CLUSTERING OF LOCAL GROUP DISTANCES: PUBLICATION BIAS OR CORRELATED MEASUREMENTS? I. THE LARGE MAGELLANIC CLOUD

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ABSTRACT

The distance to the Large Magellanic Cloud (LMC) represents a key local rung of the extragalactic distance ladder yet the galaxy’s distance modulus has long been an issue of contention, in particular in view of claims that most newly determined distance moduli cluster tightly—and with a small spread—around the “canonical” distance modulus, \((m-M)_0 = 18.50\) mag. We compiled 233 separate LMC distance determinations published between 1990 and 2013. Our analysis of the individual distance moduli, as well as of their two-year means and standard deviations resulting from this largest data set of LMC distance moduli available to date, focuses specifically on Cepheid and RR Lyrae variable-star tracer populations, as well as on distance estimates based on features in the observational Hertzsprung–Russell diagram. We conclude that strong publication bias is unlikely to have been the main driver of the majority of published LMC distance moduli. However, for a given distance tracer, the body of publications leading to the tightly clustered distances is based on highly non-independent tracer samples and analysis methods, hence leading to significant correlations among the LMC distances reported in subsequent articles. Based on a careful, weighted combination, in a statistical sense, of the main stellar population tracers, we recommend that a slightly adjusted canonical distance modulus of \((m-M)_0 = 18.49 \pm 0.09\) mag be used for all practical purposes that require a general distance scale without the need for accuracies of better than a few percent.

Key words: astronomical databases: miscellaneous – distance scale – galaxies: distances and redshifts – galaxies: individual (Large Magellanic Cloud)

Online-only material: color figures

1. INTRODUCTION

The distance to the Large Magellanic Cloud (LMC) is a key stepping stone in establishing an accurate extragalactic distance ladder. The LMC is the nearest extragalactic environment that hosts statistically significant samples of the tracer populations that are commonly used for distance determinations, including Cepheid and RR Lyrae variable stars, eclipsing binaries (EBs), and red-giant-branch (RGB) stars, as well as supernova (SN) 1987A, among others. These could thus potentially link the fairly well-understood local (solar-neighborhood and Galactic) tracers to their counterparts in more distant and more poorly resolved galaxies. In fact, at a distance of approximately 50 kpc, the LMC represents the only well-studied environment linking Galactic distance tracers to those in other large spiral and elliptical galaxies at greater distances, including M31 at a distance of \(\sim 750–780\) kpc or a distance modulus of \((m-M)_0 = 24.38–24.47\) mag (e.g., Freedman et al. 2001; McGonachie et al. 2005). Yet, despite the plethora of studies claiming to have determined independent distance measurements to the LMC, lingering systematic uncertainties remain. This has prompted significant concern in the context of using the LMC distance as a calibrator to reduce the uncertainties in the Hubble constant (cf. Freedman et al. 2001; Schaefer 2008; Pietrzynski et al. 2013). It has also led to persistent claims of “publication bias” affecting published distances to the galaxy (cf. Schaefer 2008, 2013; Rubele et al. 2012; Walker 2012).

In general, publication bias is the tendency of researchers to publish results that conform to some extent to the norm, while ignoring outputs that may be of low(er) significance or that deviate significantly from what is considered common knowledge in the relevant field. In other words, the strongest or most significant results are included for publication, while the rest of a presumably much larger set of results remain unseen. This also means that this effect is notoriously difficult to correct for, because the underlying null results are usually not published. The phenomenon of publication bias is well-known to occur in statistics and among medical trials (e.g., Sterling 1959; Rosenthal 1979; Begg & Berlin 1988; Naylor 1997; Stern & Simes 1997; Sterne et al. 2000), where it could have potentially devastating effects on people’s lives, or lead to ineffectual or even counterproductive treatments.

Liddle (2004) explains that “[p]ublication bias comes in several forms, for example if a single paper analyses several parameters, but then focusses attention on the most discrepant, that in itself is a form of bias. The more subtle form is where many different researchers examine different parameters for a possible effect, but only those who, by chance, found a significant effect for their parameter, decided to publicize it strongly.” Publication bias has also been claimed to occur in various fields related to astrophysics and cosmology, where in some cases efforts have also been made to correct for these effects (see, e.g., Slosar & Seljak 2004; Slosar et al. 2004; Schaefer 2008, 2013; Vaughan & Uttley 2008; Baier-Jones 2009; Sternberg et al. 2011; Foley et al. 2012).

In the context of the present paper, Schaefer (2008) focused his analysis on published LMC distance determinations. He specifically addressed the question as to whether or not the
publication of the final results of the Hubble Space Telescope (HST) Key Project on the Extragalactic Distance Scale (Freedman et al. 2001) had resulted in an unwarranted tightening up of the LMC’s distance scale. He considered as possible causes of such a tightening correlations among published results, widespread overestimation of uncertainty ranges, bandwagon effects, or a combination of these scenarios. He concluded with a warning that the community would do well to be vigilant and redress the effects of publication bias, which he considered the most likely cause of the clustering of LMC distance measurements he reported to have occurred during the period from 2002 until 2007 June.

Upon careful examination, however, we realized that Schaefer’s (2008) analysis—as well as his subsequent persistence in support of his 2008 conclusion that publication bias may have severally affected the body of LMC distance measurements (e.g., Schaefer 2013)—was based on a number of simplifying assumptions.

1. He concludes that the uncertainties in the post-2002 distance moduli are not distributed according to a Gaussian distribution, which he flags as a problem. However, in such a scenario, the underlying assumptions are that (1) the pre-2001 values were, in fact, distributed in a Gaussian fashion (they are not, however, as we will show in Section 3) and (2) conditions were comparable before and after the benchmark date. This latter assumption is likely also too simplistic, as we will argue in the context of Cepheid-based distance determinations in Section 4.1. We recommend—and pursue in this paper—a more detailed analysis of the individual distance moduli contributing to the overall trends observed to assess whether or not publication bias truly is to blame.

2. Schaefer (2008) based his results on published values and their uncertainties; the latter are, however, predominantly statistical uncertainties and the majority do not include systematic errors. Only a few authors include the systematic errors affecting their LMC distance estimates, however. In Section 5 we apply statistical tools to assess whether the distance moduli based on different tracer populations are statistically consistent with the “canonical” distance modulus and the recently published geometric distance based on late-type EB systems (Pietrzyński et al. 2013). We also compare the consistency among a number of different tracers and the entire body of distance measurements (see Sections 4 and 6).

3. The conclusions reached by Schaefer (2008) are, in essence, based on application of a statistical Kolmogorov–Smirnov (K-S) test, assuming a Gaussian distribution of LMC distance measurements, to a data set that should not a priori be expected to be distributed in a Gaussian fashion. Astrostatisticians have become more vocal in recent years in their opposition to the use of K-S tests in astronomy if not done with due caution (e.g., Feigelson & Babu 2013). K-S tests are only applicable to samples that consist of independent and identically distributed values. In the context of LMC distance measurements, both conditions are violated. In this paper we will show that the close match between subsequent LMC distance determinations is most likely owing to the use of highly non-independent tracer samples, analysis methods, and calibration relations.

