understood, the analysis methods applied are improved, and systematic errors might be reduced (e.g., Malkin 2013a, 2013b).

4.2. Direct Distance Determinations

Objective consideration of progress in the field of Galactic Center distance determinations singles out one paper in particular that may qualify as a landmark publication. Eisenhauer et al. (2003) were the first to determine a direct, geometric distance to the Galactic Center based on the orbital motion of S2, one of the small sample of stars orbiting the Galactic Center’s black hole on roughly Keplerian orbits.

Although the direct Galactic Center distance determinations by the Genzel and Ghez groups are arguably the most precise Galactic Center distance estimates available to date, their derivation is very sensitive to a range of modeling assumptions (e.g., Gillessen et al. 2009a; Francis & Anderson 2014). Two potentially important issues relate to the underlying assumption of Keplerian motion of the S stars around Sgr A* . First, Newton’s shell theorem, which posits that the gravity inside a spherical shell is unimportant, provides only an approximate solution to characterize the real, three-dimensional distribution of matter in the nuclear disk and central bar of the Milky Way.

Second, the initial Keplerian approximations to the S-star orbits did not take into account relativistic effects (Zucker et al. 2006; Gillessen et al. 2009a). Francis & Anderson (2014) pointed out that the corrections for the relativistic geodetic effect (de Sitter precession) attempted by Gillessen et al.

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7 At earlier times, the mean of the published Galactic Center distance estimates declined significantly and systematically, particularly in the period between approximately 1970 and 1990 (see Figure 1; see also Reid 1989, 1993; Surdin 1999; Nikiforov 2004), which may be the first suggestion of the presence of a bandwagon effect in $R_0$ estimates, although this could also simply be the result of improvements in either our physical understanding or the methods used, or both.
are consistent within the errors with the Eisenhauer et al. (2009a) considered these effects (for a detailed discussion, see Francis & Anderson 2014). Yet, in 2002, when the star S2 was near its pericenter and relativistic effects were most significant, both Zucker et al. (2006) and Gillessen et al. (2009a) reported difficulties in modeling the star’s orbital motion. This thus implies that relativistic effects must be taken into account and certainly cannot be ignored.

Perhaps surprisingly, this appears to be a case where more data actually lead to less accurate results. The potentially significant relativistic effects affecting the S-star orbits result in ever more serious cumulative differences from Keplerian motion (Francis & Anderson 2014). Nevertheless, here we consider the \( R_0 \) determinations based on the orbital motions of the S stars as a function of publication date. We refer to Figure 1(b) and Table 1 (top) for guidance. The most significant change in the central \( R_0 \) values since Eisenhauer et al. (2003, 2005) occurred with the publication of Gillessen et al. (2009a), which resulted in an upward adjustment of approximately 0.6 kpc.

Gillessen et al. (2009a) point out that their new values for \( R_0 \) are consistent within the errors with the Eisenhauer et al. (2003, 2005) results, and that adding more stars to the orbital solutions does not change the results significantly. They assert that their main improvement is owing to the more rigorous treatment of the systematic errors. In fact, it appears that this change is indeed not driven by publication bias, nor did their consideration of relativistic effects have a significant impact.

The latter statement is supported by comparing the Zucker et al. (2006) Galactic Center distance estimate with the earlier determinations of Eisenhauer et al. (2003, 2005). Instead, the Gillessen et al. (2009a) Galactic Center distance is more robust than their previous results, given that it is based on astrometric observations of much higher quality (affected by smaller astrometric uncertainties) and covering a significantly longer time span.

The latest results obtained by both Genzel’s group (Gillessen et al. 2009a, 2013) and Ghez’s collaboration (Ghez et al. 2008; Yelda et al. 2011) are indeed fully mutually consistent, as also expected from the \( R_0 \) values resulting from combining the data of both groups (Gillessen et al. 2009a). Indeed, the low value of \( R_0 = 7.7 \pm 0.4 \) kpc derived by Morris et al. (2012), members of the Ghez group, is an odd one out. The latter authors only commented that this estimate corresponds to their current best fit to the observational data from 1995 to 2011. They did not discuss their discrepant result, other than by pointing out that the uncertainty in their estimate is highly correlated with the uncertainty in the mass of the black hole. Indeed, the same degeneracy affects the central values (e.g., Gillessen et al. 2009a). In conclusion, we have not unearthed any evidence of possible publication bias in the Galactic Center distances resulting from S-star orbital modeling.

