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 October 1918 until June 2016. 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) ± 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, Θ_0. Our results imply that the International Astronomical Union-recommended Galactic Center distance ($R_0^{\mathrm{IAU}} = 8.5$ kpc) needs a downward adjustment, while its Θ_0 recommendation ($\Theta_0 = 220$ km s^{-1}) requires a substantial upward revision.

Keywords: astronomical databases — 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, both on Galactic and extragalactic scales. Calculations of many physical parameters, including of the distances, masses, and luminosities of Galactic objects, as well as the Galaxys 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 of 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, as well as 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, have 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; Nikiforov 2004; Foster & Cooper 2010; Malkin 2013a,b; Francis & Anderson 2014).

In de Grijs et al. (2014, henceforth Paper I), de Grijs & Bono (2014; Paper II), and de Grijs & Bono (2015; Paper III), we embarked on large-scale data mining of the NASA/Astrophysics Data System (ADS) to explore whether distance determinations to, respectively the Large Magellanic Cloud (LMC), the M31 group, and the Small Magellanic Cloud 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 October 1918, until early June 2016. In Section 3, we review three different types of Galactic Center distance indicators, including direct distance measurements as well as 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,b). Although the latest such compilation dates only from 2013, upon close examination it transpired that Malkin's (2013a,b) 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 as employed in Papers I, II, and III. First, we scanned all 23,516 papers until and including February 2016 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 Galaxtic 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[1], 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 Fig. 1a 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, Cepheids, and Mira variables, red clump stars), and determinations involving adoption of a kinematic disk model (Cepheids, RR Lyrae, Miras,
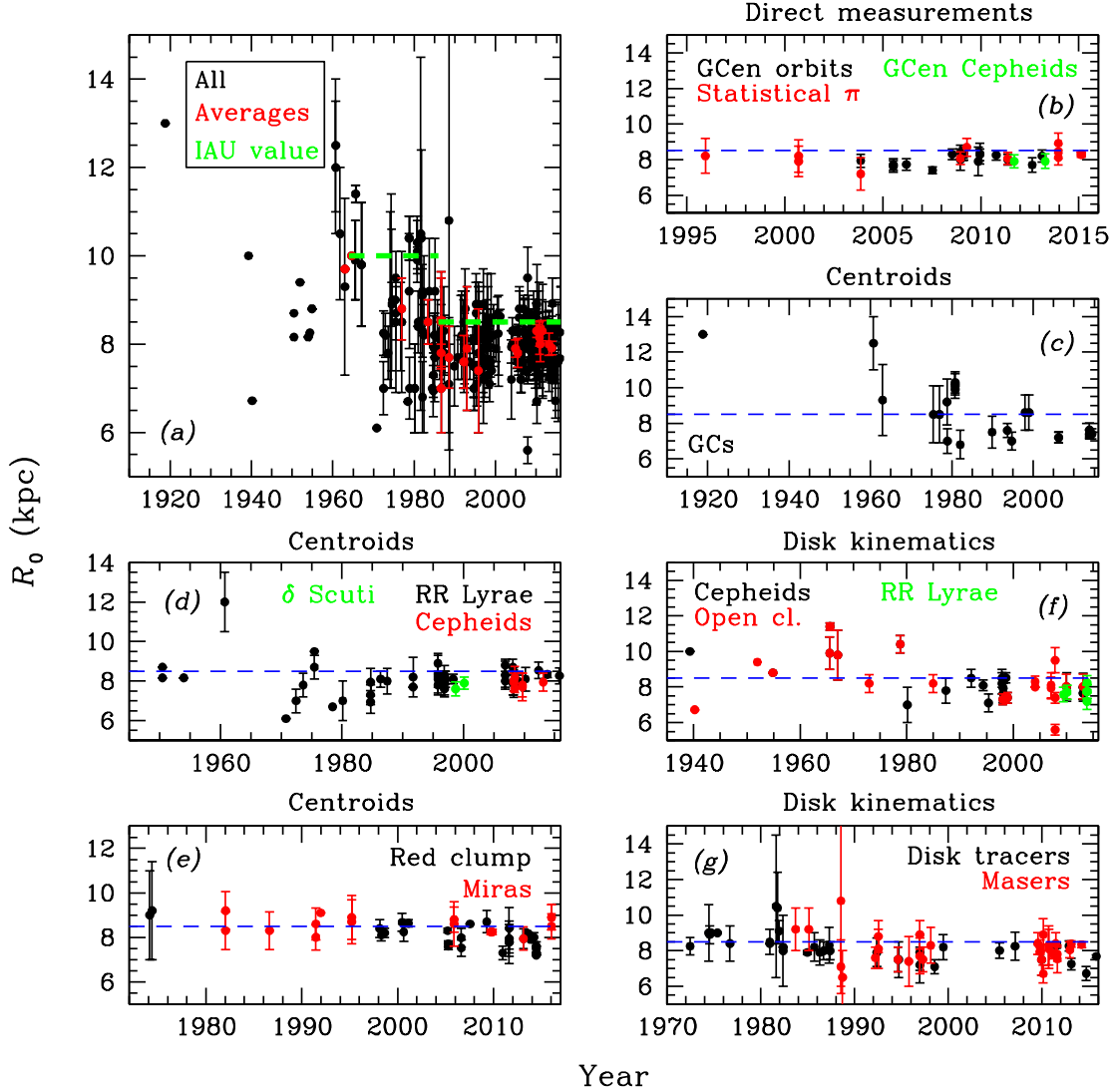
Figure 1. Galactic Center distance determinations from the literature since records began. (a) All measurements. (b)–(g) Measurements as a function of tracer used. The horizontal blue dashed lines indicate the IAU-recommended values for R_0 at the relevant publication dates.