4. As Schaefer (2008) points out himself, his database of LMC distance measurements is incomplete. He declares that this does not affect his inferences, but we found that gaps in the data set may, in fact, hide the presence of correlations among subsequent publications (cf. Section 4). For the analysis presented in this paper, we have collected the most complete and comprehensive database of published LMC distance moduli to date, so that our results will not be unduly affected by “gaps” in the coverage of our metadata.

These concerns, combined with the significantly longer period (compared with that accessible by Schaefer 2008) that has elapsed since Freedman et al.’s (2001) seminal paper, prompted us to embark on a detailed (re-)analysis of the full set of LMC distance determinations, claimed by many of their authors to be based on independent approaches (but see Section 4). The primary goal of the analysis presented in this paper is to explore the reasons behind the apparent tightening of the biennially (two-year) averaged distance moduli and the associated decrease in their standard deviations during specific periods of time. We aim at exploring whether “publication bias” is likely to play a significant role in driving this behavior or whether other effects may be at work. The longer time span we have access to compared with previous work also allows us to verify whether any clustering of data points persisted beyond the period range of Schaefer’s (2008) analysis and whether new clusters of data points may have materialized. Our detailed analysis of the complete body of published LMC distance moduli from 1990 until the end of 2013, both in full and as a function of distance tracer, is ideally suited to derive statistically robust constraints on the most appropriate mean distance modulus (projected to the LMC’s center) and its uncertainties for future use (modulo the quality of the individual determinations).

This paper is organized as follows. In Section 2, we present the full compilation of LMC distance moduli published between 1990 and the present time. Section 3 addresses general trends in the LMC distance moduli with time, while in Section 4 we consider such trends for individual distance tracers and discuss the independence (or lack thereof) of the results. We discuss the statistical basis of our analysis in Section 5. In Section 6 we place these results in a more general context, and we conclude with our recommendations of the most suitable distance modulus for common use, which naturally results from the analysis presented here. In Paper II (de Grijs & Bono 2014) we apply a similar analysis to our compilation of the equivalent sets of distance measurements for M31, M33, and a number of dwarf galaxies associated with the M31 system (and slightly beyond).

2. LMC DISTANCE MEASUREMENTS, 1990–2013

We compiled an extensive database of published distance measurements, following but significantly expanding upon Schaefer’s (2008) database. We used the compilations of Gibson (2000), Benedict et al. (2002a), Clementini et al. (2003), Steer & Madore (2007), Schaefer (2008), and de Grijs (2011; his Table 1.1) as our basis. Schaefer (2008) stated specifically that his final compilation was not necessarily complete. Therefore, we carefully checked which of the nearly 16,000 papers published between 1990 January 1 and 2013 December 31 and associated in the NASA/Astrophysics Data System with the object...
keyword “LMC” presented new distance determinations to the galaxy.

Our final compilation contains 233 separate distance determinations published from 1990 March until and inclusive of 2013 December. In addition to recording the month and year of publication, we compiled the extinction-corrected distance moduli, their statistical uncertainties and—where available—also the systematic errors. Only 47 authors published their systematic uncertainties separately, with an additional four papers specifying that their published error bars include the systematic uncertainties. For the remaining 182 LMC distance measurements, the uncertainties refer to the statistical errors only. Our overall compilation, in order of publication date as well as sorted by stellar population tracer, is available from http://astro-expat.info/Data/pubbias.html (all sources that were available at the time of our last update are listed, including those published in early 2014; our analysis is restricted to distance moduli published by 2013 December 31, however). The data tables include full bibliographic information and direct links to the source materials.

The database is predominantly based on distance measurements taken from peer-reviewed articles, although we include a total of 19 distance moduli that were published in conference proceedings. Seven of these latter values were based on Cepheids (from four different publications), six on RR Lyrae variables (from three conference papers) and three on geometric distance determinations (two using SN 1987A and one based on an early-type EB system). The remaining distance moduli published in conference proceedings were based on observations of M supergiants, Mira variable stars, and the planetary nebulae luminosity function (one determination for each method). We opted to include these values, because individual researchers will likely have checked the recent literature—including conference proceedings—for confirmation of their newly derived values. In addition, only two conference articles were followed up by publications in the peer-reviewed literature in the period from 1990 until the present time (Popowski & Gould 1998 versus 1999; Dall’Ora et al. 2004a versus 2004b). The distance moduli published in both cases were different between the earlier conference publication and the follow-up peer-reviewed article. The Dall’Ora et al. (2004a) conference paper was presented in 2003 May, followed by a peer-reviewed article more than a year later in 2004 July. Popowski & Gould (1998) used the Bono et al. (2001) calibration, while their 1999 paper was based on the updated Bono et al. (2003) calibration relations. We considered this sufficiently distinct to warrant inclusion of both articles in our database; the differences between the resulting distance moduli act as a reminder of the systematic uncertainties involved.

Rather than combining individual values based on different assumptions or input parameters (cf. Schaefer 2008), we opted to include all (final) LMC distance measurements published in a given paper. Schaefer (2008) argues (and we agree) that the range spanned by such alternative values provides a valuable estimate of the systematic uncertainty inherent to the distance determined, and that these values are highly non-independent. It is nevertheless instructive to compare the different values derived from varying one’s assumptions based on realistic boundaries. We will take into account any correlations among results from a given study, as well as correlations between studies based on similar (or the same) assumptions, when we discuss trends as a function of year of publication for the different tracers individually in Section 4.

Examples of correlated results based on small variations of the underlying assumptions in a given study include

1. variations in the extinction corrections,7 metallicities/α abundances or p (“projection”) factors8 assumed (e.g., Caputo 1997; Benedict et al. 2002a, 2002b; Storm et al. 2006; Haschke et al. 2012);

2. use of a given type of calibration relation for a specific tracer but for different wavelengths (e.g., Di Benedetto 1994; van Leeuwen et al. 1997; Madore & Freedman 1998; Groenewegen & Oudmaijer 2000; Bono et al. 2002b; Dall’Ora et al. 2004a; An et al. 2007; Laney et al. 2012);

3. application of different calibration methods for a given tracer (e.g., Feast 1995; Luri et al. 1998; Bono et al. 2002b; Clementini et al. 2003; McNamara et al. 2007); and

4. differences in the exact shape of the ring associated with SN 1987A (Gould & Uza 1998).

However, we also realized that, in many articles that report multiple distance measurements, not only the assumptions underlying these measurements but also the tracers used to derive them or their locations across the LMC’s main body differ.9 The combination of multiple values offers one good insights into the systematic uncertainties. However, we argue that inclusion of the individual values is justified in this context, in particular because many of the distance determinations published in subsequent papers are also highly non-independent (see Section 4).

Despite these differences in the choices made, we concur with Schaefer (2008) regarding the multitude of “minor dilemmas” that occur when deciding which values to include in one’s master database. In essence, we followed his choices (as well as equivalent choices for distance moduli not included in his database). Only in one case in common do we differ in our approach. Schaefer (2008) comments on the unrealistically small uncertainty on the LMC’s distance modulus published by Keller & Wood (2006), despite the fact that these latter authors provide a detailed discussion of the uncertainties affecting their results. Upon close examination of the Keller & Wood (2006) result, we realized that they give the uncertainty on the mean of their distribution of distance moduli, assuming a Gaussian distribution (which is not really warranted given the actual distribution of data values), instead of the distribution’s spread (σ). Therefore, we have included the spread, which we determined at σ = 0.06 mag for both of their published distance moduli (Keller & Wood 2002, 2006).

