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

Richard de Grijs[1,2] and Giuseppe Bono[3,4]
[1] Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, China
[2] Department of Astronomy, Peking University, Yi He Yuan Lu 5, Hai Dian District, Beijing 100871, China
[3] Dipartimento di Fisica, Università di Roma Tor Vergata, via Della Ricerca Scientifica 1, I-00133, Roma, Italy
[4] INAF, Rome Astronomical Observatory, via Frascati 33, I-00040, Monte Porzio Catone, Italy
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ABSTRACT

Aiming at providing a firm mean distance estimate to the SMC, and thus to place it within the internally consistent Local Group distance framework we recently established, we compiled the current largest database of published distance estimates to the galaxy. Based on careful statistical analysis, we derive mean distance estimates to the SMC using eclipsing binary systems, variable stars, stellar population tracers, and star cluster properties. Their weighted mean leads to a final recommendation for the mean SMC distance of $(m - M)_0^{\rm SMC} = 18.96 \pm 0.02$ mag, where the uncertainty represents the formal error. Systematic effects related to lingering uncertainties in extinction corrections, our physical understanding of the stellar tracers used, and the SMC's complex geometry—including its significant line of sight depth, its irregular appearance which renders definition of the galaxy's center uncertain, as well as its high inclination and possibly warped disk—may contribute additional uncertainties possibly exceeding 0.15–0.20 mag.

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

1. A ROBUST DISTANCE TO THE SMC

The nearest galaxies in the Local Group contain numerous objects that can be used to determine robust distances to their hosts. In de Grijs et al. (2014; Paper I) and de Grijs & Bono (2014; Paper II), we aimed at establishing a robust, internally consistent local distance framework supported by a number of the largest Local Group galaxies that contain numerous individual distance tracers, including the LMC, M31, M32, and M33, as well as a number of well-known dwarf galaxies. Although our statistical treatment of the individual distance measures to each of these galaxies encountered unexpected difficulties at some level or another, assigning mean distances to each galaxy was fairly straightforward. This was facilitated by either the regular (symmetrical) geometry of the sample galaxies, their low line of sight inclinations, and/or their small angular sizes.

To date, no such analysis has been performed for the SMC. Despite its proximity, individual distance estimates to the galaxy cover a much larger range than those of its larger neighbor, the LMC. The latter galaxy is often considered a key rung of the extragalactic distance ladder, and as such robust determination of its distance has attracted significantly more effort (cf. Paper I) than the equivalent task pertaining to the SMC. However, this is not the only reason for the larger scatter in published SMC distance moduli and its consequently more poorly known distance.

Schaefer (2008) suggested that the tighter clustering of LMC compared with SMC distance moduli may be related to sociological effects ("publication bias") in the distance determination to the LMC following the publication of the final results of the *Hubble Space Telescope* Key Project (HSTKP) on the Extragalactic Distance Scale (Freedman et al. 2001). He argued that since the SMC was not included in the HSTKP sample, its ensemble of distance measurements might be less affected by publication bias. However, in Paper I we showed that publication bias is unlikely to blame for the tight clustering of LMC distance moduli over the past two decades. Instead, we pointed out that improvements in both the quality of the available data sets—combined with increasing numbers of target objects during the period of interest—and the theoretical background at the basis of many methods of distance determination were a more likely explanation of the convergence in LMC distance moduli.

We believe that this comparison of the Magellanic Clouds is too simplistic. Schaefer (2008) glossed over a number of important aspects of the SMC's geometry that make obtaining a clear-cut mean distance much more challenging for this galaxy than for the LMC. In essence, the difficulties relate to three aspects. First, the SMC is an irregular galaxy, exhibiting a bar-like main body with hints of spiral arms and a very extended "Wing" to the east (for a clear illustration of the latter, see e.g., Figure 15 in Sewiło et al. 2013; see also Rubele et al. 2015 or http://www.esa.int/spaceinimages/Images/2015/02/Exploring_the_colours_of_the_Small_Magellanic_Cloud). This renders the definition of the galaxy's center troublesome. Few authors comment on this specifically, although Kochanek (1997), for instance, states that "our distances and the Westerlund (1990) value for the SMC are larger than the Caldwell & Laney (1991) values because of differences in defining the Cloud centers." More recently, Rubele et al. (2015) embarked on an exploration of the SMC's spatially resolved star formation history, while simultaneously deriving distances to different areas across the galaxy. They report distances projected onto both the SMC's kinematic and stellar density centers, $(m - M)_0^{\rm kin} = 18.97 \pm 0.01$ mag and $(m - M)_0^{\rm stars} = 18.91 \pm 0.02$ mag, which thus implies that one's choice of SMC center could introduce systematic uncertainties of the order of 0.05–0.1 mag in the resulting distance modulus. In this paper, we aim at determining the "mean" SMC distance to the bulk of its stellar population, i.e., to a position in the midst of the galaxy's main body. However, as we will see, the centroids of the different distance indicators we use vary slightly across the face of the SMC.

Second, the SMC is known to be significantly extended along the line of sight. Depending on one's tracer and sample selection, the SMC's depth could be anything from 6–12 kpc (Crowl et al. 2001) up to 20 kpc (Groenewegen 2000; for recent discussions, see, e.g., Kapakos & Hatzidimitriou 2012; Subramanian & Subramaniam 2012; Cignoni et al. 2013; Kalirai et al. 2013; Nidever et al. 2013), although the Cepheid population associated with the main body implies a shallower depth of 1.76 ± 0.6 kpc (Subramanian & Subramaniam 2015). Clearly, any tracer population spanning even a fraction of these reported line of sight distances will exhibit a significant spread in distances which, in turn, will translate into larger uncertainties and scatter. In addition, selection biases or small-number statistics will exacerbate the resulting scatter.

Third, whereas the LMC is viewed close to face-on, the SMC's inclination is much less well-defined and appears to depend on the stellar tracer (and thus the age of the stellar population) used for its determination. Based on their analysis of both red clump (RC) stars and RR Lyrae variables, Subramanian & Subramaniam (2012) concluded that the SMC's orientation is almost face-on, characterized by inclination angles of $i = 0\overset{\circ}{.}58$ and $i = 0\overset{\circ}{.}50$ for the RC stars (1280 regions, each containing 100–3000 RC stars) and RR Lyrae variables (1904 objects), respectively. Similarly, Haschke et al. (2012) found a low inclination of $i = 7^\circ \pm 15^\circ$ based on their sample of 1494 RR Lyrae stars. On the other hand, the large population of Cepheid variables in the SMC traces a much more highly inclined disk structure, with inclination estimates ranging from $i = 45^\circ \pm 7^\circ$ (Laney & Stobie 1986; 23 Cepheids) to $i = 68^\circ \pm 2^\circ$ (Groenewegen 2000; 236 Cepheids), $i = 70^\circ \pm 3^\circ$ (Caldwell & Coulson 1986; 63 Cepheids), and most recently $i = 74^\circ \pm 9^\circ$ (Haschke et al. 2012; 2522 Cepheids). Meanwhile, Rubele et al. (2015) very recently embarked on near-infrared (IR) color–magnitude diagram (CMD) analysis to derive $i = 39\overset{\circ}{.}3 \pm 5\overset{\circ}{.}5$ for the inclination of the SMC's disk, with its northeastern quadrant closest to us. They also find that a warped outer disk (by up to 3 kpc) fits their data best. Careful geometric corrections of individual objects back to the galaxy's center will reduce the scatter in the calibration relations, but this is not always possible.