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 Fig. 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 et al. (1993), and Malkin (2013a). The latter 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 estimate, 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, $13 \leq R_0 \leq 25$ 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 ∼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. 301–302), 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 implicatiom 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 non-axisymmetric models can provide sufficiently strong constraints on R_0. In addition, these authors found evidence for an extinction component associated with the Galactic bar which affects the observational incompleteness of globular clusterss on the far side of the 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 1b shows the run of these determinations as a function of publication date (black points). The latest result from the Genzel group is $R_0 = 8.2 \pm 0.34$ kpc (Gillessen et al. 2013), while the Ghez group published $R_0 = 8.0 \pm 0.3$ 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 $R_0 = 8.16 \pm 0.40$ 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 $R_0 = 8.46^{+0.42}_{-0.41}$ kpc (Do et al. 2013, combined with Ghez et al. 2008) and $R_0 = 8.33 \pm 0.11$ kpc (Chatzopoulos et al. 2015, combined with Gillessen et al. 2009a).

Table 1. Adopted 'direct' distances used in this paper, expressed in units of kpc.

Publ. date (mm/yyyy)	R_0 (kpc)	Reference	Notes
		Galactic Center orbital modeling	
11/2003	7.94 ± 0.33	Eisenhauer et al. (2003)	S2 only, 1992–2001; systematic uncertainty 0.16 kpc
07/2005	7.62 ± 0.32	Eisenhauer et al. (2005)	S2 only, 1992–2004
07/2005	7.72 ± 0.33	Eisenhauer et al. (2005)	S2 only, 1992–2004, excl. data from 2002
03/2006	7.73 ± 0.32	Zucker et al. (2006)	S2 only, 1992–2004; corrected for relativistic effects
07/2007	7.4 ± 0.2	Olling (2007; Ghez, priv. commun.)	bias-free 'orbital parallax method' (Armstrong et al. 1992)
07/2008	8.3 ± 0.3	Ghez et al. (2008)	S2 only, 1995–2007
12/2008	8.0 ± 0.6	Ghez et al. (2008)	S2 only, 1995–2007; black hole freely moving
12/2008	8.4 ± 0.4	Ghez et al. (2008)	S2 only, 1995–2007; black hole at rest
02/2009	8.33 ± 0.35	Gillessen et al. (2009b)	S stars, 1992–2008; incl. systematic uncertainties
02/2009	8.40 ± 0.29	Gillessen et al. (2009b)	S stars excl. S2, 1992–2008; incl. syst. errors
12/2009	8.28 ± 0.15	Gillessen et al. (2009b)	S stars, 1992–2008, combined ESO/Keck data sets; syst. unc. 0.29 kpc
12/2009	8.34 ± 0.27	Gillessen et al. (2009b)	S2 only, 1992–2008, combined ESO/Keck data sets; syst. unc. 0.52 kpc
05/2011	8.0 ± 0.3	Yelda et al. (2011)	S2 only, 1995–2007; new distortion corrections
08/2012	7.7 ± 0.4	Morris et al. (2012)	S stars, 1995–2011
02/2013	8.2 ± 0.34	Gillessen et al. (2013)	5 S stars, 1992–2012
		Nuclear star cluster: Statistical parallaxes	
12 1995	8.21 ± 0.98	Huterer et al. (1995)	50 M giants
09 2000	8.2 ± 0.9	Genzel et al. (2000)	104 stars with proper motions; 71 stars with z velocities
09 2000	7.9 ± 0.85	Genzel et al. (2000)	Corrected for the effects of a central point mass
11 2003	7.2 ± 0.9	Eisenhauer et al. (2003)	Uniform, isotropic, phase-mixed system
12 2008	8.07 ± 0.35	Trippe et al. (2008)	664 late-type giants
05 2011	8.07 ± 0.32	Trippe et al. (2011)	Velocity dispersion; systematic uncertainty 0.13 kpc
12 2013	$8.12^{+0.43}_{-0.41}$	Do et al. (2013)	Isotropic velocity distribution
12 2013	8.92 ± 0.58	Do et al. (2013)	Anisotropic spherical Jeans models
12 2013	$8.46^{+0.42}_{-0.38}$	Do et al. (2013)	Combined with Ghez et al. (2008)
02 2015	8.27 ± 0.09	Chatzopoulos et al. (2015)	Systematic uncertainty 0.1 kpc
02 2015	8.33 ± 0.11	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 $R_0 = 7.9^{+0.1}_{-0.2}$ kpc (see also Bono et al. 2013; Matsunaga 2013). The latter value was scaled based on adoption of $(m-M)_0 = 18.50$ mag for the distance modulus to the Large Magellanic Cloud. 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.[2] If this small distance differential between the nuclear Cepheids and the actual Galactic Center is real, this may imply that the former objects are seen in projection onto the Galactic Center. In fact, 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–

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[2] On the other hand, a comparison of Matsunaga et al.'s (2011) Galactic Center distance estimate with those based on the centroids of the distributions of different Cepheid samples (Section 3.3) suggests that any differences are negligible.