Careful assessment of the \( R_0 \) values obtained from statistical parallax measurements of the nuclear star cluster also show broad consistency during the 20 yr leading up to 2015 (for a brief discussion, see Section 3.1).

The unprecedented volume of our catalog of Galactic Center distance determinations has allowed us to conclude that the globular cluster, Cepheid, and red clump centroids suggest smaller Galactic Center distances than the direct distance estimates, while the RR Lyrae and Mira variables result in larger Galactic Center centroid distances (e.g., Table 3).

Indeed, it has been suggested that some tracers, and in particular the \((t > 10 \text{ Gyr})\) old tracers (i.e., the RR Lyrae stars), might or might not follow the Galactic bar (e.g., Zoccali & Valenti 2016). This implies that distance determinations based on these tracers might depend on the line of sight of the adopted sample. Moreover, we do not yet have similarly robust identifications of RR Lyrae stars located in the Galactic Center as we do for the Galactic Center Cepheid sample. This suggests that RR Lyrae variables might be more prone to possible systematic effects (e.g., Zoccali & Valenti 2016). In addition, there are reasons to believe that the red clump results might also be affected by large systematic uncertainties. In fact, if a metallicity gradient is present from the Galactic Center to the outer bulge (e.g., Zoccali et al. 2008; Pietrukowicz et al. 2012, 2015; Uttenthaler et al. 2012), this also means that the mean magnitude and color of red clump stars change when approaching the Galaxy’s inner core.

A separate concern regarding systematic effects introduced by our homogenization is the following. If, as we have done for many RR-Lyrae-based Galactic Center distance determinations, we adopt any of the prevailing \( M_V \) versus [Fe/H] relations, we have to deal with a strong dependence on the reddening correction and the metallicity distribution of RR Lyrae in the central Galaxy. Specifically, we have adopted \( M_V(RR) = 0.72 \) mag. If the original papers quoting Galactic Center distance determinations used any other absolute magnitude calibration (see Table 3), we converted the \( R_0 \) value to a distance modulus, corrected it for the difference in calibration used, and eventually converted it back to a linear distance. If we were to adopt the \( K \)-band magnitudes for our calibration instead, the dependence on metallicity and on the reddening uncertainties is smaller. However, in this case we
Table 3
Adopted, Homogenized Centroid-based Distances Used in This Paper

| Publ. Date (mm/yyyy) | $R_0$ (kpc) | Reference | Original Calibration | Notes |
|----------------------|-------------|-----------|----------------------|-------|
| 08/1993              | 7.6 ± 0.4   | Maciel (1993) | $M_V$ (HB) = 0.6 mag  | 46 GCS, [Fe/H] > −1.2 dex |
| 09/1994              | 7 ± 0.5     | Rastorguev et al. (1994) | $M_V$ (RR) = 0.6 mag | ... |
| 00/1998              | 8.6 ± 1.0   | Surdin & Fokkistov (unpublished) | ... | Quoted in Surdin (1999) as "submitted" |
| 00/1999              | 9.0 ± 1.0   | Surdin (1999) | ... | ... |
| 03/2006              | 7.0 ± 0.3   | Bonatto et al. (2009) | $M_V$ (HB) = 0.20[Fe/H] + 1.00 mag | 126 GCS |
| 04/2006              | 7.2 ± 0.3   | Bica et al. (2006) | $M_V$ (HB) = 0.16[Fe/H] + 0.84 mag | 116 GCS |
| 10/2013              | 7.63 ± 0.38 | Nikiforov & Smirnova (2013) | $M_V$ (HB) = 0.16[Fe/H] + 0.84 mag | All methods |
| 10/2013              | 7.42 ± 0.23 | Nikiforov & Smirnova (2013) | $M_V$ (HB) = 0.16[Fe/H] + 0.84 mag | All spatial methods |
| 10/2013              | 7.36 ± 0.24 | Nikiforov & Smirnova (2013) | $M_V$ (HB) = 0.16[Fe/H] + 0.84 mag | Shapley’s method and related spatial methods |
| 06/2014              | 7.4 ± 0.2   | Francis & Anderson (2014) | $M_V$ (RR) = 1.067 + 0.502[M/H] +0.108[M/H]$^2$ mag | 154 GCS, syst. unc. 0.2 kpc |