For instance, let us take $i = 70^\circ$ as an extreme example, combined with the SMC's size given by de Vaucouleurs et al. (1991), $a \times b = 9487 \times 5588$ arcsec^2 and a "best" distance modulus to the galaxy of $(m - M)_0 = 18.96$ mag (this paper). Projection of individual distance measurements from the disk's outer edge would then require a correction of −0.26 (+0.29) mag and −0.16 (+0.17) mag in distance modulus for objects located at the extremes of the disk's major and minor axes, respectively, projected behind (in front of) the galaxy's center, compared to a face-on orientation. Accounting for the presence or absence of a warped disk will introduce additional systematic uncertainties: adopting a maximum extent for the warp of 3 kpc, the additional correction would be of the order of 0.1 mag. While application of such corrections will largely reduce the scatter in individual distance measurements, the uncertainties in the disk's inclination, combined with the possibility of the presence of a warp in the outer disk, may introduce systematic effects in excess of 0.10 mag in the resulting distance moduli.

Additional systematic uncertainties affecting the robustness of distance determinations to the SMC relate to corrections for reddening, absolute calibration of the relevant conversion relations, and metallicity differences (for in-depth discussions, see also Paper I; de Grijs 2011). Corrections for metallicity differences and systematic offsets in the calibration relations adopted are tracer-specific. As such, we discuss these systematic effects separately for the Cepheid, RR Lyrae, and RC-based distances, respectively, in Sections 3.1, 3.2, and 4.1. On the other hand, the effects of extinction, a combination of absorption and scattering by dust and gas, affect all methods to largely similar extents. Corrections for reddening are among the most significant in the context of systematic uncertainties feeding through into distance determinations. This is, hence, driving development of "reddening-free" approaches, including e.g., the period–Wesenheit (PW) calibration relations developed for variable-star analysis (see Section 3).

De Grijs (2011, his Chapter 6.1.1) provides a detailed discussion of the systematic uncertainties associated with the effects of extinction as pertaining to distance determinations. Briefly, these include uncertainties related to our sufficiently precise knowledge of (i) the prevailing extinction law, (ii) the intrinsic photometric properties of one's calibration objects, and (iii) the geometry of the dust distribution. The choice of extinction law is particularly important when comparing similar types of objects drawn from Galactic and Magellanic Cloud samples, since "the" Galactic extinction law (which may, in fact, vary along different lines of sight) differs systematically from that in the Magellanic Clouds (for recent studies, see e.g., Dobashi et al. 2009; Bot et al. 2010). Nevertheless, the differences are generally $\lesssim$0.05 mag at wavelengths longwards of $\lambda = 1\,\mu$m and shortwards of $\lambda = 0.8\,\mu$m. The significantly reduced effects of extinction at IR wavelengths, combined with the often smaller scatter of physical properties, is driving research efforts, e.g., in relation to variable-star period–luminosity relations (PLRs), from the classical, optical regime to these longer wavelengths.

Adoption of the most appropriate extinction law additionally requires a detailed knowledge of the geometry of the mixture of dust and stars, and the relevant filling factor, allowing for patchy versus smooth distributions of the dust component; the commonly used "foreground screen" geometry is often an oversimplification. For the same optical depth, a uniform mixture of dust and stars causes less extinction than the foreground-screen model, because part of the extinction lies behind the source. These effects are often compounded by the unknown effects caused by population changes, i.e., the "age-extinction(-metallicity) degeneracy." Finally, one has to consider the possibility that, even if the extinction component acts as an obscuring layer in front of the object of interest, it may not represent a uniform layer but could be better characterized by differential extinction. Haschke et al. (2012) provide an excellent example of the potentially devastating effects of adopting different assumptions for one's extinction properties. For both their Cepheid and RR Lyrae samples in the SMC, they derive systematic uncertainties in the resulting SMC distance modulus of 0.17–0.19 mag, depending on whether they apply individual reddening corrections to each of their sample objects or instead use a blanket extinction correction pertaining to carefully selected areas. The latter assumption leads to significantly larger distance moduli.

In this paper, we aim at extending and validating the local distance framework established in Papers I and II by adding the SMC to our ensemble of Local Group galaxies. As for Papers I and II, we searched the NASA/Astrophysics Data System (ADS) article database for any articles referring to the SMC. The volume of publications returned from the first journal papers until the end of 2015 January included 11,095 separate entries. We systematically combed through these papers, in reverse chronological order, looking for new or updated distance estimates to the SMC.

We aimed at compiling a database of SMC distance determinations that is as complete as possible for the period from 1990 January until and including 2015 January. As long as we cover a period that allows us to discern any statistical trends, the precise choice of starting date for our modern period is not important. For consistency with Papers I and II, and given that all important SMC distance tracers are well represented in the period since 1990, here we also adopt 1990 as the start of the period of interest.[5] This period is covered by a total of 9746 articles in the NASA/ADS database. We will use these for our statistical analysis. For further reference, for the period prior to 1990, we included distance estimates that were referred to in the body of later papers we perused in detail: in essence, for these earlier entries we followed the reference trail. This eventually led us to the earliest reference to the SMC as an extragalactic object, which was in fact among the earliest suggestions that the SMC might be an object outside of our own Galaxy. This was proposed at a time well before the Great Debate on the scale of the universe had taken place between Shapley and Curtis, in 1920 (Curtis 1921; Shapley 1921). Indeed, Hertzsprung (1913) boldly attempted to measure a trigonometric parallax to the SMC, reporting a value of 10^{-4} arcsec. Although this corresponds to a distance of 30,000 light years, his paper refers to a distance of merely 3000 light years. Whether or not this was a genuine typographical error or one of the first cases of publication bias remains unclear (J. Lub, 2014, private communication).

Our database analysis resulted in a total of 304 SMC distance estimates, spanning a large range of approaches, stellar populations, and distance tracers. Figure 1 shows the full set of SMC distance measurements in the database, with panels showing the full historical data set as well as the individual distances published since 1990 for the most commonly used tracers. As for Papers I and II, the full database is availabe from http://astro-expat.info/Data/pubbias.html,[6] as a function of both publication date and distance indicator. Its structure is similar to that used for our LMC distances database presented in Paper I. In the remainder of this paper, we will analyze the distance estimates to the SMC pertaining to a number of individual distance tracers, including eclipsing binary systems (EBs; Section 2), Cepheid and RR Lyrae variable stars (Section 3), stellar population tracers such as the RC and (red) giant stars (Section 4), and star clusters (Section 5). We will discuss the results from the individual distance indicators and derive a common, robust mean distance to the SMC in Section 6.

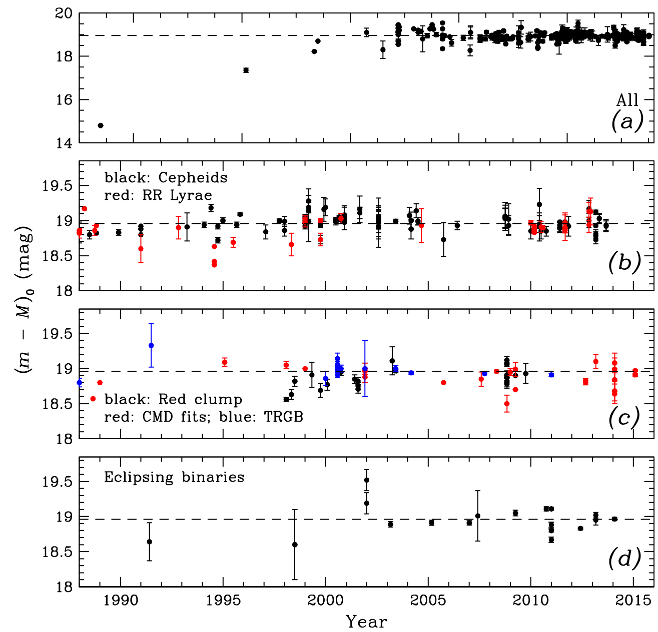

Figure 1. Published extinction-corrected SMC distance moduli as a function of publication date (month) for all data sets pertaining to the SMC body or any of the galaxy's components. The horizontal dashed lines indicate our final, recommended distance modulus, $(m - M)_0 = 18.96$ mag (Section 6). (a) Full data set, clearly showing the historical trend. (b) Variable stars (Section 3). (c) Stellar population tracers (Section 4). CMD: color–magnitude diagram. TRGB: tip of the red giant branch. (d) Eclipsing binary systems (Section 2).