7 Reddening corrections have been and continue to be a major source of uncertainty: a number of different reddening maps are in common use (for a discussion, see Haschke et al. 2011), which has in part led to the long–short distance dichotomy discussed in Section 3. This is why, specifically in the context of variable-star analyses, the focus has gradually shifted from the use of wavelength- and reddening-dependent period–luminosity relations to reddening-free Wesenheit relations (cf. Inno et al. 2013; Ripepi et al. 2013).

8 Projection (p) factors are commonly used to convert radial to pulsation velocities.

9 These articles include Reid (1998), Udalski (1998), Luri et al. (1998), Popowski & Gould (1998, 1999), Feast (1999), Walker (1999), Carretta et al. (2000), Romaniello et al. (2000), Sakai et al. (2000), McNamara (2001), Benedict et al. (2002a)—and Benedict et al. (2002a versus 2002b)—Clementini et al. (2003), Groenewegen & Salaris (2003), Salaris et al. (2003), Rastorgueva et al. (2005), Ngeow & Kunbur (2008), Borissova et al. (2009), Subramanian & Subramaniam (2010), Haschke et al. (2012), and Inno et al. (2013).
3. TRENDS IN DISTANCE DETERMINATIONS TO THE LMC

Figure 1 displays the individual LMC distance moduli published between 1990 and 2013. The top left-hand panel shows all determinations, irrespective of distance tracer. The other three panels provide more details as regards the behavior of specific tracers with time. In all cases, except for the values determined by Keller & Wood (2002, 2006; see Section 2), the error bars included are those provided in the original papers. Where authors distinguish between statistical and systematic uncertainties, we only show the statistical uncertainties. (Note that, where available, the statistical uncertainties reported in the individual articles are specifically included in our online database.)

We made this choice for a number of reasons. First, the uncertainties quoted for the majority of published LMC distance moduli are statistical uncertainties. Showing only the statistical uncertainties where we also have the systematic errors thus represents a cleaner comparison among the distance values. Second, where multiple distance moduli were determined in a given paper, the spread among the derived values provides a good handle on the systematic uncertainties. Third, in many cases, the effects of systematic uncertainties are unclear or may have been underestimated (cf. Schaefer 2008). Systematic uncertainties in the LMC distance modulus can come in a variety of guises. They could be related to (1) one’s zero-point calibration, (2) the functional form of the calibration relations (see Section 4), (3) Lutz–Kelker-type biases in parallax measurements (see de Grijs 2011; his chapter 6.1.2), (4) systematics in the metallicity scale or extinction corrections adopted, or (5) transformations between filter systems. They may also be due to assumptions made to derive the underlying physical behavior or geometry of one’s tracer population (e.g., as for the SN 1987A ring and the precise locus of its line emission; cf. Gould & Uza 1998). An important type of systematic uncertainty is immediately apparent from inspection of the top left-hand panel of Figure 1, which takes the form of the well-known “long—short dichotomy.” Particularly at early times during the period of interest on which we focus here, authors would derive LMC distance moduli that were either “short” or “long.” Values straddled \((m-M)_0 \sim 18.3\) mag and \(\sim 18.6\) mag, respectively, hence leading to a dichotomy in published LMC distance moduli prior to about 2002 (see the top left-hand panel of Figure 1). This is a typical example of publication bias in astronomy (for discussions of the long—short dichotomy, see Carretta et al. 2000; Sandage & Tammann 2006). In this context, it is puzzling that Schaefer (2008) uses his conclusion that the errors in the LMC distance moduli published in 2002–2007 (when the dichotomy had all but disappeared) deviate from a Gaussian distribution as evidence that there must be a problem with the overall post-2002...
data set. This implicitly assumes that the post-2002 values are independent and distributed in a Gaussian fashion; we will show that both assumptions are not justified once one analyzes the data set in detail. Thus, while the 1997–2001 distance uncertainties may indeed have been larger than expected from a Gaussian distribution, this should not have been a surprise given that the pre-2001 distance values exhibited a clear long–short dichotomy owing to publication bias.

This dichotomy disappeared around 2002–2004 (but compare Dambis et al. 2013 with the canonical LMC distance modulus for more recent evidence of lingering systematics); yet, Schaefer (2008) interprets the post-2002 behavior as a result of publication bias and he perpetuates this view until the present time (Schaefer 2013). Here we question that latter conclusion. In Section 4, we will explore the trends for individual distance tracers so as to ascertain the reasons for a number of statistically significant reductions in the quoted error bars.

4. PUBLICATION BIAS OR CORRELATED METHODS?

In Figures 2–5 we show our metadata in a number of different ways to quantify and explore the trends that may be apparent in the actual distance moduli and their quoted uncertainties.

Figure 2 displays two-year averages of the published LMC distance moduli for all tracers, as well as for those tracers for which we have statistically significant numbers of measurements. In particular, we show the results for the Cepheid and RR Lyrae variable stars (80 and 60 entries, respectively), and for distance tracers based on certain features in the color–magnitude diagrams (CMDs) of LMC star clusters, for which we have collected 38 entries. Among the latter, we include results based on main-sequence (MS)/MS turnoff (MSTO) fitting (Carretta et al. 2000; McNamara 2001; Walker et al. 2001; Kerber et al. 2002; Groenewegen & Salaris 2003; Salaris et al. 2003), subdwarf fitting (Carretta et al. 2000), as well as on fits to white dwarf cooling sequences (Carretta et al. 2000), horizontal-branch (HB) stars (Gratton 1998; Reid 1998), the tip of the RGB (TRGB; Salaris & Cassisi 1997; Romaniello et al. 2000; Sakai et al. 2000; Bellazzini et al. 2004), and the red clump (RC; 24 entries). The full bibliography, as well as the set of individual values and their uncertainties for all distance tracers, are available at http://astro-expat.info/Data/pubbias.html. The only tracers that we do not examine individually in Section 4 are the long-period variable stars (9 entries), EBs (15 entries), SN 1987A (15 entries, published mostly between 1994 and 2000), novae (1 entry), the planetary nebulae luminosity function (3 entries), and average values based on multiple calibrations (7 entries). We will, however, return to the geometric distance tracers, specifically to the EBs, in Section 6.

For comparison, in Figures 2 and 3 we also show the level of the “canonical” LMC distance modulus, \((m - M)_0 = 18.50\) mag (Freedman et al. 2001; horizontal dashed lines), as well as its publication date (vertical blue dotted lines). The error bars on the biennial average distance moduli represent the standard deviations (1σ spreads) in the data values. Aiming at highlighting periods of (statistically) lower-than-expected uncertainties and/or smaller-than-expected scatter among subsequent data points,

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{As Figure 1, but averaged over two-year periods and divided into common distance tracers. The bottom panels associated with each main panel show histograms of the number of data values contributing to the two-year averages. The error bars represent the spread in (standard deviations of) the distance moduli; data points without error bars represent single entries during the relevant two-year period. The vertical blue dotted lines indicate the publication date of Freedman et al.’s (2001) canonical distance modulus. The horizontal error bars in the top left-hand corners of each main panel show the time period over which the data values have been averaged.}
\end{figure}

(A color version of this figure is available in the online journal.)

\[\text{(A color version of this figure is available in the online journal.)}\]
we show two-year running averages of the published LMC distance moduli in Figure 3. Inspection of the panels for the individual distance tracers reveals a number of periods during which the average values are statistically more tightly clustered and/or associated with very small error bars (spreads). We will examine the reasons underlying this behavior in the following subsections. In Figure 3, the red horizontal bars indicate these periods of interest.