Globular Clusters; ([Fe/H]$^{50c}$) = −1.5 dex

| Rp-Lyrae; ([Fe/H]$^{50c}$) = −1.0 dex |
|---------------------------------------|
| 09/1991 8.7 ± 1.0 | Walker & Terndrup (1991) | $M_V$ (RR) = 0.85 mag | ... |
| 09/1991 8.2 ± 0.0 | Walker & Terndrup (1991) | $M_V$ (RR) = 0.85 mag | ... |
| 10/1995 8.28 ± 0.40 | Carney et al. (1995) | $M_V$ (RR) = 0.85 mag | ... |
| 10/1995 8.9 ± 0.5 | Carney et al. (1995) | $M_V$ (RR) = 0.85 mag | ... |
| 11/1996 8.4 ± 0.4 | Layden et al. (1996) | $M_V$ (RR) = 1.05[Fe/H] + 0.95 mag | ... |
| 11/1996 9.2 ± 0.5 | Layden et al. (1996) | $M_V$ (RR) = 0.60 mag | ... |
| 11/1996 8.7 ± 0.6 | Layden et al. (1996) | Combined approach | "Best" value |
| 01/1997 8.0 ± 0.4 | Feast (1997) | $M_V$ (RR) = 1.853 mag | ... |
| 01/1997 8.0 ± 0.4 | Feast (1997) | $M_V$ (RR) = 0.37[Fe/H] + 1.13 mag | ... |
| 04/1998 8.7 ± 0.25 | Udalski (1998) | $M_V$ (RR) = 0.88 mag | ... |
| 11/2006 8.8 ± 0.3 | Collinge et al. (2006) | $M_V$ (RR) = 0.72 mag | ... |
| 11/2006 8.8 ± 0.3 | Collinge et al. (2006) | $M_V$ (RR) = 0.92 mag | ... |
| 11/2006 9.1 ± 0.7 | Collinge et al. (2006) | Combined approach | ... |
| 02/2008 8.7 ± 0.4 | Kunder et al. (2008) | $M_V$ (RR) = 0.72 mag | ... |
| 02/2008 8.7 ± 0.6 | Kunder et al. (2008) | $M_V$ (RR) = 0.92 mag | ... |
| 02/2008 7.94 ± 0.37 | Groenewegen et al. (2008) | $M_V$ (RR) = 1.19 + 0.5[Fe/H] + 0.09[Fe/H]$^2$ mag | ... |
| 04/2008 7.87 ± 0.64 | Groenewegen et al. (2008) | $M_V$ (RR) = 1.850 mag | ... |
| 04/2008 8.0 ± 0.7 | Groenewegen et al. (2008) | $M_V$ (RR) = 1.850 mag | ... |
| 12/2008 8.2 ± 0.3 | Kunder & Chaboyer (2008) | $M_V$ (RR) = 1.19 + 0.5[Fe/H] + 0.09[Fe/H]$^2$ mag | ... |
| 03/2010 8.1 ± 0.6 | Majiess (2010) | $M_V$ (RR) = 1.850 mag | ... |
| 05/2012 8.35 ± 0.42 | Pietrukowicz et al. (2012) | $M_V$ (RR) = 2.288 + 0.882 log Z + 0.108 log(Z)$^2$ mag | ... |
| 10/2013 8.14 ± 0.05 | Dăkányi et al. (2013) | Log Z = [Fe/H] − 1.765 dex | ... |
| 10/2015 8.08 ± 0.01 | Pietrukowicz et al. (2015) | Log Z = [Fe/H] − 1.765 dex | ... |

Type II Cepheids, incl. κ Pav

Type II Cepheids

Type II Cepheids

Type II Cepheids + bulge model

100 Miras, Cepheids, RC stars; syst. unc. 0.26 kpc
would introduce a dependence on the pulsation period, since RR Lyrae exhibiting longer periods are brighter. Where appropriate, we have also assumed that $[\text{Fe}/\text{H}] = -1.0$ dex for RR Lyrae in the bulge (e.g., Bonn et al. 2003). If we assume that a typical mean period for a fundamental RR Lyrae in the bulge is around 0.55–0.60 days and the mean metallicity is around $[\text{Fe}/\text{H}] = -1$ dex, $(M_K) = -0.5$ mag (Marconi et al. 2015). At the present time, we have access to too few $K$-band calibrated RR Lyrae distance measurements to the Galactic Center (only two such calibrations are available: Carney et al. 1995; Dambis 2009). Overall, the adjustments thus made take into account the metallicity dependence of the RR Lyrae distance scale to the best of our current ability.