2. ECLIPSING BINARY SYSTEMS

We start our analysis of the distance to the center of the SMC by examining the galaxy's large sample of EBs, because these represent the best geometric distance tracers at the SMC's distance. Since the pioneering efforts by Bell et al. (1991) and Pritchard et al. (1998), EB-based distance determination to the SMC has become fairly routine. We carefully analyzed all relevant papers containing EB-based distance determinations in order to base our conclusions on the most appropriate EB sample.

First, we limited our sample to EBs associated with the SMC's main body. This eliminated HV 2226 (Bell et al. 1991), the only SMC EB with an individual distance estimate located in the galaxy's Wing. We next assessed the remaining sample of 96 distance determinations for duplicates and redundant measurements. The early distance determinations to OGLE SMC-SC7 066175[7] (Pritchard et al. 1998) and OGLE SMC-SC5 202153 (Ostrov 2001) were superseded by more recent estimates by Hilditch et al. (2005) and Harries et al. (2003), respectively, using more up-to-date model approaches. Of the remaining objects, the sample of Harries et al. (2003) contains four objects in common with Drechsel & Neßlinger (2010), while the sample of Hilditch et al. (2005) contains four (different) EBs in common with that of North et al. (2009, 2010, see also Gauderon et al. 2007). One SMC EB, OGLE SMC-SC5 038089, is included in all of Harries et al.

[5] Also note that the individual measurements were not obtained in isolation; calibrations of recent data rely on calibrations of earlier results. Updates to the input physics are continuously implemented, thus improving the resulting outputs. Extending our analysis to several decades before the cut-off used both in this paper and in Papers I and II, would therefore contribute little, if anything, to the results presented here.

[6] For a permanent link to this page and its dependent pages, direct your browser to http://web.archive.org/web/20150313155101/http://astro-expat.info/Data/pubbias.html.

[7] OGLE is the Optical Gravitational Lensing Experiment (http://ogle.astrouw.edu.pl). Object OGLE SMC-SC7 066175 is located in OGLE SMC scan region 7.

(2003), North et al. (2010), and Drechsel & Neßlinger (2010). However, North et al. (2010) suggest to discard their estimate on account of unreliable color measurements.

We checked whether there might be any systematic offsets between the distance estimates of Harries et al. (2003) and Drechsel & Neßlinger (2010), and between Hilditch et al. (2005) and North et al. (2010). Although the subsample sizes are admittedly small, we did not find any systematic differences between either set of distance estimates. As such, for those objects in common and which were not affected by other deteriorating effects (see below), we adopted the average values of Harries et al. (2003) and Drechsel & Neßlinger (2010) for OGLE SMC-SC5 038089, OGLE SMC-SC6 215965, OGLE SMC-SC7 243913, and OGLE SMC-SC11 030116, and those of Hilditch et al. (2005) and North et al. (2010) for OGLE SMC-SC4 110409 and OGLE SMC-SC5 026631.

We discarded OGLE SMC-SC4 163552 from our final sample because of the effects of a third light contribution noted by North et al. (2010). In addition, North et al. (2010) indicated that their measurements of OGLE SMC-SC5 180185, OGLE SMC-SC5 261267, and OGLE SMC-SC5 277080 were affected by unreliable colors. We therefore discarded the former two objects from our sample, given that we do not have access to independent measurements, while for the latter object we adopted the distance estimate of Hilditch et al. (2005).

These considerations left us with a final SMC EB sample of 75 objects. The full data set at the basis of this analysis is provided in Table 1. All of these SMC EBs were composed of early-type (O- and B-type) components. The geometric average position of all sample objects is located firmly within the SMC's main body, at R.A. (J2000) $= 00^{\rm h}\ 52^{\rm m}\ 58\overset{\rm s}{.}2$, decl. (J2000) $= -72°\ 55'\ 14\overset{''}{.}7$, i.e., slightly south of the main body's stellar density center, R.A. (J2000) $= 00^{\rm h}\ 52^{\rm m}\ 44\overset{\rm s}{.}8$, decl. (J2000) $= -72°49'43''$ listed in the NASA/IPAC Extragalactic Database.[8]

Although neither Harries et al. (2003) nor Hilditch et al. (2005) include uncertainties on their individual distance measurements, the former authors suggest that their typical systematic and random uncertainties are of the order of 0.10 and 0.15 mag, respectively, in distance modulus. The latter authors refer to Harries et al. (2003) to support their claim of a 0.10 mag systematic uncertainty. For the purpose of determining a weighted mean distance modulus, we adopt uncertainties of 0.10 mag in distance modulus for those EBs without individual uncertainty estimates. Increasing this to 0.15 mag does not appreciably change our result. The resulting weighted mean distance modulus to our sample of 75 early-type EBs (etEBs) is

$$(m - M)_0^{\rm etEB} = 18.93 \pm 0.03 \text{ mag}. \tag{1}$$

Adopting a normal distribution for the distance estimates leads to $(m - M)_0^{\rm etEB} = 18.95$ mag and a standard deviation (Gaussian σ) of 0.26 mag. This compares well with the mean distance modulus quoted by Harries et al. (2003), $(m - M)_0 = 18.89 \pm 0.04 \pm 0.10$ mag, where the first and second uncertainty estimates represent the statistical and systematic errors, respectively. Similarly, Hilditch et al. (2005) find $\langle (m - M)_0 \rangle = 18.91 \pm 0.03 \pm 0.1$ mag for their full EB sample.

Since distance estimates to etEBs are subject to fairly large systematic uncertainties owing to the need for adoption of stellar atmosphere models (cf. Pietrzyński et al. 2013; Paper I), which are notoriously difficult to correct for, longer-period late-type (cool) giant EBs are preferable as geometric distance tracers. Unfortunately, the numbers of such SMC EBs with reliable distance estimates are still small. Nevertheless, Graczyk et al. (2014) combined new measurements of four late-type EBs (ltEBs) with their earlier estimate of the distance to OGLE-SC10 137844 (Graczyk et al. 2012, 2013) to arrive at

$$(m - M)_0^{\rm ltEB} = 18.965 \pm 0.025 \pm 0.048 \text{ mag}, \tag{2}$$

where the uncertainties again refer to the statistical and systematic errors, respectively.

3. VARIABLE STARS AS DISTANCE INDICATORS

In the absence of significant numbers of geometric distance tracers, variable-star PLRs and PW relations have become fundamental tools to study the nearest rungs of the astrophysical distance ladder, although lingering systematic uncertainties persist. The most commonly used PLRs are derived from Cepheid and RR Lyrae variable stars, which we will cover separately in this section. In addition, the SMC hosts Mira and semi-regular variables, red giant branch (RGB) pulsators, and carbon stars. All of these tracers have been used in attempts to determine the galaxy's distance; we will refer to these efforts in our discussion of giant stars as distance tracers in Section 4.2.

3.1. Cepheids

Cepheids are the most commonly used distance tracers in relation to the SMC. Since records began (Shapley 1940), we have collected some 120 individual Cepheid-based distance measurements to the SMC or its components. In this section, we will explore what we can learn from the roughly 70 modern, post-2000 measurements included in our database.

The majority of Cepheid-based SMC distance estimates rely on classical, fundamental-mode (FU) Cepheid PLRs and PW relations, while a small number of additional measurements are based on first- and second-overtone (FO/SO) pulsators, as well as on double- or mixed-mode ("beat"), Type II, and bump Cepheids. The numbers of these latter measurements are too small to perform a proper statistical analysis, with the possible exception of the FO Cepheid-based distances. However, their associated distance moduli can be used to corroborate the statistical analysis facilitated by the much larger number of classical FU Cepheids. We will now first explore what we can learn from this most common type of Cepheids.