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 non-standard 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; Nataf et al. 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 Fig. 1c–e showed the 'raw,' uncorrected centroid data collected in our database, Fig. 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 $M_V(\mathrm{HB}) = 0.60$ mag for globular clusters, $M_V(\mathrm{RR}) = 0.72$ 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., $M_I^{\mathrm{RC}} = -0.23$ mag and $M_K^{\mathrm{RC}} = -1.57$ mag, with $M_K^{\mathrm{RC}} = M_{K_s}^{\mathrm{RC}} + 0.044$ mag (Grocholski & Sarajedini 2002). In addition, we adopted a homogenized distance scale based on $(m-M)_0^{\mathrm{LMC}} = 18.50$ mag, thus also ensuring internal consistency with the recommended distance benchmarks derived in Papers I–III.
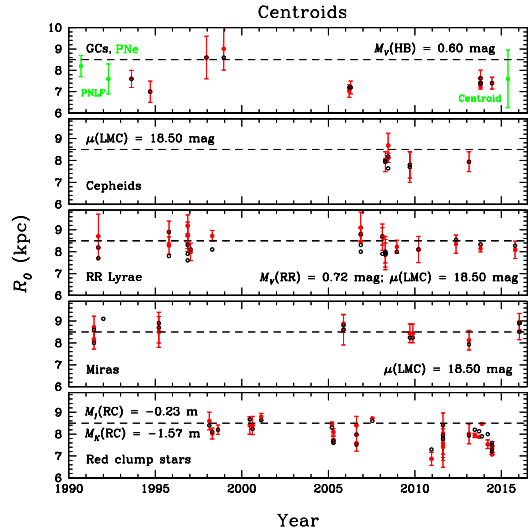
The left-hand side of Table 3 provides an overview of

Figure 2. Homogenized, post-1990 Galactic Center distance estimates based on centroid determinations. The tracers used and the calibrations applied are indicated in the individual panels; GCs: Globular clusters; PNe: Planetary nebulae; PNLF: PN luminosity function; $\mu(\mathrm{LMC})$: LMC distance modulus. Where estimates have been recalibrated, the original data points are shown as black open circles (without error bars for reasons of clarity), while the homogenized values appear as red bullets with their corresponding error bars. The horizontal dashed lines represent the IAU-recommended Galactic Center distance.

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, σ) 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 populations at or near the solar circle, combined with a kinematic disk (mass) model of the Milky Way galaxy. Suitable tracers include Cepheid

Table 2. Adopted, homogenized centroid-based distances used in this paper. Entries in **bold font** are newly updated (homogenized) distance estimates.