Specifically, for the Cepheid-based distance determinations, we identified the period from 2001 to 2009 for further scrutiny; for the RR Lyrae stars, we will consider the ranges 1999–2003 and 2003–2007, and for the CMD features we will carefully examine the publications leading to the distance moduli published in the period since 2006 until the present time. The individual data points in these date ranges are shown in Figure 4. We also examined any trends in the (statistical) spreads as a function of publication date: see Figure 5 and Section 6. To determine whether the tight clustering of data points is an artifact caused by publication bias or simply owing to correlations among subsequent publications, we will examine both the nature of the tracer samples and the calibration relations used.

4.1. Cepheids

The top right-hand panels of Figures 2 and 3 show a statistically significant reduction in the uncertainties associated with the two-year averages between 2001 and 2009. During the entire period, the number of data points contributing to the average values was at least five, so that the average values and spreads are well-defined. This sudden reduction in the spread is corroborated by the top right-hand panels of Figure 5, which shows the (annual) spread in distance moduli, $\sigma$, and the errors on the means, $\varepsilon_{\mu} = \sigma / \sqrt{N}$ (where $N$ is the number of measurements included in the determination of $\sigma$) as a function of year of publication: the $1\sigma$ spreads become significantly smaller during the period 2001–2009 compared with the pre-2001 spreads.

In addition, the two-year averages appear to cluster very tightly near the canonical LMC distance modulus. This is exemplified in the top left-hand panel of Figure 5. This panel shows the differences in the (annual) average distance moduli for the Cepheid-based distance determinations with respect to both the canonical value and the (annual) average values based on all distance determinations.

4.1.1. Cepheid-like Tracers

During this period, 37 determinations of the LMC distance modulus based on Cepheids were published (for the full bibliography, see http://astro-expat.info/Data/pubbias.html). Here we explore the reason(s) for this tight clustering and the reduction in the spread of the derived values over this period.

A detailed examination of the individual articles shows that our database of Cepheid-based distances published during the 2001–2009 period is based—directly or indirectly—on five different Cepheid(-like) tracers. These include (1) classical Cepheids, (2) bump Cepheids (three distance determinations published in three articles by two independent teams, i.e., Bono et al. 2002a versus Keller & Wood 2002, 2006), (3) triple-mode pulsators (Moskalik & Dziembowski 2005), (4) Type II Cepheids (Matsunaga et al. 2009), and (5) $\delta$ Scuti variable stars (three distance determinations by McNamara et al. 2007).
Figure 4. Individual LMC distance moduli for zoomed-in date ranges identified on statistical grounds as characterized by small scatter and tight clustering of distance values. The red open circles represent the average values for the date ranges indicated by the horizontal red bars at the bottom of all panels. Top: most Cepheid-based distance determinations are based on fundamental-mode pulsators from the full OGLE II database, except where indicated. “1866:” cluster Cepheids in NGC 1886; “4258:” based on relative distance moduli between the LMC and NGC 4258; BC: bump Cepheids; δS: δ Scuti stars; FO: first-overtone pulsators; TM: triple-mode pulsators; T2: Type II Cepheids. Middle: “c,” “d:” distance moduli based on RRc (first-overtone) and RRd (double-mode) variables, respectively; GS99: Groenewegen & Salaris (1999); Ret: distance moduli based on RR Lyrae stars in the Reticulum globular cluster. Bottom: all CMD-based distances are based on calibration of RC magnitudes. (A color version of this figure is available in the online journal.)

(i.e., 29: see our online database) of the Cepheid-based LMC distance moduli are based on classical Cepheids, of which one publication (Bono et al. 2002b) actually uses first-overtone (FO) rather than fundamental-mode (FU) pulsators.

The vast majority of articles based on FU variables (22) are based on (predominantly large) samples obtained from the Optical Gravitational Lensing Experiment II (OGLE II) photometric database (i.e., the Cepheid sample of Udalski et al. 1999). Five determinations in four studies (Groenewegen & Salaris 2003; Storm et al. 2004; Gieren et al. 2005; Testa et al. 2007) use OGLE II observations of the Cepheids in the LMC cluster NGC 1866 for all or part of their analyses. Two other studies (Newman et al. 2001; Macri et al. 2006) used the relative distance moduli between the LMC and NGC 4258, although both teams rely on OGLE II-based period–luminosity relations (PLRs) to obtain the distance moduli to the individual galaxies. This implies that a large fraction of the Cepheid-based distance measurements in the 2001–2009 period were based on the same—or on subsets of the same—basic photometric database, so that these samples were not independent. The distance moduli for each of the individual tracers are included in Table 1.

4.1.2. Calibration

Most classical Cepheid-based distance determinations covered here, as well as the derivations based on δ Scuti stars and Type II Cepheids, are based on PLRs, which are characterized by a slope and a zero-point luminosity. The zero-point calibrations in almost all publications leading to the 2001–2009 classical Cepheid-based LMC distance moduli are based on distances to well-understood Galactic classical Cepheids. In turn, these were obtained on the basis of either Hipparcos, HST Fine Guidance Sensor, or interferometric parallax measurements, or Baade–Wesselink (BW)-type calibrations. Many of the LMC calibration relations adopt PLR slopes that are the same as those in the Milky Way. The results based on the calibration relations used in the different articles discussed here are thus highly correlated.

Although we cannot explicitly rule out a degree of publication bias, we therefore conclude that the tight clustering and small spread observed for Cepheid-based LMC distance moduli in the 2001–2009 period is most likely driven by the public availability of the OGLE II Cepheid database, which was published in a convenient form in 1999. A time lag of 1.5–2 yr between
**Figure 5.** Left: differences in distance moduli for three common distance tracers. Black bullets: mean differences between all published distance moduli for a given period and those for a specific tracer. Red open circles: mean differences between the distance moduli for a given tracer and the canonical distance modulus. Right: mean spreads in the data values, $\sigma$, and errors on the means, $\epsilon_m = \sigma / \sqrt{N}$, as a function of date of publication for the three common distance tracers and (bottom right-hand panels, red open circles) for all measurements. The units of $\sigma$ and $\epsilon_m$ in the right-hand panels are given in magnitudes. (A color version of this figure is available in the online journal.)