Finally, we explored whether any of the centroid tracers or those used for the kinematics-based Galactic Center distance estimates exhibited statistically significant trends in the modern, post-1990 era. In the context of exploring possible bandwagon effects, one should, of course, only consider the original Galactic Center distance estimates, before homogenization. The significant scatter among the data points pertaining
to any of the kinematics tracers precludes us from resolving any such trend. Among the centroid tracers, we do not have sufficient numbers of data points for the globular clusters, planetary nebulae, or Cepheids spanning a sufficiently long time span to draw statistically justifiable conclusions either (see Figure 2).

For all other tracers we only find statistically insignificant ($\leq 1\sigma$) trends of $R_0$ as a function of publication date, both for the full 1990–2016 time span and for the more recent period since 2005. However, we find that in general the uncertainties have been steadily decreasing for all tracers, which are largely owing to improvements in the calibration approaches used and access to new and larger samples of tracer objects (for a related discussion, see Paper I). In conclusion, neither the centroid- nor the kinematics-based Galactic Center distance tracers published since 1990 suggest the presence of any significant trends of $R_0$ with publication date. Table 4 includes the homogenized, kinematics-based distances used in this paper.

5. SUMMARY AND CONCLUSIONS

Aiming at deriving a statistically well-justified Galactic Center distance based on a large variety of tracers and reducing any occurrence of publication bias, we embarked on an extensive data-mining effort of the scientific literature, eventually yielding 273 new or revised $R_0$ estimates published since records began in 1918 October until 2016 June. Our large database of Galactic Center distance estimates, a fully linked version of which is made available to the scientific community, allowed us to explore the pros and cons of a variety of different approaches used to determine the distance to the Galactic Center.

We separated our compilation into direct and indirect distance measurements. The former include distances such as those based on orbital modeling of the so-called S stars orbiting Sgr A*, the closest visual counterpart of the Milky Way’s central supermassive black hole, as well as those relying on statistical parallaxes of either the nuclear star cluster or the stellar population in the inner Galactic core. Careful assessment of the body of published Galactic Center distances based on these methods resulted in our Galactic Center distance recommendation of $R_0 = 8.3 \pm 0.2$ (statistical) $\pm 0.4$ (systematic) kpc.

A much larger body of Galactic Center distance determinations is based on indirect methods, either those relying on centroid determinations for a range of different tracer populations (e.g., globular clusters; Cepheid, RR Lyrae, or Mira variables; or red clump stars) or measurements based on kinematic observations of objects at the solar circle, combined with a mass and/or rotational model of the Milky Way. The latter approaches are affected by significantly larger uncertainties than the former, while the central, mean Galactic Center distances based on the kinematic methods are systematically smaller than those based on centroid determinations. Most centroid-based distances are in good agreement with those resulting from the direct methods.

We did not find any conclusive evidence of the presence of a bandwagon effect in the post-1990 Galactic Center distance measurements, neither among the direct distance estimates nor among those based on centroid determinations. Our set of kinematics-based distance measurements cannot be used to explore this issue given the significant uncertainties associated with the latter methods. However, the latter measurement can indeed be used to constrain the Galaxy’s rotation velocity at the solar galactocentric distance using the $\Theta_0/R_0$ ratios employed by their respective authors. We found a gradual increase in the mean value of $\Theta_0$ from $\langle \Theta_0 \rangle = 232$ km s$^{-1}$ in the 1990s to $\langle \Theta_0 \rangle = 266$ km s$^{-1}$ more recently. (Both values represent the means of the distributions of rotation speeds; their standard deviations are of order 20–30 km s$^{-1}$.) Our results thus imply that the IAU-recommended Galactic Center distance ($R_0^{IAU} = 8.5$ kpc) needs a downward adjustment, while the recommendation for the Galactic rotation velocity at the solar circle ($\Theta_0 = 220$ km s$^{-1}$) requires an upward revision.