Despite their common use as distance tracers, significant systematic uncertainties remain in the application of Cepheid light-curve observations to the distance problem. First, metallicity differences between comparison populations may affect the resulting PLR slopes significantly (e.g., Sakai et al. 2004; Tammann et al. 2008; Bono et al. 2010; Matsunaga et al. 2011; Groenewegen 2013), although these effects are reduced at near-IR wavelengths (e.g., Storm et al. 2000; Bono et al. 2010) and they seem absent at the longer, mid-IR wavelengths probed by the *Spitzer Space Telescope* (Majaess et al. 2013). In contrast, the reddening-free Wesenheit

[8] http://ned.ipac.caltech.edu

Table 1
Data Set Adopted to Determine the Best Early-type EB Distance Modulus to the SMC

Object Name (OGLE SMC)	R.A. (J2000) (hh mm ss.ss)	Decl. (J2000) (dd mm ss.s)	$(m-M)_0$[b] (mag)	Reference[a]	Object Name (OGLE SMC)	R.A. (J2000) (hh mm ss.ss)	Decl. (J2000) (dd mm ss.s)	$(m-M)_0$[b] (mag)	Reference[a]
SC1 099121	00 38 51.93	−73 34 33.4	19.29	Hi05	SC5 266513	00 50 57.34	−73 12 29.4	19.13 ± 0.118	N10
SC4 056804	00 46 33.14	−73 22 17.0	18.66	Hi05	SC5 277080	00 51 11.38	−73 05 21.7	18.95	Hi05
SC4 103706	00 47 25.55	−73 27 17.3	18.65	Hi05	*SC5 277080*	00 51 11.38	−73 05 21.7	18.52 ± 0.056	N10[d]
SC4 110409	00 47 00.16	−73 18 43.5	18.40	Hi05	SC5 283079	00 50 58.56	−73 04 36.1	19.11 ± 0.054	N10
SC4 110409	00 47 00.16	−73 18 43.5	19.06 ± 0.061	N10	SC5 300549	00 51 23.57	−72 52 24.1	18.52	Hi05
SC4 110409	00 47 00.16	−73 18 43.5	18.73 ± 0.33	[c]	SC5 305884	00 51 20.17	−72 49 42.9	18.86	Hi05
SC4 113853	00 47 03.95	−73 15 20.5	19.00 ± 0.078	N10	SC5 316725	00 51 05.95	−72 40 56.7	18.90	Ha03
SC4 117831	00 47 31.66	−73 12 01.5	18.99 ± 0.062	N10	SC5 255984	00 51 29.63	−73 21 38.3	18.54	Hi05
SC4 121084	00 47 32.14	−73 09 08.8	19.28 ± 0.051	N10	SC5 311566	00 51 34.83	−72 45 46.5	18.66	Hi05
SC4 121110	00 47 04.63	−73 08 39.8	19.08 ± 0.057	N10	SC6 011141	00 52 03.95	−73 18 49.1	19.20	Hi05
SC4 121461	00 47 24.66	−73 09 35.1	19.05 ± 0.083	N10	SC6 077224	00 51 50.13	−72 39 22.7	18.73	Ha03
SC4 159928	00 48 13.56	−73 19 31.2	19.29 ± 0.066	N10	SC6 152981	00 52 41.89	−72 46 22.8	18.64	Hi05
SC4 160094	00 48 10.21	−73 19 37.4	18.96 ± 0.102	N10	SC6 158118	00 52 19.28	−72 41 51.7	18.77	Ha03
SC4 163552	00 47 53.20	−73 15 57.0	18.49	Hi05[d]	SC6 180084	00 53 42.43	−73 23 20.3	18.78	Hi05
SC4 163552	00 47 53.20	−73 15 57.0	18.35 ± 0.079	N10[d]	*SC6 215965*	00 53 33.35	−72 56 24.1	18.83	Ha03
SC4 175149	00 48 34.75	−73 06 53.0	18.52 ± 0.057	N10	*SC6 215965*	00 53 33.36	−72 56 24.5	18.67 ± 0.04	DN10
SC4 175333	00 48 15.33	−73 07 05.1	18.61 ± 0.074	N10	SC6 215965	00 53 33.36	−72 56 24.5	18.75 ± 0.11	[e]
SC5 016658	00 49 02.93	−73 20 55.9	19.13 ± 0.068	N10	SC6 221543	00 53 39.89	−72 52 19.4	19.09	Hi05
SC5 026631	00 48 59.84	−73 13 28.8	18.79	Hi05	SC6 251047	00 53 43.94	−72 31 24.2	18.69	Hi05
SC5 026631	00 48 59.84	−73 13 28.8	19.13 ± 0.036	N10	SC6 311225	00 54 02.03	−72 42 21.9	18.52	Hi05
SC5 026631	00 48 59.84	−73 13 28.8	18.96 ± 0.17	[c]	SC6 319960	00 54 05.25	−72 34 26.2	19.05	Hi05
SC5 032412	00 48 56.62	−73 11 38.8	19.19 ± 0.044	N10	*SC7 066175*	00 54 38.22	−72 32 06.40	18.6 ± 0.5	P98[h]
SC5 038089	00 49 01.82	−73 06 07.2	18.80 ± 0.02	DN10	SC7 066175	00 54 38.22	−72 32 06.4	18.77	Hi05
SC5 038089	00 49 01.85	−73 06 06.9	18.92	Ha03	SC7 120044	00 55 31.64	−72 43 07.6	18.72	Hi05
SC5 038089	00 49 01.85	−73 06 06.9	18.89 ± 0.042	N10[f]	SC7 142073	00 55 54.44	−72 28 08.7	18.62	Hi05
SC5 038089	00 49 01.85	−73 06 06.9	18.86 ± 0.12	[e]	SC7 189660	00 56 37.31	−72 41 43.6	19.38	Hi05
SC5 060548	00 48 35.40	−72 52 56.5	19.22	Hi05	SC7 193779	00 56 21.80	−72 37 01.7	19.27	Hi05
SC5 095194	00 49 50.49	−73 19 31.4	19.29	Hi05	*SC7 243913*	00 56 56.34	−72 49 06.4	19.10	Ha03
SC5 095337	00 49 15.34	−73 22 05.8	19.17 ± 0.097	N10	*SC7 243913*	00 56 56.34	−72 49 06.4	19.11 ± 0.02	DN10
SC5 095557	00 49 18.19	−73 21 55.3	19.19 ± 0.052	N10	SC7 243913	00 56 56.34	−72 49 06.4	19.11 ± 0.1	[e]
SC5 100485	00 49 20.02	−73 17 55.5	18.84 ± 0.052	N10	SC7 255621	00 57 26.51	−72 36 45.8	18.95	Hi05
SC5 100731	00 49 29.33	−73 17 57.9	19.28 ± 0.090	N10	SC8 087175	00 58 30.96	−72 39 14.4	19.10	Hi05
SC5 106039	00 49 20.08	−73 13 35.9	18.95 ± 0.050	N10	SC8 104222	00 58 25.08	−72 19 10.4	19.13	Hi05
SC5 111649	00 49 17.26	−73 10 23.6	18.86 ± 0.046	N10	SC8 209964	01 00 16.02	−72 12 44.3	18.62	Hi05
SC5 123390	00 49 22.61	−73 03 43.3	18.75 ± 0.078	N10	SC9 010098	01 00 52.90	−72 47 48.6	19.18	Hi05
SC5 140701	00 49 43.10	−72 51 09.5	18.62	Hi05	SC9 047454	01 00 52.05	−72 07 06.0	19.12	Hi05
SC5 180064	00 50 44.70	−73 17 40.3	19.05	Hi05	SC9 064498	01 01 17.34	−72 42 32.5	18.75	Hi05
SC5 180185	00 50 02.71	−73 17 34.2	19.45 ± 0.073	N10[f]	SC9 175323	01 03 21.27	−72 05 37.8	18.88 ± 0.04	DN10
SC5 180576	00 50 13.51	−73 16 32.8	19.14 ± 0.106	N10	SC10 033878	01 03 21.27	−72 05 37.8	18.84	Ha03
SC5 185408	00 50 24.61	−73 14 55.8	19.12 ± 0.057	N10	SC10 037156	01 03 28.82	−72 01 28.9	19.11	Hi05
SC5 202153	00 50 27.93	−73 03 16.1	19.13	Ha03	SC10 094559	01 05 06.82	−72 24 57.4	18.64	Hi05
SC5 202153	00 50 27.95	−73 03 16.5	19.36 ± 0.22	O01[g]	SC10 108086	01 05 30.57	−72 01 21.4	18.76	Hi05
SC5 208049	00 50 44.98	−72 58 44.5	19.48	Hi05	SC10 110440	01 05 09.59	−71 58 42.3	18.29	Hi05
SC5 243188	00 51 18.78	−73 30 16.3	19.33	Hi05	*SC11 030116*	01 06 24.86	−72 12 48.3	18.71	Ha03
SC5 261267	00 51 35.04	−73 17 11.1	19.35 ± 0.068	N10[f]	*SC11 030116*	01 06 24.88	−72 12 48.7	18.88 ± 0.04	DN10
SC5 265970	00 51 28.12	−73 15 17.9	19.25 ± 0.048	N10	SC11 030116	01 06 24.88	−72 12 48.7	18.79 ± 0.11	[e]
SC5 266015	00 51 16.73	−73 13 02.7	19.23 ± 0.038	N10	SC11 057855	01 07 31.44	−72 19 52.9	18.92	Ha03
SC5 266131	00 51 35.63	−73 12 44.1	19.11 ± 0.081	N10	*HV 2226*	01 24	−73.3	18.64 ± 0.27	B91[i]