Publ. date (mm/yyyy)	R_0 (kpc)	Reference	Original Calibration	Notes[a]
			Globular clusters; $\langle[\mathrm{Fe/H}]^{\mathrm{GCs}}\rangle = -1.5$ dex	
08/1993	7.6 ± 0.4	Maciel (1993)	$M_V(\mathrm{HB}) = 0.6$ mag	46 GCs, $[\mathrm{Fe/H}] > -1.2$ dex
09/1994	7 ± 0.5	Rastorguev et al. (1994)	$M_V(\mathrm{RR}) = 0.6$ mag	$\cdots$
00/1998	8.6 ± 1.0	Surdin & Feoktistov (unpubl.)	$\cdots$	quoted in Surdin (1999) as 'submitted'
00/1999	$\mathbf{9.0} \pm 1.0$	Surdin (1999)	$M_V(\mathrm{HB}) = 0.20[\mathrm{Fe/H}] + 1.00$ mag	126 GCs
03/2006	$\mathbf{7.0} \pm 0.3$	Bonatto et al. (2009)	Calibration from Bica et al. (2006)	$\cdots$
04/2006	7.2 ± 0.3	Bica et al. (2006)	$M_V(\mathrm{HB}) = 0.16[\mathrm{Fe/H}] + 0.84$ mag	116 GCs
10/2013	7.63 ± 0.38	Nikiforov & Smirnova (2013)	$M_V(\mathrm{HB}) = 0.16[\mathrm{Fe/H}] + 0.84$ mag	all methods
10/2013	7.42 ± 0.23	Nikiforov & Smirnova (2013)	$M_V(\mathrm{HB}) = 0.16[\mathrm{Fe/H}] + 0.84$ mag	all spatial methods
10/2013	7.36 ± 0.24	Nikiforov & Smirnova (2013)	$M_V(\mathrm{HB}) = 0.16[\mathrm{Fe/H}] + 0.84$ mag	Shapley's method and related spatial methods
06/2014	7.4 ± 0.2	Francis & Anderson (2014)	$M_V(\mathrm{RR}) = 1.067 + 0.502[\mathrm{M/H}]$ $+0.108[\mathrm{M/H}]^2$ mag	154 GCs, syst. unc. 0.2 kpc
			Cepheids	
04/2008	7.94 ± 0.37	Groenewegen et al. (2008)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	Cepheids and RR Lyrae; syst. unc. 0.26 kpc
04/2008	7.99 ± 0.09	Groenewegen et al. (2008)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	Type II Cepheids
06/2008	$\mathbf{8.11} \pm 0.21$	Feast et al. (2008)	$(m - M)_0^{\mathrm{LMC}} = 18.37$ mag	Type II Cepheids
06/2008	$\mathbf{8.69} \pm 0.56$	Feast et al. (2008)	$(m - M)_0^{\mathrm{LMC}} = 18.37$ mag	Type II Cepheids, incl. κ Pav
09/2009	7.8 ± 0.6	Majaess et al. (2009)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	Type II Cepheids
09/2009	7.7 ± 0.7	Majaess et al. (2009)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	Type II Cepheids + bulge model
02/2013	7.94 ± 0.37	Matsunaga (2013)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	100 Miras, Cepheids, RC stars; syst. unc. 0.26 kpc
			RR Lyrae; $\langle[\mathrm{Fe/H}]^{\mathrm{RR}}\rangle = -1.0$ dex	
09/1991	$\mathbf{8.7} \pm 1.0$	Walker & Terndrup (1991)	$M_V(\mathrm{RR}) = 0.85$ mag	$N = 44$, Baade's Window; $R_V = 3.1$
09/1991	$\mathbf{8.2} \pm 0.$	Walker & Terndrup (1991)	$M_V(\mathrm{RR}) = 0.85$ mag	$N = 44$, Baade's Window; $R_V = 3.35$, Carney et al. (1992) distance scale
10/1995	$\mathbf{8.28} \pm 0.40$	Carney et al. (1995)	$M_V(\mathrm{RR}) = 0.85$ mag	$N = 58$, Baade's Window
10/1995	8.9 ± 0.5	Carney et al. (1995)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	$N = 58$, Baade's Window (but see Feast 1997)
11/1996	$\mathbf{8.4} \pm 0.4$	Layden et al. (1996)	$(m - M)_0^{\mathrm{LMC}} = 18.28$ mag $M_V(\mathrm{RR}) = 0.15[\mathrm{Fe/H}] + 0.95$ mag	Baade's Window
11/1996	$\mathbf{9.2} \pm 0.5$	Layden et al. (1996)	$(m - M)_0^{\mathrm{LMC}} = 18.28$ mag $M_V(\mathrm{RR}) = 0.60$ mag	Baade's Window
11/1996	$\mathbf{8.7} \pm 0.6$	Layden et al. (1996)	Combined approach	'best' value
01/1997	$\mathbf{8.0} \pm 0.4$	Feast (1997)	$(m - M)_0^{\mathrm{LMC}} = 18.53$ mag $M_V(\mathrm{RR}) = 0.37[\mathrm{Fe/H}] + 1.13$ mag	$N = 18$
04/1998	$\mathbf{8.7} \pm 0.25$	Udalski (1998)	$M_V(\mathrm{RR}) = 0.88$ mag	$N = 73$
11/2006	8.8 ± 0.3	Collinge et al. (2006)	$M_V(\mathrm{RR}) = 0.72$ mag	$N = 159$, Baade's Window
11/2006	$\mathbf{8.8} \pm 0.3$	Collinge et al. (2006)	$M_V(\mathrm{RR}) = 0.92$ mag	$N = 159$, Baade's Window
11/2006	$\mathbf{9.1} \pm 0.7$	Collinge et al. (2006)	Combined approach	$N = 159$, Baade's Window
02/2008	8.7 ± 0.4	Kunder et al. (2008)	$M_V(\mathrm{RR}) = 0.72$ mag	$\cdots$
02/2008	$\mathbf{8.7} \pm 0.6$	Kunder et al. (2008)	$M_V(\mathrm{RR}) = 0.92$ mag	$\cdots$
04/2008	7.94 ± 0.37	Groenewegen et al. (2008)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	Cepheids+RR Lyrae
04/2008	7.87 ± 0.64	Groenewegen et al. (2008)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	$N = 37$, Sollima et al. (2006) PLC calibration
04/2008	8.0 ± 0.7	Groenewegen et al. (2008)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	$N = 37$, Sollima et al. (2006) PLR calibration
12/2008	$\mathbf{8.2} \pm 0.3$	Kunder & Chaboyer (2008)	$M_V(\mathrm{RR}) = 1.19 + 0.5[\mathrm{Fe/H}]$ $+0.09[\mathrm{Fe/H}]^2$ mag	$N = 2690$, bulge
03/2010	8.1 ± 0.6	Majaess (2010)	$(m - M)_0^{\mathrm{LMC}} = 18.50$ mag	$\cdots$
05/2012	$\mathbf{8.35} \pm 0.42$	Pietrukowicz et al. (2012)	$M_V(\mathrm{RR}) = 2.288 + 0.882 \log Z$ $+0.108(\log Z)^2$ mag	$\log Z \equiv [\mathrm{Fe/H}] - 1.765$ dex
10/2013	$\mathbf{8.14} \pm 0.05$	Dékány et al. (2013)	Catelan et al. (2004) calibration	Systematic uncertainty 0.14 kpc
10/2015	$\mathbf{8.08} \pm 0.01$	Pietrukowicz et al. (2014)	Catelan et al. (2004) calibration	Systematic uncertainty 0.40 kpc

Table 2. (Continued)