Finally, in view of the recent Gaia Data Release 1 (Lindegren et al. 2016), this is an opportune time to consider the impact on Galactic Center distance determinations of the improved parallax measurements of upward of a billion stars that the mission will provide by the end of its nominal 5 yr duration. The final Gaia catalog will map a significant fraction of the Galactic volume, with particularly high (distance-dependent) parallax precision for stars in the solar neighborhood, gradually decreasing toward the Galactic Center.

Because of the high extinction and significant crowding in the Galaxy’s inner regions, Gaia’s optical (G-band) measurements will reach the Galaxy’s central regions, but not the center itself. It is anticipated that Gaia’s direct distance determinations of stars near the Galactic Center will be accurate to approximately 20%, i.e., significantly worse than the distance estimates provided by any of the direct methods discussed in Section 3.1 or the Cepheid-based result of Matsunaga et al. (2011). However, Gaia’s homogeneous and extensive final catalog will undoubtedly facilitate a significantly improved statistical determination of $R_0$ based on kinematic measurements as well as inside the solar circle. In addition, Gaia will provide improved distance measurements to large numbers of standard candles, thus almost certainly improving their zero-point accuracies, which in turn will allow us to test for the effects of population differences associated with the use of secondary distance tracers.

Gaia is currently among the best-placed facilities to resolve the remaining uncertainties in the Galactic distance scale, which is no longer seriously affected by statistical uncertainties. The prevailing uncertainties preventing us from determining a more accurate distance to the Galactic Center are systematic in nature. Among the latter, the effects not just of variations in the extinction but of possible variations in the prevailing extinction law are among the most important stumbling blocks.

The data set analyzed in this paper is, unfortunately, unsuitable for systematic studies of the uncertainties introduced by variations in the extinction law (e.g., Nishiyama et al. 2009; Nataf et al. 2016, and references therein). This is particularly so, because the vast majority of the individual data points retrieved from the literature have been extinction-corrected by their respective authors using the most appropriate approaches available at the time of their analyses. This implies the inherent presence of intrinsic inhomogeneities in the extinction corrections, which are impossible to fully correct for at the present time.

In addition, we point out that current empirical estimates of reddening laws in the local universe are mainly based on optical and near-infrared photometry. To further constrain possible systematic effects, independent approaches based on either analyses of diffuse interstellar bands (e.g., Munari &
### Table 4
Adopted, Homogenized Kinematics-based Distances Used in This Paper