Note. Objects referenced using italic font were not included in our final analysis for reasons indicated in these footnotes.

[a] References: B91—Bell et al. (1991), DN10—Drechsel & Neßlinger (2010), Ha03—Harries et al. (2003), Hi05—Hilditch et al. (2005), N10—North et al. (2010), O01—Ostrov 2001, P98—Pritchard et al. (1998).

[b] Where no uncertainties are provided by the original authors, we adopted uncertainties of 0.10 mag to determine the weighted mean.

[c] Average of Hi05 and N10; the error indicates the range.

[d] Discarded because of a third light contribution.

[e] Average of Ha03 and DN10.

[f] Discarded because of unreliable colors.

[g] Superseded by Ha03.

[h] Superseded by Hi05.

[i] Wing EB.

magnitudes do not appear to depend on a population's metallicity, even at optical wavelengths (cf. Inno et al. 2013a).

Second, PLR-based distance calibrations are most commonly done in a relative sense, by deriving the differential distance modulus between a calibration population's PLR and that of the target sample. The majority of Cepheid-based distance estimates to the SMC use Galactic Cepheids as their baseline for absolute distance determination. A number of authors have pointed out that at least two types of systematic uncertainties may affect the validity of such an approach. Most subtly, Galactic Cepheid PLRs at optical and near-IR wavelengths are linear for all periods, within the intrinsic uncertainties. In contrast, the LMC PLRs are known to exhibit a clear "break" (a change of slope) in the relations at a period of approximately 10 days; it appears that the SMC PLRs may exhibit either a break at $\log(P/\mathrm{d}) \simeq 0.4$ or a downward curvature toward shorter periods (e.g., Tammann et al. 2008; Bono et al. 2010; Matsunaga et al. 2011). This would clearly invalidate any direct differential distance modulus determination, yet many authors proceed along these lines nevertheless. Once again, it turns out that use of the reddening-free PW relations avoids this critical issue: Inno et al. (2013a) use a sample of 2571 FU Cepheids observed through JHK_s filters to conclude that the PW slopes in both the Magellanic Clouds and the Milky Way are linear. Still, in a follow-up paper Inno et al. (2013b) take great care to determine the differential LMC–SMC distance modulus only at a pivotal period of $\log(P/\mathrm{d}) = 0.5$ (0.3) for FU (FO) Cepheids.

Second, absolute distance calibration based on comparison with Galactic objects is known to be plagued by significant systematic effects. These calibrations are often based on parallax measurements, which are unfortunately very small and have typical uncertainties in excess of 30%. *HST*-based parallaxes are less seriously affected by these parallax errors (e.g., Benedict et al. 2002, 2007) than the earlier *Hipparcos* measurements, although the revised *Hipparcos* parallaxes (van Leeuwen et al. 2007) provide a significantly improved calibration data set.[9]

In the interest of full disclosure, we point out that in this paper we have opted to use differential LMC–SMC distance moduli where provided, combined with $(m - M)_0^{\mathrm{LMC}} = 18.50$ mag (cf. Paper I), to compile a homogenized database of SMC distances. This is particularly important in the context of pre-2000 LMC/SMC distance determinations (e.g., Udalski 2000), compared with later measurements based on significantly overlapping tracer samples (e.g., Inno et al. 2013a), given the persistent "long" versus "short" LMC distance dichotomy that affected this field prior to the new millennium (for a detailed discussion, see Paper I). After all, establishing a robust LMC distance modulus was one of the main aims of Paper I; we are now using that result to our advantage in this paper.

When we keep in mind these caveats and combine these concerns with the complex geometry of the SMC, it is indeed highly surprising that the post-2000 (and, in fact, many earlier) Cepheid-based SMC distance determinations cluster very closely around an SMC distance modulus of $(m - M)_0 \sim 19.0$ mag. At first glance, this might imply that (i) none of these effects are sufficiently important to have a significant effect, (ii) multiple caveats may affect many of these distance determinations simultaneously, somehow counteracting each others' effects, or (iii) we are witnessing the effects of (presumably unconscious) publication bias.

For our detailed analysis of the body of FU Cepheid-based SMC distances, we will first homogenize the distance scale by "correcting" when necessary any distance estimate to the commonly adopted LMC benchmark distance modulus of $(m - M)_0^{\mathrm{LMC}} = 18.50$ mag (for a detailed discussion, see Paper I). Many of the authors cited in our database provide, in fact, differential LMC–SMC distance moduli. In such cases, we homogenize the database by adding these differential values to the canonical LMC distance modulus adopted here (for similar approaches applied to a large number of nearby galaxies, see also Ferrarese et al. 2000; Sakai et al. 2004).

Of the PLR- and PW-based post-2000 SMC distance estimates in our database, we now highlight a few that need special care in our subsequent statistical analysis. Udalski (2000) derives an LMC distance of $(m - M)_0 = 18.24$ mag based on the *I*-band PW relation, although his differential LMC–SMC distance modulus is $\Delta\mu_0 = 0.51 \pm 0.05$, which is well within the commonly accepted range. McCumber et al. (2005) selected a subset of Cepheids from the *BV*-based compilation of Mathewson et al. (1986) to determine a distance modulus of $(m - M)_0 = 18.73 \pm 0.24$ mag to a field in the SMC's Wing. Since we are interested in deriving the most appropriate distance to the *main body* of the SMC, we will discard this measurement. In addition, careful analysis of the premises on which Mathewson et al. (1986) based their Cepheid distance scale implies that they adopted $(m - M)_0^{\mathrm{LMC}} = 18.45$ mag ($D_{\mathrm{LMC}} = 49$ kpc). Finally, Haschke et al. (2012) attempted to correct their optical (*VI*), OGLE-based sample of 2522 FU Cepheids for the effects of foreground extinction both by taking the area-averaged attenuation and by comparing the observed and intrinsic colors of their sample stars (i.e., essentially using a period–luminosity–color relation) to derive individual extinction values. The resulting difference in the derived distance modulus is $\Delta(m - M)_0 = 0.17$–0.19 mag. This thus serves as a strong indication of the importance of minimizing the systematic uncertainties. We will henceforth use their distance modulus resulting from extinction correction on a star-by-star basis.