Publ. date (mm/yyyy)	R_0 (kpc)	Reference	Original Calibration	Notes
			Miras	
06/1991	$\mathbf{8.7} \pm 0.5$	Whitelock et al. (1991)	$(m-M)_0^{\mathrm{LMC}} = 18.47$ mag	$\cdots$
06/1991	$\mathbf{8.1} \pm 0.5$	Whitelock et al. (1991)	$(m-M)_0^{\mathrm{LMC}} = 18.47$ mag	$\cdots$
00/1992	9.1	Whitelock (1992)	$\cdots$	$\cdots$
03/1995	$\mathbf{8.5} \pm 0.7$	Glass et al. (1995)	$(m-M)_0^{\mathrm{LMC}} = 18.55$ mag	$\cdots$
03/1995	$\mathbf{8.7} \pm 0.7$	Glass et al. (1995)	$(m-M)_0^{\mathrm{LMC}} = 18.55$ mag	If located in the Galactic bar
11/2005	8.6 ± 0.7	Groenewegen & Blommaert (2005)	$(m-M)_0^{\mathrm{LMC}} = 18.50$ mag	$N = 2691$
11/2005	$\mathbf{8.9} \pm 0.4$	Groenewegen & Blommaert (2005)	$(m-M)_0^{\mathrm{LMC}} = 18.48$ mag	$N = 2691$; Feast (2004) calibration
09/2009	$\mathbf{8.43} \pm 0.08$	Matsunaga et al. (2009)	$(m-M)_0^{\mathrm{LMC}} = 18.45$ mag	Systematic uncertainty 0.42 kpc
11/2009	$\mathbf{8.43} \pm 0.08$	Matsunaga et al. (2009)	$(m-M)_0^{\mathrm{LMC}} = 18.45$ mag	Systematic uncertainty 0.42 kpc
02/2013	$\mathbf{8.13} \pm 0.37$	Matsunaga (2013)	$(m-M)_0^{\mathrm{LMC}} = 18.45$ mag	Cepheids, Miras, RC stars; syst. unc. 0.26 kpc
01/2016	8.9 ± 0.4	Catchpole et al. (2016)	$(m-M)_0^{\mathrm{LMC}} = 18.49$ mag	$2.1 \le \log P[\mathrm{days}] < 2.6$
01/2016	8.5 ± 0.4	Catchpole et al. (2016)	$(m-M)_0^{\mathrm{LMC}} = 18.49$ mag	$2.6 \le \log P[\mathrm{days}] < 2.7$
01/2016	8.9 ± 0.4	Catchpole et al. (2016)	$(m-M)_0^{\mathrm{LMC}} = 18.49$ mag	Combined approach
			Red clump stars	
02/1998	$\mathbf{8.6} \pm 0.4$	Paczyński & Stanek (1998)	$M_I^0 = -0.28$ mag	$\cdots$
04/1998	$\mathbf{8.0} \pm 0.25$	Udalski (1998)	$M_I = (0.09 \pm 0.03)[\mathrm{Fe/H}]^{\mathrm{RC}}$ $-(0.23 \pm 0.03)$ mag	$[\mathrm{Fe/H}]^{\mathrm{RC}} = +0.2$ dex; 73 RRab Lyrae, RC stars
08/1998	8.2 ± 0.15	Stanek & Garnavich (1998)	$M_I = -0.23$ mag	$\cdots$
06/2000	$\mathbf{8.40} \pm 0.4$	Stanek et al. (2000)	$M_I^0 = -0.16$ mag	$\cdots$
08/2000	$\mathbf{8.39} \pm 0.42$	Alves (2000)	$M_K = -1.61 \pm 0.03$ mag	$\cdots$
02/2001	$\mathbf{8.79} \pm 0.16$	Gould et al. (2001)	$M_K = -1.61$ mag	Updated zero points
03/2005	$\mathbf{8.5} \pm 0.1$	Nishiyama et al. (2005)	$M_K = -1.61$ mag	$\cdots$
04/2005	$\mathbf{8.1} \pm 0.15$	Babusiaux & Gilmore (2005)	$M_K = -1.68$ mag	$\cdots$
04/2005	$\mathbf{7.7} \pm 0.15$	Babusiaux & Gilmore (2005)	$M_K = -1.61$ mag	$\cdots$
08/2006	$\mathbf{7.59} \pm 0.10$	Nishiyama et al. (2006)	$M_K = -1.59$ mag	$\cdots$
08/2006	$\mathbf{8.40} \pm 0.42$	Nishiyama et al. (2006)	$M_K = -1.68$ mag	Recalibration of Alves (2000)
07/2007	$\mathbf{8.7}$	Rattenbury et al. (2007)	$M_I^0 = -0.26$ mag	Upper limit
12/2010	$\mathbf{6.9} \pm 0.3$	McWilliam & Zoccali (2010)	$M_K = -1.44$ mag	$\cdots$
08/2011	$\mathbf{7.43} \pm 0.63$	Fritz et al. (2011)	$M_{K_\mathrm{s}} = -1.47$ mag	K_s
08/2011	$\mathbf{7.43} \pm 0.95$	Fritz et al. (2011)	$M_{K_\mathrm{s}} = -1.47$ mag	H
08/2011	$\mathbf{8.03} \pm 0.94$	Fritz et al. (2011)	$M_{K_\mathrm{s}} = -1.47$ mag	L'
08/2011	$\mathbf{7.58} \pm 0.65$	Fritz et al. (2011)	$M_{K_\mathrm{s}} = -1.47$ mag	mean
02/2013	$\mathbf{8.01} \pm 0.37$	Matsunaga (2013)	$M_K = -1.59$ mag	Cepheids, Miras, RC stars
06/2013	$\mathbf{7.94} \pm 0.1$	Nataf et al. (2013)	$M_{K_\mathrm{s}} = -1.50$ mag	$\cdots$
09/2013	$\mathbf{7.87}$	Cao et al. (2013)	$M_{K_\mathrm{s}} = -1.50$ mag	$\cdots$
11/2013	$\mathbf{8.5}$	Wegg & Gerhard (2013)	$M_K = -1.72$ mag	$\cdots$
03/2014	$\mathbf{7.5} \pm 0.2$	Gardner et al. (2014)	$M_K = -1.44$ mag	$\cdots$
06/2014	$\mathbf{7.4} \pm 0.3$	Francis & Anderson (2014)	$M_K = -1.53 \pm 0.01$ mag $M_I = -0.24 \pm 0.01$ mag	*Hipparcos* recalibration
06/2014	$\mathbf{7.5}$	Francis & Anderson (2014)	$M_K = -1.53 \pm 0.01$ mag $M_I = -0.24 \pm 0.01$ mag	Recalibration of Alves (2000)
06/2014	$\mathbf{7.2}$	Francis & Anderson (2014)	$M_K = -1.53 \pm 0.01$ mag $M_I = -0.24 \pm 0.01$ mag	Recalibration of Babusiaux & Gilmore (2005)
06/2014	$\mathbf{7.1}$	Francis & Anderson (2014)	$M_K = -1.53 \pm 0.01$ mag $M_I = -0.24 \pm 0.01$ mag	Recalibration of Nishiyama et al. (2006)