**Table 1**

Mean LMC Distance Moduli Based on Cepheid-like Tracers, 2001–2009

| Distance Tracer                  | $(m - M)_V$ (mag) | Syst. Error $^b$ |
|---------------------------------|-------------------|------------------|
| Classical Cepheids (FU)         | 18.49 ± 0.08      | $^c$             |
| – NGC 4258 relative moduli      | (18.36 ± 0.05)    | 0.26             |
| – NGC 1866 member stars         | (18.48 ± 0.11)    | 0.21             |
| Classical Cepheids (FO)         | 18.51 ± 0.03      | 0.15             |
| Bump Cepheids                   | 18.54 ± 0.01      | 0.10             |
| Triple-mode pulsators           | 18.44 ± 0.10      | 0.13$^d$         |
| Type II Cepheids                | 18.46 ± 0.10      | $^c$             |
| δ Scuti stars                   | 18.49 ± 0.05      | 0.07             |
| All Cepheid-like tracers        | 18.48 ± 0.08      | $^c$             |

Notes.

$^a$ Distance moduli and their statistical uncertainties; the latter represent the spreads in the individual data points that contribute to the final values.

$^b$ Based on taking into account the uncertainties quoted for the individual published values.

$^c$ No systematic error determined; the distance modulus based on all Cepheid-like tracers is the average of all individual tracers listed in this table (each given equal weight), while the statistical uncertainty represents the spread among the individual values.

$^d$ Systematic uncertainty from Moskalik & Dziembowski (2005).

$^e$ No systematic uncertainty available (single source).

this data release and the first peer-reviewed articles based on it seems reasonable. This, combined with easy access to the original *Hipparcos* parallaxes (ESA 1997; Perryman et al. 1997), has led to many authors using the same zero points and *ogle II* PLR slopes. This is, hence, the most likely main driver of the tight clustering observed for the Cepheid-based LMC distance moduli. The *ogle II* PLR slopes are well-defined by virtue of the large numbers of Cepheids contributing to the relationships, which has in turn led to a reduction in the associated uncertainties in and spread among the distance moduli.

### 4.2. RR Lyrae Variables

The bottom left-hand panel of Figure 3 shows a statistically significant clustering of distance moduli and a pronounced reduction in the associated spread from 1999 onward. This follows much greater variation in both measurables during the years prior to this period. We identified two periods during which the RR Lyrae-based LMC distance moduli exhibit statistically significant clustering behavior. The first period (P1) starts in 1999 and runs through 2002, immediately followed by a second period (P2) from 2003 until the end of 2006.
4.2.1. RR Lyrae Types

Just as for the Cepheids, the RR Lyrae-based distance tracers are also composed of a mixture of physically different object types. Although the majority of RR Lyrae samples considered between 1999 and 2006 are dominated by FU RR Lyrae (RRab), FO RR Lyrae (RRc) and double-mode pulsators (RRd) make up sizeable fractions of the most commonly used samples: of the 18 articles with published RR Lyrae-based LMC distance moduli in P1+P2 (see http://astro-expat.info/Data/pubbias.html), seven\(^\text{10}\) are fully or partially based on the RR Lyrae sample of Clementini et al. (2003)—or a prepublication version of their database (e.g., Carretta et al. 2000; Benedict et al. 2002a)—which contains 77 RRab, 38 RRc, and 10 RRd variables. The Dall’Ora et al. (2004a, 2004b) distance determinations are based on a sample of 21 RRab and nine RRc variables, while the sample of Marconi & Clementini (2005) is composed of 7 RRab and 7 RRc stars. In most analyses based on multiple types of RR Lyrae pulsators, the FO pulsators were “fundamentalized,” i.e., an appropriate correction (\(\Delta \log P [\text{days}] \approx +0.127\); e.g., Dall’Ora et al. 2004a, 2004b) was applied to their periods, so that the same period–luminosity–metallicity (PLZ) relation could be used.

Of the remaining publications, Alcock et al. (2004) and Clement et al. (2005), who share team members among their co-authors (and, hence, most likely used similar methods; this is unclear given that the latter reference is only an abstract), based their results on a set of 330 genuine RRc variables located near the LMC bar, which were selected from the MACHO (MASSive Compact Halo Objects) database. Finally, Kovács (2000) used 181 MACHO RRd stars. We have indicated the distance moduli resulting from the use of only RRc and RRd variables in the middle panels of Figure 4. Having assessed the RR Lyrae sample selection criteria employed in the period between 1999 and 2006, we conclude that there is substantial overlap among publications, which hence renders their independence questionable.

4.2.2. Calibration

Second, we explored the methods used and which contribute to the average RR Lyrae-based LMC distance moduli. These can be categorized into three main classes, (1) those publications that use a form of the \(M_V-[\text{Fe}/\text{H}]\) luminosity–metallicity relation (LMR), \(\alpha[\text{Fe}/\text{H}]_{\text{RR}} + \beta\) (seven articles),\(^\text{11}\) (2) those authors that base their distance estimates on a PLZ relation (six articles),\(^\text{12}\) and (3) those that use theoretical pulsation modeling to derive luminosities and, hence, a distance modulus (Kovács 2000; Alcock et al. 2004; Marconi & Clementini 2005). The zero points of the LMRs and the PLZ relations are generally based on parallax measurements to local field or globular cluster (GC) RR Lyrae in the Milky Way, either based on Hipparcos or HST parallaxes. The general consensus among authors using an LMR is that the slope \(\alpha \approx [0.18–0.20] \log \text{mag} \text{dex}^{-1}\) (but see below), while most authors who relied on PLZ relations adopted those of Bono et al. (2003) and their precursors by largely the same authors. Once again, we see that there is significant overlap between the methods used in the publications that eventually result in the average LMC distance moduli reported here.

Over the entire range of RR Lyrae-based distance determinations examined, there has been a gradual shift in the preferred method from LMRs to near-infrared (NIR) PLZ relations. Empirical and theoretical arguments indicate that LMRs might not be linear over the entire metallicity range covered by field RR Lyrae stars (e.g., Bono et al. 2003; Sandage & Tammann 2006). Moreover, they are affected by evolutionary effects such as off-zero-age HB evolution. This implies that the mass distribution inside the RR Lyrae instability strip is poorly known. Note that these considerations apply to both field and cluster RR Lyrae. NIR PLZ relations are minimally affected by these problems (e.g., Del Principe et al. 2006; Sollima et al. 2006; for a review, see Bono et al. 2011).

4.2.3. Distance Determinations Based on Globular Cluster RR Lyrae

Finally, we considered the spatial distributions of the RR Lyrae samples. Twelve (P1: 4; P2: 8) of the 18 studies undertaken during the entire period of interest explore the properties of RR Lyrae stars in the galaxy’s inner regions and/or fields in or near the LMC bar. Of the remaining six publications, five (P1: Bono 2003; P2: Dall’Ora et al. 2004a, 2004b; Rastorguev et al. 2005; Sollima et al. 2006) focus on the RR Lyrae variables in the LMC GC Reticulum. We note that the latter studies do not necessarily provide a well-constrained distance to the LMC’s center. This is the main reason as to why we opted against inclusion of distance moduli to individual clusters in our compilation; Reticulum is an exception, because of its benchmark use by a number of authors.

Only two articles venture beyond the inner galaxy or Reti- culum: Groenewegen & Salaris (1999) and McNamara (2001) both based their LMC distance estimate on a study of RR Lyrae stars in (the same) seven old LMC GCs. In the middle panels of Figure 4, we have separately indicated the LMC distance moduli based on studies of the Reticulum GC, as well as the GC results of Groenewegen & Salaris (1999) and McNamara (2001). The Reticulum-based distance determinations do not appear to be systematically offset from the field RR Lyrae distance estimates. This analysis strengthens us in our conclusion that the basic samples used for RR Lyrae-based distance determinations between 1999 and 2006 were highly interdependent. Correlations among the resulting distance values may thus be expected and should certainly not come as a surprise.