In addition to the PLR- and PW-based Cepheid distance estimates to the SMC, more direct attempts have been made—using much smaller sample sizes—by application of the BW/Barnes–Evans "quasi-geometrical" surface brightness approach (e.g., Storm et al. 2000, 2004, 2011; Barnes et al. 2004; Groenewegen 2013). Based on only five Cepheids, Storm et al. (2000) find an SMC distance modulus of $(m - M)_0 =$

[9] Udalski (2000) eloquently explained and clearly showed that absolute magnitude calibration of bright Galactic Cepheids, based on the original *Hipparcos* parallaxes, should be approached with significant caution. Such calibrations predict $M_V^{\mathrm{Ceph}} = -4.2$ mag for $\log(P/d) = 1.0$ (Feast & Catchpole 1997; Lanoix et al. 1999; Groenewegen & Oudmaijer 2000), which Udalski (2000) assesses as too bright (see also Abrahamyan 2004), i.e., they are affected by large systematic uncertainties in the zero-point calibration (for a discussion, see Paper I). Calibrations of fainter objects tend to be more reliable; they are usually based on "quasi-geometrical" methods such as the Barnes–Evans variant of the Baade–Wesselink (BW) surface brightness method (e.g., Storm et al. 2000, 2004, 2011; Barnes et al. 2004; Groenewegen 2013) or pre-*Hipparcos* Galactic calibrations (e.g., Laney & Stobie 1994), which are less affected by systematic uncertainties in the photometric zero point owing to, e.g., uncertain extinction corrections or Lutz–Kelker-type biases (cf. de Grijs 2011; his Chapter 6.1.2). *HST* and revised *Hipparcos* parallax calibrations are, fortunately, used fairly extensively to determine distances to Local Group galaxies (for SMC distances, see e.g., Majaess et al. 2008; Inno et al. 2013a).

19.19 ± 0.12 mag if using V and K magnitudes, but $(m-M)_0 = 18.90 \pm 0.07$ mag based on VR_J photometry. Using the same five stars, they derive $(m-M)_0 = 18.88 \pm 0.14$ mag (corrected for depth effects) and $(m-M)_0 = 18.92 \pm 0.14$ mag in their 2004 and 2011 papers, respectively, using the same near-IR surface brightness technique.

Groenewegen (2013) uses six SMC Cepheids and a number of different near-IR BW-type approaches to estimate $(m-M)_0 = 18.73$–18.81 mag. He acknowledges that these distances are smaller than expected from the full body of SMC distance measurements and states that this "is not predicted by theoretical investigations, but these same investigations do not predict a steep dependence on period [as found here] either, indicating that additional theoretical work is warranted." One possible solution to reconcile these shorter BW distances with the longer PLR/PW-based distances may be found in the possible metallicity dependence of the p ("projection") factor[10] used in BW analyses (Groenewegen 2013).

In view of these concerns, we will not include BW-type analyses in determining the weighted mean SMC distance. We are therefore left with an ensemble of 32 SMC distance estimates published between 2000 June and 2013 August based on PLR and PW analyses. The resulting weighted mean distance, using the statistical uncertainties as weights, is

$$(m-M)_0^{\rm FU\ Ceph} = 19.00 \pm 0.02 \text{ mag}, \tag{3}$$

with a standard deviation (implying both a significant line of sight depth and the lingering effects of systematic uncertainties) of 0.08 mag. Our weighting approach is fully justified on statistical grounds, because the minimum numbers of Cepheids contributing to the individual SMC distance measurements are 91 (Ferrarese et al. 2000) and 94 (Sakai et al. 2004).[11] As such, our method is not compromised by finite sampling properties, in which case the distributions of individual FU Cepheid distance moduli would formally follow a t distribution with a given number of degrees of freedom. However, provided that the number of data points used to derive the respective distance moduli is larger than approximately 50, the results from a t distribution are almost the same as those from a normal (Gaussian) distribution, and the associated error bar reflects the most likely uncertainty in the mean. Our working samples thus represent large populations where the effects of small-sample statistics can be ignored. Since the limit of a t distribution for a large number of data points is a normal (Gaussian) distribution, the statistical inferences for a large number of data points will be the same. Hence, this fully justifies our approach. The remaining 29 distance moduli are based on much larger numbers of FU Cepheids, often in excess of a few thousand objects.[12] The only exceptions here include the samples used by Abrahamyan (2004), Bono et al. (2008, 2010), and Majaess et al. (2013), which contain 234, ~200, 344, and ~100 objects (based on inspection of their Figure 1), respectively. Nevertheless, these numbers of FU Cepheids still meet our minimum rule-of-thumb number of 50 quoted above.

We will now place these results for FU Cepheids in the context of other Cepheid-based distances. Our database includes 13 SMC distance estimates based on FO Cepheids, taken from four articles by the same group (Bono et al. 2001, 2002; Inno et al. 2013a, 2013b). These authors used I-band and near-IR PW analysis to obtain their results. Their weighted mean distance is $(m-M)_0^{\rm FO\ Ceph} = 19.01 \pm 0.02$ mag. An interesting result from Inno et al. (2013a) is that the PLR slope of the FO pulsators differs from the corresponding slope of their FU counterparts. This means that the FO Cepheids should not be "fundamentalized" to improve the statistical sample of FU pulsators, as is often done in the literature. We note, however, that Groenewegen (2000) analyzed their FU and FO Cepheids separately and deemed them sufficiently consistent (contrary to the result of Inno et al. 2013a) to lead to a single differential LMC–SMC distance modulus.

The single SO Cepheid distance modulus reported is $(m-M)_0^{\rm SO\ Ceph} = 19.11 \pm 0.08$ mag (Bono et al. 2001), while double-mode (or beat) Cepheid OGLE (VI)-based analysis implies $(m-M)_0^{\rm beat} = 19.05 \pm 0.02$ mag (Kovács 2000). All of these measurements are internally consistent and commensurate with the weighted mean distance we derived for the FO Cepheids. Indeed, Inno et al. (2013a) similarly concluded that mixed-mode Cepheids follow the same PW relations in the SMC as their FO counterparts.

Finally, we also retrieved SMC distance moduli based on both Type II and bump Cepheids. The single bump-Cepheid measurement yields $(m-M)_0^{\rm bump\ Ceph} = 18.93 \pm 0.06$ mag (Keller & Wood 2006), where we determined the uncertainty ourselves based on the published data, because the authors only provided the uncertainty on the mean rather than the standard deviation of the distribution (see the relevant discussion in Paper I). We have found four independent SMC distance estimates based on Type II Cepheids (Majaess et al. 2009; Ciechanowska et al. 2010; Matsunaga et al. 2011), resulting in a weighted mean distance of $(m-M)_0^{\rm TII} = 18.87 \pm 0.06$ mag, for which we used the random uncertainties as weights. These objects are closer in nature to RR Lyrae stars (see Section 3.2) than to classical Cepheids (e.g., Bono et al. 1997; Wallerstein 2002).

Table 2 lists all Cepheid-based distances used in this paper, for all different Cepheid types considered, recalibrated to a canonical LMC distance modulus of $(m-M)_0^{\rm LMC} = 18.50$ mag where necessary. Figure 2(a) provides a summary of our final Cepheid data sets. The black solid bullets represent PLR- and PW-based distance estimates using samples of FU Cepheids, while the red solid bullets indicate BW-type distances to FU Cepheids. Blue solid bullets correspond to FO Cepheid-based distances, and black open circles indicate distance estimates based on Type II Cepheids. Finally, the green open squares are labeled with the specific types of Cepheids used for their determination.