| Publ. date | $R_0$ (kpc) | Reference | Original Calibration | $\theta_0$ (km s$^{-1}$) | Notes$^a$ |
|------------|-------------|-----------|---------------------|--------------------------|----------|
| 02/1992    | 8.3 ± 0.5   | Caldwell et al. (1992) | $(m - M)_{\text{LMC}} = 18.55 \text{ mag}$ | 248 ± 16 | $N = 212$ |
| 05/1994    | 8.20 ± 0.30 | Pont et al. (1994) | $(m - M)_{\text{LMC}} = 18.47 \text{ mag}$ | 257 ± 7 |  |
| 05/1995    | 7.4 ± 0.5   | Dambis et al. (1995) | $(m - M)_{\text{LMC}} = 18.47 \text{ mag}$ | … |  |
| 11/1997    | 8.6 ± 0.5   | Feast & Whitelock (1997) | $(m - M)_{\text{LMC}} = 18.47 \text{ mag}$ | … | $R_0$ from Pont et al. (1994) new PLR |
| 11/1997    | 8.3 ± 0.6   | Feast & Whitelock (1997) | $(m - M)_{\text{LMC}} = 18.47 \text{ mag}$ | … | $R_0$ from Metzger et al. (1998) new PLR |
| 01/1998    | 7.7 ± 0.3   | Glushkova et al. (1998) | $(m - M)_{\text{LMC}} = 3.30 \text{ mag}$ | 200 ± 15 | $N = 202; \text{ open clusters, Cepheids, RSGs}$ |
| 02/1998    | 7.66 ± 0.32 | Metzger et al. (1998) | $(m - M)_{\text{LMC}} = 18.50 \text{ mag}$ | 237 ± 12 | Systematic uncertainty 0.44 kpc |
| 02/1998    | 7.95 ± 0.31 | Metzger et al. (1998) | $(m - M)_{\text{LMC}} = 18.50 \text{ mag}$ | 237 ± 12 | $N = 7; \text{ solar circle; no orbital ellipticity}$ |
| 02/1998    | 7.61 ± 0.30 | Metzger et al. (1998) | $(m - M)_{\text{LMC}} = 18.50 \text{ mag}$ | 237 ± 12 | $N = 7; \text{ solar circle; 4% orbital ellipticity}$ |
| 08/1998    | 7.76 ± 0.29 | Feast et al. (1998) | $(m - M)_{\text{LMC}} = 18.70 \text{ mag}$ | … | $N = 266$ |
| 06/2009    | 7.8 ± 0.3   | Glushkova et al. (1999) | $(m - M)_{\text{LMC}} = 3.30 \text{ mag}$ | 204 ± 15 | $N = 202; \text{ open clusters, Cepheids, RSGs; use caution}$ |
| 01/2010    | 8.0 ± 0.8   | Shen & Zhang (2010) | … | 239 ± 12 | … |
| 02/2013    | 7.66 ± 0.36 | Bobylev (2013) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 267 ± 17 | $N = 14; P > 5 \text{ days}$ |
| 02/2013    | 7.64 ± 0.32 | Bobylev (2013) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 217 ± 11 | $N = 18; \text{ proper motions}$ |
| 02/2013    | 7.98 ± 0.79 | Zhu & Shen (2013) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 239 ± 23 | $N = 215$ |
| 06/2009    | 8.43 ± 0.40 | Dambis (2009) | $(m - M)_{\text{LMC}} = 18.27 \text{ mag}$ | 229 ± 12 | … |
| 11/2013    | 7.81 ± 0.30 | Dambis et al. (2013) | $(m - M)_{\text{LMC}} = 18.32 \text{ mag}$ | 234 ± 10 |  |
| 11/2013    | 8.4 ± 0.4   | Dambis et al. (2013) | $(m - M)_{\text{LMC}} = 18.30 \text{ mag}$ | 195 ± 5 |  |
| 11/2013    | 8.0 ± 0.4   | Shen & Zhang (2010) | … | 239 ± 12 | … |
| 10/2013    | 7.8 ± 0.3   | Glushkova et al. (1999) | $(m - M)_{\text{LMC}} = 3.30 \text{ mag}$ | 204 ± 15 | $N = 202; \text{ open clusters, Cepheids, RSGs; use caution}$ |
| 02/2013    | 8.0 ± 0.4   | Gerashenko (2004) | … | … | $N = 34; \text{ Fokker’s method}$ |
| 02/2007    | 7.95 ± 0.62 | Shen & Zhu (2007) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 244 ± 14 | $N = 270$ |
| 02/2007    | 8.1 ± 0.7   | Shen & Zhu (2007) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 244 ± 14 | Mean value (open clusters, OB stars) |
| 11/2007    | 7.4 ± 0.3   | Bobylev et al. (2007) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 195 ± 7 | $N = 375$ |
| 11/2007    | 9.5 ± 0.7   | Bobylev et al. (2007) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 195 ± 7 | Young open clusters (<50 Myr) |
| 11/2007    | 5.6 ± 0.3   | Bobylev et al. (2007) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 195 ± 7 | Old open clusters (>50 Myr) |
| 12/2009    | 8.03 ± 0.70 | Zhu (2009) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 235 ± 10 | $N = 301$ |
| 01/2009    | 8.03 ± 0.70 | Zhu & Shen (2013) | $(m - M)_{\text{LMC}} = 3.42 \text{ mag}$ | 260 ± 15 | $N = 301$ |

Notes. Entries in bold font are newly updated (homogenized) distance estimates.

$^a$ New abbreviation used: RSGs, red supergiant stars.

$^b$ Note that Glushkova et al. (1998) and Glushkova et al. (1999) are identical peer-reviewed articles, although this duplicate publication is not formally acknowledged. Nevertheless, the Galactic Center distance estimates differ by 0.1 kpc between both papers, which remains unexplained.

Zwitter 1997; Wallerstein et al. 2007; Munari et al. 2008; Kashuba et al. 2016 or spectroscopic studies (e.g., Kudritzki et al. 2012) may shed new light on this long-standing problem. Indeed, detailed, large-scale studies such as that of Nataf et al. (2016), perhaps combined with high spatial resolution observations of carefully selected, homogeneous samples of Galactic Center objects at near- to mid-infrared wavelengths (such as those anticipated to result from WFIRST operation or from campaigns with the next generation of 30 m class ground-based telescopes), seem most promising to overcome the remaining systematics in the reddening laws.

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