We also explored the possible reason(s) for the origin of the rather sudden reduction in average distance modulus between P1 and P2. A close examination of the middle right-hand panel of Figure 4 reveals that most distance determinations cluster very tightly around or just below the level of the canonical distance modulus, which is significantly shorter than the canonical value. However, this data point does not appreciably affect the average level during P2, however. The scatter among

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10 Specifically, Carretta et al. (2000), Benedict et al. (2002a), Clementini et al. (2003), Maio et al. (2004), Gratton et al. (2003), Feast (2004), and Marconi & Clementini (2005).

11 Specifically, Groenewegen & Salaris (1999), Carretta et al. (2000), McNamara (2001), Clementini et al. (2003), Maio et al. (2004), Gratton et al. (2005), and Feast (2004).

12 Including Bono (2003), Dall’Ora et al. (2004a, 2004b), Borissova et al. (2004), Rastorguev et al. (2005), and Sollima et al. (2006).
the data points in the middle left-hand panel is greater, and so are the error bars (spreads) associated with a number of the distance moduli. The data points driving an offset of the mean distance moduli to a level above the canonical value are based on McNamara’s (2001) distance determinations. First, we point out that—perhaps surprisingly—the GC distance moduli of Groenewegen & Salaris (1999), \( (m - M)^{\odot} = 18.61 \pm 0.28 \) mag, and McNamara (2001), \( (m - M)^{\odot} = 18.61 \pm 0.04 \) mag, are identical. Both teams used LMRs, although with very different slopes: \( \alpha = 0.18 \) versus \( 0.30 \) mag dex\(^{-1} \) (Groenewegen & Salaris 1999 versus McNamara 2001). For the same zero point, this difference in slope leads to a luminosity difference of 0.18 mag for the typical metallicity of LMC RR Lyrae stars usually adopted, \( [\text{Fe}/\text{H}] = -1.5 \) dex, in the sense that the LMR with the steeper slope would lead to a brighter magnitude.

The former authors used the technique of “reduced parallax” and found that—for the same slope and exactly the same sample of RR Lyrae variables—they obtained a zero point, \( \beta = 0.77 \pm 0.26 \) mag, which is \( \sim 0.28 \) mag brighter than the zero point obtained from statistical-parallax calibration. McNamara (2001), on the other hand, calibrated the LMR on the basis of the PLR of Galactic high-amplitude \( \delta \) Scuti stars and found \( \beta = 0.92 \pm 0.09 \) mag, a difference of \( \Delta \beta = 0.15 \) mag, which largely negates the effect of the difference in \( \alpha \) between both studies. It thus appears that both analyses, although based on the same set of seven LMC GCs, use independent methods to yield the same distance to the LMC. In other words, the systematically larger LMC distance derived from the RR Lyrae stars in these seven GCs may represent real distance variance, or instead imply that the centroid of the GCs’ distribution is not co-located with the center of the LMC as defined by its bar.

4.3. Features in the Color–Magnitude Diagram

Even a cursory glance at the bottom right-hand panel of Figure 3 immediately shows that the LMC distance moduli based on CMD-feature calibration converge significantly from 2006 onward. A closer look at the publications leading to the average values shown in this figure reveals that there is a simple reason for this statistically significant clustering. For the period up to 2004/2005, various authors used a range of CMD features to derive their distance moduli, including the HB level, the TRGB, the magnitude of the helium-burning RC, as well as MS/MSTO fitting. However, with the exception of Rubele et al.’s (2012) distance determination, since 2006 the RC magnitude has been the only diagnostic CMD feature used to estimate the distance to the LMC.

Of the six RC-based distance determinations between 2006 and 2013 (see our online database), most used NIR photometry of predominantly central fields in the LMC. At NIR wavelengths, population effects—such as those caused by differences in ages and metallicities—are minimal, although not necessarily negligible. (Rubele et al. 2012) also used NIR observations, which were newly obtained with the ESO/VISTA telescope as part of the ESO public survey of the Magellanic System.) In addition, most authors used the same set of population corrections, i.e., those proposed by Girardi & Salaris (2001) and Salaris & Girardi (2002), or fully equivalent methods. Given that the apparent magnitudes of RC stars across the LMC can be easily deprojected to the LMC center, it is not surprising that all recent CMD-based distance determinations yield very similar values. It is not necessary to attribute this effect to publication bias.

5. STATISTICAL ANALYSIS

To decide whether the published distance moduli show a significant difference from the published reference values of \( \mu_{\text{ref}} = 18.50 \pm 0.10 \) mag (Freedman et al. 2001) and \( \mu_{\text{ref}} = 18.493 \pm 0.008 \) mag (Pietrzyński et al. 2013; statistical uncertainties only), we perform a statistical test based on well-established statistical principles. We regard the published distance moduli as the mean values derived from a large population of indicators (representing, e.g., the ogle Cepheid or RR Lyrae samples), and their associated standard deviations as the standard deviation of these large populations. We assume that these values are well-defined and disregard possible effects of sampling statistics. This approach is justified, because all published distance moduli were derived from studies based on large numbers of data points, so the effects of small-number statistics can be ignored. In this framework, we can write the test statistic as

\[
z = \frac{\mu_{\text{dist}} - \mu_{\text{ref}}}{\sqrt{\sigma_{\text{dist}}^2 + \sigma_{\text{ref}}^2}}
\]

where \( \mu_{\text{dist}} \) is the published distance modulus and \( \mu_{\text{ref}} \) the reference distance modulus of interest; \( \sigma_{\text{dist}} \) corresponds to the standard deviation of the given published distance modulus and \( \sigma_{\text{ref}} \) is that for the reference distance modulus. The expression \( \sigma_{\text{dist}}^2 + \sigma_{\text{ref}}^2 \) is the variance of the difference of means as defined by the law of total variance for independent quantities. This expression assumes that errors in the distance moduli follow a Gaussian distribution. The resulting value represents a two-sided hypothesis test, since the published values can be greater than (positive \( z \) score) or less than (negative \( z \) score) the reference moduli.

Using the test statistic, we compute \( z \) scores for our compilation of distance moduli and compare these scores with thresholds at the 0.05 and 0.01 levels of significance, which correspond to differences of 2 and 3 standard deviations, respectively. In other words, significances of 0.05 and 0.01 represent confidence intervals of 95 and 99\%, respectively. If the absolute value of a \( z \) score is larger than the threshold values at these levels of significance, then the null hypothesis of this test, i.e., that the means are statistically equal, is rejected, making the values statistically different at that level. Under the frequentist-statistics interpretation, rejecting the null hypothesis at a 0.05 or 0.01 level of significance means that the probability that the null hypothesis is correct (hence making our conclusion incorrect) is at most 0.05 or 0.01, respectively. The threshold values at the 0.05 and 0.01 levels are 1.96 and 2.58, respectively.