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[10] Projection (p) factors are commonly used to convert radial to pulsation velocities.

[11] The single exception to this statement is the sample composed of 13 FU Cepheids used by McCumber et al. (2005), although we do not use this measurement. The latter authors state that "the distribution of [these] 13 Cepheids ... appears to be roughly Gaussian," while their quoted uncertainty of 0.24 mag reflects the more uncertain nature of their mean distance modulus compared with the other recent measurements included in our database.

[12] Groenewegen (2000): 2048 (OGLE)/1511 (*Hipparcos*); Udalski (2000): up to 3300; Pietrzyński et al. (2003): no numbers quoted, but the sample is based on the large OGLE database; Majaess et al. (2008): 2140; Feast (2011) and Matsunaga et al. (2011): 2436; Haschke et al. (2012): 2522; Inno et al. (2013a, 2013b): 2571 and 2626, respectively.

Table 2
Adopted, Homogenized Cepheid Distances Used in this Paper

Publl. Date (yyyy/mm)	$(m - M)_0$ (mag)	Reference	PLR/ PW	Filter(s)	Notes
		FU Cepheids			
2000 Jun	18.997 ± 0.024	Ferrarese et al. (2000)	PLR	J	Madore & Freedman (1991) calibration
2000 Jun	19.013 ± 0.022	Ferrarese et al. (2000)	PLR	H	Madore & Freedman (1991) calibration
2000 Jun	18.989 ± 0.022	Ferrarese et al. (2000)	PLR	K	Madore & Freedman (1991) calibration
2000 Jun	18.99 ± 0.05	Ferrarese et al. (2000)	PLR	JHK	Cardelli et al. (1989) reddening law
2000 Sep	19.01 ± 0.05	Udalski (2000)	PW	I	…
2000 Nov	19.08 ± 0.11	Groenewegen (2000)	PW	VI	…
2000 Nov	19.04 ± 0.17	Groenewegen (2000)	PLR	K_s	…
2000 Nov	19.01 ± 0.03	Groenewegen (2000)	PW	VI	Udalski et al. (1999) calibration
2000 Nov	18.975 ± 0.022	Groenewegen (2000)	…		Mean of 6 IR determinations
2000 Nov	19.004 ± 0.015	Groenewegen (2000)	…		Mean of all 8 determinations
2000 May	18.99 ± 0.03	Pietrzyński et al. (2003)	PLR	K	…
2004 Jan	19.070 ± 0.119	Abrahamyan (2004)	PLR	$BVIJHK$	…
2004 Jun	18.99 ± 0.05	Sakai et al. (2004)	PLR	VI	Madore & Freedman (1991) calibration
2004 Jun	18.99 ± 0.05	Sakai et al. (2004)	PLR	VI	Udalski et al. (1999) calibration
2005 Sep	18.78 ± 0.24	McCumber et al. (2005)	PLR	I_V	Subset of Mathewson et al. (1986)
2008 Sep	19.06 ± 0.20	Bono et al. (2008)	PW	BV	$P > 6$ days, metallicity corrected
2008 Sep	19.03 ± 0.14	Bono et al. (2008)	PW	VI	$P > 6$ days
2008 Sep	19.04 ± 0.14	Bono et al. (2008)	PW	BI	$P > 6$ days
2008 Sep	19.06 ± 0.16	Bono et al. (2008)	PW	BVI	$P > 6$ days
2008 Nov	18.93 ± 0.14	Majaess et al. (2008)	PLR	VI	…
2008 Nov	19.02 ± 0.22	Majaess et al. (2008)	PLR	VJ	…
2010 May	19.23 ± 0.23	Bono et al. (2010)	PW	BV	…
2010 May	18.95 ± 0.12	Bono et al. (2010)	PW	VI	…
2010 May	18.91 ± 0.20	Bono et al. (2010)	PW	JK_s	…
2011 May	18.98 ± 0.01	Matsunaga et al. (2011)	PLR,PW	IK	…
2011 May	18.93 ± 0.05	Matsunaga et al. (2011)	PLR,PW	IK	Metallicity corrections
2011 Aug	18.98 ± 0.01	Feast (2011)	PW	VI	…
2012 Oct	19.00 ± 0.10	Haschke et al. (2012)	PLR	…	Individual reddening
2013 Feb	18.93 ± 0.02	Inno et al. (2013a)	PW	$VIJHK_s$	Systematic uncertainty 0.10 mag
2013 Apr	19.03 ± 0.06	Inno et al. (2013b)	PW	$VIJHK_s$	…
2013 Aug	18.938 ± 0.077	Majaess et al. (2013)	PLR	3.6 μm	…
2013 Aug	18.921 ± 0.075	Majaess et al. (2013)	PLR	4.5 μm	…
		FO Cepheids			
2001 Aug	19.16 ± 0.19	Bono et al. (2001)	PW	VI	Incl. FO components in FO/SO pulsators
2002 Jul	19.06 ± 0.13	Bono et al. (2002)	PW	IK	Theoretical calibration
2002 Jul	18.98 ± 0.21	Bono et al. (2002)	PLR	I	Theoretical calibration
2002 Jul	19.02 ± 0.19	Bono et al. (2002)	PLR	K	Theoretical calibration
2002 Jul	19.02 ± 0.14	Bono et al. (2002)	PW	IK	Empirical calibration
2002 Jul	18.91 ± 0.17	Bono et al. (2002)	PLR	I	Empirical calibration
2002 Jul	18.97 ± 0.35	Bono et al. (2002)	PLR	K	Empirical calibration
2002 Jul	19.04 ± 0.09	Bono et al. (2002)	…	I	Weighted mean, theoretical calibration
2002 Jul	18.98 ± 0.10	Bono et al. (2002)	…	I	Weighted mean, empirical calibration
2002 Jul	19.04 ± 0.11	Bono et al. (2002)	…	K	Weighted mean, theoretical calibration
2002 Jul	19.01 ± 0.13	Bono et al. (2002)	…	K	Weighted mean, empirical calibration
2013 Feb	19.12 ± 0.03	Inno et al. (2013a)	PW	$VIJHK_s$	Systematic uncertainty 0.10 mag
2013 Apr	19.03 ± 0.07	Inno et al. (2013b)	PW	$VIJHK_s$	…
		Type II Cepheids			
2009 Dec	18.85 ± 0.11	Majaess et al. (2009)	PW	VI	…
2010 Sep	18.85 ± 0.07	Ciechanowska et al. (2010)	PLR	JK	Systematic uncertainty 0.07 mag
2011 May	18.90 ± 0.07	Matsunaga et al. (2011)	PW	IK	…
2011 May	18.89 ± 0.05	Matsunaga et al. (2011)	PLR	I	…
		Other Cepheid Types			
2000 Aug	19.05 ± 0.017	Kovács (2000)	…	VI	Double-mode (beat) Cepheids Syst. unc. 0.043 mag; theoretical models

Table 2
(Continued)

Publ. Date (yyyy/mm)	$(m - M)_0$ (mag)	Reference	PLR/ PW	Filter(s)	Notes
2001 Aug	19.11 ± 0.08	Bono et al. (2001)	PW	*VI*	SO Cepheids
2006 May	18.93 ± 0.06	Keller & Wood (2006)	⋯	*VR*	Bump Cepheids; Pulsation models