[a] Abbreviations used: GCs, globular clusters; N, number of objects; P, period; PLC, period–luminosity–color relation; PLR, period–luminosity relation; RC, red clump; syst. unc., systematic uncertainty.

Table 3. Mean original and homogenized Galactic Center distances and their standard deviations (σ) based on published post-1990 estimates. 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.

| | Centroids | | | | | Kinematics | | | |
| | Before correction | | After correction | | | Before correction | | After correction | |
Tracer	Mean	σ	Mean	σ	Tracer	Mean	σ	Mean	σ
Globular clusters	7.63	0.66	7.60	0.56	Cepheids+RR Lyrae	7.88	0.44	8.15	0.43
Cepheids	8.02	0.32	7.88	0.19	Open clusters	7.73	0.98	7.76	1.07
RR Lyrae	8.15	0.34	8.45	0.39	Disk tracers	7.68	0.49	$\cdots$	
Miras	8.57	0.35	8.58	0.27	Masers	8.01	0.53	$\cdots$	
Red clump stars	7.91	0.53	7.96	0.42					

and RR Lyrae variable stars, open clusters, and maser sources, as well as the distributions of HI and CO. Figure 3 shows the relevant measurements published since 1990. As before, we have attempted to homogenize these estimates where possible, particularly the Cepheid-, RR Lyrae-, and open cluster-based distances. The latter are benchmarked with respect to the distance to the Hyades, $(m - M)_0^{\mathrm{Hya}} = 3.42$ mag, which also ensures internal consistency with the LMC distance modulus adopted in this series of papers. The mean R_0 values and their associated standard deviations based on kinematic disk modeling are included on the right-hand side of Table 3.

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, Θ_0, and R_0 to transfer all these measurements onto a common scale. McMillan & Binney (2010) carefully re-evaluated 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 $R_0 = 8.9 \pm 0.9$, and Θ_0 from 200 ± 20 km s^{-1} to 279 ± 33 km s^{-1}. Despite these large ranges in R_0 and Θ_0, which are largely driven by one's choice of Galactic rotation curve, these au-
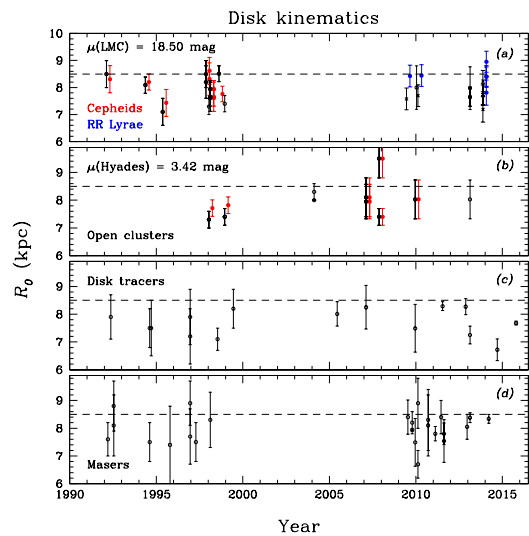

Figure 3. Post-1990 Galactic Center distance estimates based on kinematic disk models for a variety of tracers, as indicated in the individual panels. Where possible, we have homogenized the Galactic Center distances based on RR Lyrae and Cepheid variables, as well as those based on open cluster distances. 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.

thors found that—with one exception—the Θ_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, Fig. 4 shows that, in practice, the Θ_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 three-year 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 de-

Table 4. Adopted, homogenized kinematics-based distances used in this paper. Entries in **bold font** are newly updated (homogenized) distance estimates.