Table 2 provides an overview of the level of “compliance” of all published distance moduli for three specific tracers (Cepheids, RR Lyrae, and CMD features) with the reference distance moduli over wide intervals of publication date, coinciding with the intervals adopted for the analysis presented in Table 3. First, we note that the “non-compliance rate” with respect to the Pietrzyński et al. (2013) reference value is significantly higher than that with respect to the “canonical” distance modulus of Freedman et al. (2001). This can be ascribed entirely as owing to the much smaller statistical uncertainty associated with the former value. Second, we point out that since 2001, the published distance moduli based on all three tracer populations have been similar to Freedman et al.’s (2001) value at better than the 0.05 level of significance; for normally distributed data points, this corresponds to the 2\( \sigma \) level or 95\% confidence. Although the Pietrzyński et al. (2013) result has much smaller statistical uncertainties, the general trend seen is the same: the LMC distance
moduli published since 2001 are very well represented by the
Weighted Mean 18.492
The Astronomical Journal
of magnitudes.

The LMC distance modulus of Walker et al. (2001), (m − M)0 = 18.492 mag is no longer flagged up as an outlier by our test statistic. The assumption that the cluster would be located in the LMC disk plane. (Releasing that latter assumption would increase the confidence level (i.e., worse than the 0.05 level of significance). The assumption that the cluster would be located in the LMC disk plane. (Releasing that latter assumption would increase the confidence level (i.e., worse than the 0.05 level of significance). The assumption that the cluster would be located in the LMC disk plane. (Releasing that latter assumption would increase the confidence level (i.e., worse than the 0.05 level of significance).

Haschke et al.’s (2012) LMC distance modulus of (m − M)0 = 18.492 ± 0.08 mag based on Cepheid observations and adopting an area-averaged reddening value is given a z score of 2.73. However, once they correct for the reddening using values specific to each individual Cepheid variable in their sample, the resulting distance modulus of (m − M)0 = 18.65 ± 0.07 mag is no longer flagged up as an outlier by our test statistic. The LMC distance modulus of Walker et al. (2001), (m − M)0 = 18.33 ± 0.05 mag, attracts a z score of −3.22. This distance modulus was obtained based on CMD fits to NGC 1866, under the assumption that the cluster would be located in the LMC disk plane. (Releasing that latter assumption would increase the cluster’s distance modulus to 18.35 mag.) We note that Salaris et al. (2003), Groenewegen & Salaris (2003), and Storm et al. (2006) derive very similar distance moduli to the cluster.

Finally, application of our test statistic to the distance moduli obtained from analysis of the geometric distance indicators, EB systems, and SN 1987A confirms our earlier conclusions. For the EB distances, the values of Guinan et al. (1998) and Fitzpatrick et al. (2003) disagree with the Pietrzyński et al. (2013) reference value at worse than the 0.01 level of significance; the Udalski et al. (1998) result differs at worse than the 0.05 level of significance. There are no EB differences with respect to the Freedman et al. (2001) value at the 0.01 level of significance, but the Fitzpatrick et al. (2003) result differs at the 0.05 level of significance. We already discussed the main physical reasons for these differences in Section 6; the same reasons apply to the Udalski et al. (1998) determination.

As regards the SN 1987A-based distance moduli, they all agree with the Freedman et al. (2001) value at the 99% confidence level, although a number of distance determinations thus derived disagree with the more recent reference value at that level: of the 15 distance moduli published based on analyses of SN 1987A, Gould (1995), Eastman et al. (1996), Lundqvist & Sonneborn (1997), and Gould & Uza (1998) published distance moduli that yield z scores of, respectively, −3.02, −5.38, 3.50, and −3.02 with respect to the Pietrzyński et al. (2013) reference value. Note that the high negative z score of the Eastman et al. (1996) result is artificially inflated because these authors did not report an uncertainty on their estimate. The other values do not show a preference for a systematic difference, so we are left to conclude that the high z scores may be related to the underlying assumptions made.

6. VERDICT

In the previous sections, we made a case of highly correlated results among populations for a given distance tracer, rather than attributing the observed tight clustering of the distance moduli and the clear reduction in the associated spreads to publication bias.13 Here, we will additionally explore the behavior of the spread in the distance moduli and the errors on the means as a function of publication date. Figure 5 (left-hand panels) shows the differences, averaged over two-year intervals, of the Cepheid-, RR Lyrae-, and CMD-based distance moduli with respect to both the canonical distance modulus of 18.50 mag and the ensemble of all determinations published during the relevant time spans. In almost all cases, the two-year average distance moduli are consistent with the canonical distance modulus

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**Table 2**

| Difference | Period | Cepheids | RR Lyrae | CMD Features |
|------------|--------|----------|----------|--------------|
| w.r.t.     |        | Ntot | Threshold | Ntot | Threshold | Ntot | Threshold |
| Freedman   | since 01/1990 | 82  | 4 | 1 | 56 | 4 | 1 | 39 | 7 | 4 |
|            | since 01/2001 | 48  | 2 | 1 | 34 | 0 | 0 | 19 | 0 | 0 |
|            | since 01/2005 | 28  | 2 | 1 | 18 | 0 | 0 | 9  | 0 | 0 |
| Pietrzyński| since 01/1990 | 82  | 21 | 13 | 56 | 12 | 8 | 39 | 16 | 10 |
|            | since 01/2001 | 48  | 12 | 7  | 34 | 6  | 4  | 19 | 6  | 2  |
|            | since 01/2005 | 28  | 10 | 6  | 18 | 4  | 2  | 9  | 2  | 1  |

**Notes.** Thresholds (“significance levels”) of 0.05 and 0.01 correspond to a difference of 2 and 3 standard deviations or confidence intervals of 95 and 99%, respectively.

**Table 3**

| Period | 2001 Jan–2013 Dec | 2005 Jan–2013 Dec |
|--------|-------------------|-------------------|
| All    | Mean 18.481       | 18.486            |
|        | σ 0.097           | 0.091             |
|        | N 125             | 68                |
| Cepheids | Mean 18.486       | 18.484            |
|        | σ 0.100           | 0.107             |
|        | N 48              | 28                |
| RR Lyrae | Mean 18.472       | 18.471            |
|        | σ 0.094           | 0.103             |
|        | N 38              | 22                |
| CMD features | Mean 18.499       | 18.505            |
|        | σ 0.153           | 0.133             |
|        | N 19              | 9                 |
| Weighted | Mean 18.492       | 18.492            |
|        | σ 0.089           | 0.090             |

**Notes.** Means and population standard deviations are given in units of magnitudes.

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13 We specifically point out that most of these conclusions pertain to very similar time intervals as that considered by Schaefer (2008), yet we do not concur with his conclusions.
within the 1σ spreads (as indicated by the red open circles), in particular since the late 1990s, i.e., well before Freedman et al.’s (2001) seminal publication. Again, combined with our analysis in Section 4, this leads us to suggest that the observed trend(s) may be largely driven by the common availability of the Hipparcos data and the community’s easy access to the full Hipparcos parallax database.

The right-hand panels of Figure 5 show the spreads and the errors on the means among the distance moduli as a function of publication date. For the Cepheid- and RR Lyrae-based distance moduli, there are no clearly discernable trends. However, the uncertainties are increasingly reduced as a function of increasing publication date for the CMD-based distances over the entire period covered. The bottom right-hand panels additionally include the same trend for the full ensemble of distance measurements (labeled “All”). The full sample of distance moduli also shows an obvious decrease in the spread between 1998 and 2008. This trend is clearly driven by the reduction in the uncertainties associated with the CMD-based measurements. In turn, this is most likely due to the improved local calibration of the absolute RC magnitude (and as a function of wavelength).

So far, we have focused on the results based on a number of well-represented individual distance tracers. However, combined analyses can be used to reinforce the results obtained from different tracers. We concur with Schaefer (2008) that this might indeed lead to a degree of publication bias, because it is intrinsic to human nature to publish results that conform to some extent to the norm, while strongly deviating results may not see the light of day in peer-reviewed publications. On the other hand, cross checking the results obtained from a variety of tracers can also help to prevent such effects from occurring in the first place, in particular if the techniques employed are independent (for a discussion, including a historical perspective, see Tammann et al. 2008). For instance, Laney et al. (2012) used the LMC’s H- and K-band RC magnitudes to derive LMC distance moduli, with and without population corrections, and concluded that the very small differences found as a function of NIR wavelength “imply that any correction to the K-band Cepheid PL[R] due to metallicity differences between Cepheids in the LMC and the solar neighborhood must be quite small.”

Where does this leave us in the context of using the LMC’s distance as a key rung of the local extragalactic distance ladder? While we conclude that the effects of publication bias may have been overplayed in previous publications, the resulting LMC distance moduli are likely still affected by poorly understood systematic uncertainties. This is exemplified by the increasing spreads and the variation in the mean distance modulus in the more recent past, in particular as pertaining to the Cepheid variables; see Figure 3 (top right-hand panel). Similarly, the sustained variation in the mean two-year running distance moduli based on RR Lyrae variables (see Figure 3, bottom left-hand panel), combined with the sizeable standard deviations and our much improved understanding of the physical processes dominating RR Lyrae variability, supports the persistence of systematic uncertainties.

Fortunately, the LMC is located sufficiently nearby that a few types of geometric distance tracers are fairly readily available, including the enigmatic SN 1987A’s ring (a light echo) and an ever increasing number of EB systems. While results based on studies using the SN 1987A ring should be treated with caution (cf. Gould & Uza 1998; de Grijs 2011, his chapter 3.7.2), significant progress has recently been made in the use of EBs in the LMC as high-precision distance anchors. Pietrzyński et al. (2013) determined the direct distances to eight long-period, late-type EB systems in the LMC. Their resulting distance modulus, \( m - M_0 = 18.493 \pm 0.008 \pm 0.047 \) mag (where the first and second uncertainties refer to the statistical and systematic errors, respectively), is accurate to 2.2% and confirms that the canonical distance modulus of \( m - M_0 = 18.50 \pm 0.10 \) is indeed a very reasonable approximation.

Pietrzyński et al. (2013) make a convincing case for the use of long-period cool giant stars, because one can accurately measure both the linear and the angular sizes of their components. This presents more problems for hot, early-type systems. However, Schaefer (2013) calls their result into question; in addition to repeating his concerns regarding a bandwagon effect, he points out that Pietrzyński et al.’s (2013) LMC distance of \( D_{\text{LMC}} = 49.97 \pm 0.19 \) (stat.) \( \pm 1.11 \) (syst.) kpc is significantly different from the average distance of four hot, early-type EBs, \( D_{\text{LMC}} = 47.1 \pm 1.4 \) kpc, published by Guinan et al. (1998), Fitzpatrick et al. (2002, 2003), and Ribas et al. (2002). This systematic difference between the results of both groups is most likely an indication of systematic uncertainties, which would particularly affect the earlier results. These were based on systems composed of hot early-type stars, which implies that these authors were limited to using theoretical models (energy distributions); accounting for the systematic uncertainties associated with this approach is notoriously difficult. Pietrzyński et al. (2013) discovered giant stars in EB systems, which uniquely allowed them to use the very well calibrated surface-brightness–\( (V-K) \) color relation for such stars to determine their angular sizes, so that their error estimates are more robust and less affected by lingering systematic effects (G. Pietrzyński 2013, private communication).

In relation to this issue, Schaefer’s (2013) comment actually ignores the recent EB results from one independent study (Bonanos et al. 2011) and one by Prada Moroni et al. (2012), composed of a subset of authors contributing to the Pietrzyński et al. (2013) results (see Figure 1, bottom right-hand panel). Both implied a systematically greater distance to the LMC than the 1998–2003 counterexamples produced by Schaefer (2013). In addition, one of the most recently published LMC distance moduli in our database (Marconi et al. 2013) is based on theoretical pulsation modeling of the light and radial velocity curves of an EB; it also yields a distance that is in good agreement with that derived by Pietrzyński et al. (2013).

Schaefer (2013) also points out that Pietrzyński’s team had previously reported the distance to one of its EB systems, OGLE-LMC-ECL-09114, as \( D = 50.1 \pm 1.4 \) kpc (Pietrzyński et al. 2009), but their updated analysis leads to a new estimate of \( D = 49.3 \pm 0.5 \) kpc. We note that the earlier value was associated with a large error bar, \( m - M_0 = 18.50 \pm 0.55 \) mag. The small change in system parameters determined by Pietrzyński et al. (2013), which is well within those 1σ uncertainties, is driven by a significant body of new observations obtained during the system’s eclipses (G. Pietrzyński, private communication). This allowed these authors to improve their model and also take into account limb darkening and other secondary effects, as shown in their supplementary Table 5.

In view of our analysis and discussion of the statistically significant clustering of LMC distance moduli and the observed reduction in their spread over the past two decades, we conclude that strong publication bias is unlikely to have affected the majority of published LMC distance moduli. Note that our conclusions pertain to the largest, most complete data set of LMC distance moduli available to date, superseding all previous
compilations. To get a handle on the systematic spread in distance determinations owing to, e.g., depth effects and real cosmic variance, we determined the average distance moduli and the associated population standard deviations for all published distance determinations, as well as for those based on Cepheid and RR Lyrae variables and on CMD features, for two recent periods, i.e., since 2001 and since 2005 until the present time. The results are shown in Table 3. The final section of Table 3 lists the weighted means and standard deviations based on a careful combination, in a statistical sense (i.e., following Watkins et al. 2013, their Appendix A), of the mean distance moduli and their uncertainties for the Cepheid and RR Lyrae variables, the CMD features, and the latest EBs result of Pietrzyński et al. (2013). Our main underlying assumption adopted here was that the individual data points are distributed normally (i.e., approximately in a Gaussian fashion); this is a good first-order approximation to all data sets pertaining to the three specific tracers included in the table.

For a more in-depth statistical analysis, we refer the reader to Section 5. In view of these results, as well as those listed in Table 1, we recommend that a slightly updated canonical distance modulus of \( m - M = 18.49 \pm 0.09 \) mag be used for all practical purposes that require a general distance scale without the need for accuracies better than a few percent. In Paper II in this series, we extend our analysis to the body of distance measurements for M31, M33, and a number of their companion galaxies, and place our recommendations in the context of distance measures to Local Group galaxies and beyond.

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