Publ. date (mm/yyyy)	R_0 (kpc)	Reference	Original Calibration	Θ_0 (km s^{-1})	Notes[a]
			Cepheids		
02/1992	**8.3** ± 0.5	Caldwell et al. (1992)	$(m-M)_0^{\mathrm{LMC}} = 18.55$ mag	248 ± 16	$N = 212$
05/1994	**8.20** ± 0.30	Pont et al. (1994)	$(m-M)_0^{\mathrm{LMC}} = 18.47$ mag	257 ± 7	$\cdots$
05/1995	**7.4** ± 0.5	Dambis et al. (1995)	$(m-M)_0^{\mathrm{Hya}} = 3.30$ mag	$\cdots$	$\cdots$
11/1997	**8.6** ± 0.5	Feast & Whitelock (1997)	$(m-M)_0^{\mathrm{LMC}} = 18.47$ mag	$\cdots$	R_0 from Pont et al. (1994); new PLR
11/1997	**8.3** ± 0.6	Feast & Whitelock (1997)	$(m-M)_0^{\mathrm{LMC}} = 18.47$ mag	$\cdots$	R_0 from Metzger et al. (1998); new PLR
01/1998	**7.7** ± 0.3	Glushkova et al. (1998)	$(m-M)_0^{\mathrm{Hya}} = 3.30$ mag	200 ± 15	$N = 202$: open clusters, Cepheids, RSGs
02/1998	7.66 ± 0.32	Metzger et al. (1998)	$(m-M)_0^{\mathrm{LMC}} = 18.50$ mag	237 ± 12	Systematic uncertainty 0.44 kpc
02/1998	7.95 ± 0.31	Metzger et al. (1998)	$(m-M)_0^{\mathrm{LMC}} = 18.50$ mag	237 ± 12	$N = 7$, solar circle; no orbital ellipticity
02/1998	7.61 ± 0.30	Metzger et al. (1998)	$(m-M)_0^{\mathrm{LMC}} = 18.50$ mag	237 ± 12	$N = 7$, solar circle; 4% orbital ellipticity
08/1998	**7.76** ± 0.29	Feast et al. (1998)	$(m-M)_0^{\mathrm{LMC}} = 18.70$ mag	$\cdots$	$N = 266$
00/1999	**7.8** ± 0.3	Glushkova et al. (1999)	$(m-M)_0^{\mathrm{Hya}} = 3.30$ mag	204 ± 15	$N = 202$: open clusters, Cepheids, RSGs; use caution[b]
01/2010	8.0 ± 0.8	Shen & Zhang (2010)		239 ± 12	$\cdots$
02/2013	7.66 ± 0.36	Bobylev (2013)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	267 ± 17	$N = 14$; $P > 5$ days
02/2013	7.64 ± 0.32	Bobylev (2013)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	217 ± 11	$N = 18$; proper motions
02/2013	7.98 ± 0.79	Zhu & Shen (2013)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	239 ± 23	$N = 215$
			RR Lyrae		
06/2009	**8.43** ± 0.40	Dambis (2009)	$(m-M)_0^{\mathrm{LMC}} = 18.27$ mag	229 ± 12	$\cdots$
02/2010	**8.4** ± 0.4	Dambis (2010)	$(m-M)_0^{\mathrm{LMC}} = 18.30$ mag	195 ± 5	$\cdots$
11/2013	**8.41** ± 0.40	Dambis et al. (2013)	$(m-M)_0^{\mathrm{LMC}} = 18.32$ mag	234 ± 10	Recalibration of Carney et al. (1995)
11/2013	**7.81** ± 0.40	Dambis et al. (2013)	$(m-M)_0^{\mathrm{LMC}} = 18.32$ mag	234 ± 10	Recalibration of Groenewegen et al. (2008)
11/2013	**8.95** ± 0.39	Dambis et al. (2013)	$(m-M)_0^{\mathrm{LMC}} = 18.32$ mag	234 ± 10	Recalibration of Collinge et al. (2006)
11/2013	**8.40** ± 0.36	Dambis et al. (2013)	$(m-M)_0^{\mathrm{LMC}} = 18.32$ mag	234 ± 10	Average value
			Open clusters		
01/1998	**7.7** ± 0.3	Glushkova et al. (1998)	$(m-M)_0^{\mathrm{Hya}} = 3.30$ mag	200 ± 15	$N = 202$: open clusters, Cepheids, RSGs
00/1999	**7.8** ± 0.3	Glushkova et al. (1999)	$(m-M)_0^{\mathrm{Hya}} = 3.30$ mag	204 ± 15	$N = 202$: open clusters, Cepheids, RSGs; use caution[b]
02/2004	8.3 ± 0.3	Gerasimenko (2004)	$\cdots$	$\cdots$	$N = 146$; Weaver's method
02/2004	8.0	Gerasimenko (2004)	$\cdots$	$\cdots$	$N = 34$; Fokker's method
02/2007	7.95 ± 0.62	Shen & Zhu (2007)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	244 ± 14	$N = 270$
02/2007	8.1 ± 0.7	Shen & Zhu (2007)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	244 ± 14	Mean value (open clusters, OB stars)
11/2007	7.4 ± 0.3	Bobylev et al. (2007)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	195 ± 7	$N = 375$
11/2007	9.5 ± 0.7	Bobylev et al. (2007)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	195 ± 7	Young open clusters (< 50 Myr)
11/2007	5.6 ± 0.3	Bobylev et al. (2007)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	195 ± 7	Old open clusters (> 50 Myr)
12/2009	8.03 ± 0.70	Zhu (2009)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	235 ± 10	$N = 301$
02/2013	8.03 ± 0.70	Zhu & Shen (2013)	$(m-M)_0^{\mathrm{Hya}} = 3.42$ mag	260 ± 15	$N = 301$

[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.

viations. Between 1990 and 2007, the majority of Θ_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 Θ_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 $\Theta_0^{\mathrm{IAU}} = 220$ km s^{-1}. In fact, this is confirmed statistically: 33 of the 55 post-1990 values of Θ_0 used in this paper attained values of $\Theta_0 \geq 230$ km s^{-1} (only 17 out of 55 publications derived $\Theta_0 < 220$ 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
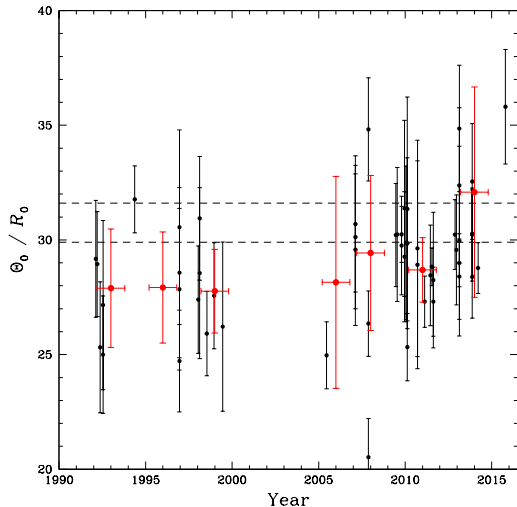
Figure 4. Θ_0/R_0 ratios used for determination of the Galactic Center distance based on kinematic disk modeling, published since 1990. The horizontal dashed lines indicate the theoretically expected range (McMillan & Binney 2010). The red data points are three-year averages, where the horizontal 'error bars' indicate the relevant time period sampled and the vertical error bars represent the corresponding standard deviations.

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 $\Theta_0 \in [235, 260]$ km s^{-1} at the present time (e.g., Shen & Zhu 2007; Bovy et al. 2009; Zhu 2009; McMillan & Binney 2010; Sato et al. 2010; Shen & Zhang 2010; Brunthaler et al. 2011; McMillan 2011; Honma et al. 2012; Schönrich 2012; 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,b; 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,b; Paper I) or by a sudden shift in preferred values following a landmark publication.

Malkin (2013a,b) explored evidence of the former using his compilation of 53 R_0 determinations published over a period of some 20 years (1992–2011), but he did not find any statistically significant trend.[3] 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 Galactic Center distance estimates. These 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 method applied are improved, and systematic errors might be reduced (e.g., Malkin 2013a,b).

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. 2009;

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[3] 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 Fig. 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 of the methods used, or both.

Francis & Anderson 2014). Two potentially important issues 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. 2009). Francis & Anderson (2014) pointed out that the corrections for the relativistic geodetic effect (de Sitter precession) attempted by Gillessen et al. (2009) are based on the assumption that this precession arises in the Schwarzschild metric, whereas one should instead adopt the Kerr metric associated with a relativistically rotating central black hole. In turn, this leads to 'frame dragging' (also known as the Lense–Thirring effect), which is predicted to affect both the S stars' orbits and the light paths into the line of sight. Neither Zucker et al. (2006) nor Gillessen et al. (2009) 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. (2009) 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 Fig. 1b 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. (2009), which resulted in an upward adjustment of approximately 0.6 kpc.

Gillessen et al. (2009) 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. (2009) 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. 2009, 2013) and Ghez' 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. 2009). 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. These latter authors only commented that this estimate corresponds to their current best fit to the observational data from 1995–2011. 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. 2009). 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 years leading up to 2015 (for a brief discussion, see Section 3.1). Therefore, the current-best distance determination to the Galactic Center is, arguably, based on appropriate combined direct observations of both the S-star orbits and the Galactic Center's statistical parallax properties. Do et al. (2013) and Chatzopoulos et al. (2015) both attempted such a combination, yielding $R_0 = 8.46^{+0.42}_{-0.38}$ kpc and $R_0 = 8.33 \pm 0.11$ kpc, respectively.[4] However, other recent direct Galactic Center distance measurements yield somewhat smaller distances (e.g., Trippe et al. 2008, 2011; Yelda et al. 2011; Gillessen et al. 2013). At the present time, we therefore advocate a benchmark Galactic Center distance of $R_0 = 8.3 \pm 0.2$ kpc, where the uncertainty is the statistical error resulting from combination of the Do et al. (2013) and Chatzopoulos et al. (2015) 'combined' values. The additional, systematic uncertainty, which should be added in quadrature, is of order ± 0.4 kpc. The latter estimate follows from consideration of the full set of updated values of R_0 in Table 1, where the variety of assumptions made is reflected in the spread of the central values (see also the

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[4] Both studies were, in essence, modern applications of the idea to combine velocity dispersions with proper motion measurements in the Galactic bulge, first proposed by Minniti (1993) and Kuijken (1995).

discussion in Section 3.1).

4.3. *Indirect distance determinations*

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 distances estimates, while the RR Lyrae and Mira variables result in larger Galactic Center centroid distances (see, e.g., Table 2).

Indeed, it has been suggested that some tracers, and in particular the ($t \geq 10$ 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 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 $M_V(\mathrm{RR}) = 0.72$ mag. If the original papers quoting Galactic Center distance determinations used any other absolute magnitude calibration (see Table 2), 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 would introduce a dependence on the pulsation period, since RR Lyrae exhibiting longer periods are brighter. Where appropriate, we have also assumed that [Fe/H] $= -1.0$ dex for RR Lyrae in the bulge (e.g., Bono 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 [Fe/H]$= -1$, $\langle M_K \rangle = -0.5$ 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 Fig. 2).

For all other tracers we only find statistically *insignificant* ($\lesssim 1\sigma$) 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 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.

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 October 1918 until June 2016. 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 pub-

lished Galactic Center distances based on these methods resulted in our Galactic Center distance recommendation of $R_0 = 8.3 \pm 0.2$ (statistical) ± 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, these latter measurement can indeed be used to constrain the Galaxy's rotation velocity at the solar Galactocentric distance using the Θ_0/R_0 ratios employed by their respective authors. We found a gradual increase in the mean value of Θ_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 ($R_0^{\mathrm{IAU}} = 8.5$ 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 upwards of a billion stars that the mission will provide by the end of its nominal five-year 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 at 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 of not just 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 & 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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