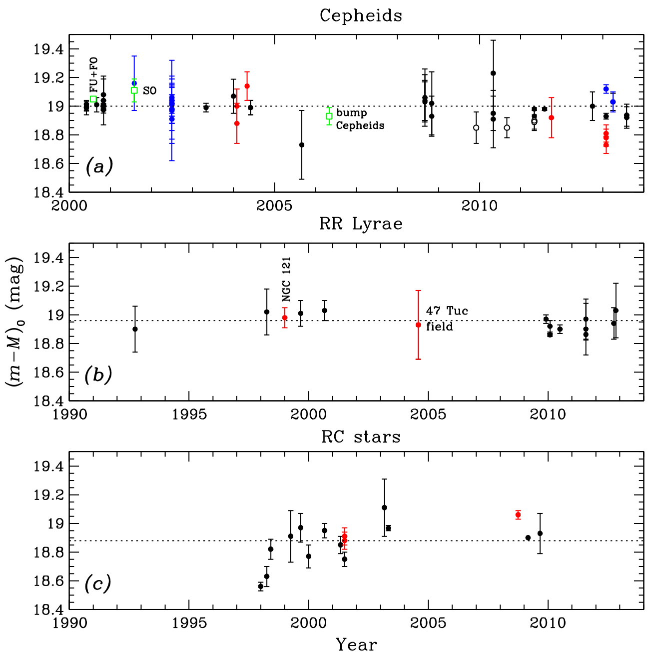

Figure 2. Cleaned data sets used for our statistical SMC distance analysis. The horizontal dotted lines represent the weighted mean levels pertaining to each sample of specific distance indicators (see the text). (a) Cepheid samples. Black solid bullets: FU Cepheids, PLR/PW-based distances. Red solid bullets: FU Cepheids, BW-type distance estimates. Blue solid bullets: FO Cepheids. Black open circles: Type II Cepheids. (b) RR Lyrae samples. Red data points represent distances to NGC 121 and an SMC background field behind the Galactic globular cluster 47 Tucanae. (c) RC stars. Red data points represent distance estimates to NGC 121.

3.2. RR Lyrae Stars

RR Lyrae stars are the most numerous variable stars in old stellar populations. Various attempts have been made to determine the distance to the SMC using its population of RR Lyrae variables. Here we will focus on the main achievements since 1990; our full database includes RR Lyrae-based distance estimates since the early attempts by Thackeray & Wesselink (1953, 1954) of distance determination to NGC 121, the oldest globular cluster in the SMC. In this section, we will only consider RR Lyrae-based SMC distance estimates pertaining to the galaxy's field population in the main body. We specifically exclude any efforts made at determining the distance to NGC 121, but we will return to that object in Section 5.1.

This restriction leaves us with 22 individual field-star distance estimates published in 17 different articles between 1992 October and 2012 November. Of these, four publications (Udalski 1998a; Udalski et al. 1999; Kapakos et al. 2011; Kapakos & Hatzidimitriou 2012) use as their basis LMC distance moduli that deviate from our adopted canonical value, $(m - M)_0^{\rm LMC} = 18.50$ mag. We either applied the relevant corrections to the SMC distance moduli reported by these authors or used the differential LMC–SMC distance modulus (if given), combined with $(m - M)_0^{\rm LMC} = 18.50$ mag, to arrive at a homogenized set of SMC distance estimates.

We carefully explored the assumptions underlying the different analyses pertaining to RR Lyrae-based distance estimates to the SMC. With increasing numbers of RR Lyrae observations in the SMC becoming available over the period of interest, the mean SMC distance modulus appears to have reached a stable value. Nevertheless, we caution that some of the analyses used in this section must be handled carefully.

For instance, Sandage et al. (1999) based their distance determination of $(m - M)_0 = 19.00 \pm 0.03$ mag on very careful calibration, but they adopted two questionable assumptions. First, their observational sample consisted of RR Lyrae from both Walker & Mack (1988) and Smith et al. (1992). The former comprised a sample of RR Lyrae stars in NGC 121, while the latter consisted of field stars in the vicinity of both NGC 121 and NGC 361. Udalski (1998b) suggests that NGC 121 is located 0.08 ± 0.04 mag behind the SMC's center (cf. Section 5.1), so that this assumption could introduce a systematic offset in the derived distance to the SMC. Second, the metallicity–luminosity relation they adopted is characterized by a very steep slope—$M_V \propto 0.30$ [Fe/H]—which is outside the range commonly agreed upon (for a discussion, see Paper I). Both assumptions might, in fact, conspire to lead to an "SMC distance modulus" that falls inside the range implied by other studies, but the basic premise of the approach used in this case is questionable. For these reasons, we will not include this result in our analysis.

Despite significant improvements in our understanding of the degeneracies affecting RR Lyrae-based distance calibration, including those owing to the effects of metallicity differences, the effects of extinction remain troublesome. This can be seen clearly by considering the set of distance moduli provided by Haschke et al. (2012), who attempted to correct their OGLE-based sample of 1494 FU RR Lyrae (RRab) for the effects of foreground extinction both by taking the area-averaged attenuation and by comparing the observed and intrinsic colors of their sample RR Lyrae stars to derive individual extinction values. The resulting difference in the derived distance modulus (applied to the same RR Lyrae sample) is $\Delta(m - M)_0 \simeq 0.2$ mag. Following our approach for the Cepheid-based distances, we will therefore use their distance modulus resulting from extinction correction on a star-by-star basis.

Extinction effects may also have caused a systematic overestimate of the SMC distance by Kapakos & Hatzidimitriou (2012). These authors identify a systematic difference in their reddening corrections compared with their earlier work (Kapakos et al. 2011), by $\Delta E(B - V) = 0.02 \pm 0.05$ mag to $\Delta E(B - V) = 0.08 \pm 0.02$ mag for the SMC's inner and outer regions, respectively, thus systematically reducing the distance difference between the LMC and SMC by $\Delta(m - M)_0 = 0.07 \pm 0.17$ mag to $\Delta(m - M)_0 = 0.27 \pm 0.07$ mag.

Table 3
Homogenized Field RR Lyrae Distances Considered in this Paper

Publ. date (mm/yyyy)	$(m-M)_0$[a] (mag)	Reference	Notes
1992 Oct	18.90 ± 0.16	Smith et al. (1992)	Field near NGC 361
1998 Apr	18.66 ± 0.16	Udalski (1998a)	...
1999/00	19.02 ± 0.05	Reid (1999)	Based on Udalski (1998a)
1999 Sep	19.00 ± 0.03	Sandage et al. (1999)	Metallicity corrected
1999 Sep	19.01 ± 0.09	Udalski et al. (1999)	...
2000 Sep	19.03 ± 0.07	Udalski (2000)	...
2004 Aug	18.93 ± 0.24	Weldrake et al. (2004)	47 Tuc field
2009 Dec	18.97 ± 0.03	Szewczyk et al. (2009)	Systematic uncertainty 0.12 mag
2010 Feb	18.86 ± 0.01	Deb & Singh (2010)	RRab, mean
2010 Feb	18.83 ± 0.01	Deb & Singh (2010)	RRab, intensity-weighted mean
2010 Feb	18.84 ± 0.01	Deb & Singh (2010)	RRab, phase-weighted mean
2010 Feb	18.92 ± 0.04	Deb & Singh (2010)	RRc, mean
2010 Feb	18.89 ± 0.04	Deb & Singh (2010)	RRc, intensity-weighted mean
2010 Feb	18.89 ± 0.04	Deb & Singh (2010)	RRc, phase-weighted mean
2010 Jun	18.91 ± 0.08	Majaess (2010)	...
2010 Jul	18.90 ± 0.03	Kapakos et al. (2010)	...
2011 Aug	18.90 ± 0.18	Kapakos et al. (2011)	RRab
2011 Aug	18.97 ± 0.14	Kapakos et al. (2011)	RRc
2011 Aug	18.863 ± 0.04	Feast (2011)	*K*, corrected for metallicity effects
2012 Oct	19.13 ± 0.13	Haschke et al. (2012)	Area-averaged reddening
2012 Oct	18.94 ± 0.11	Haschke et al. (2012)	Individual reddening
2012 Nov	19.11 ± 0.19	Kapakos & Hatzidimitriou (2012)	...

Note.
[a] Distance moduli rendered in italic font were not used for the determination of the weighted mean RR Lyrae-based SMC distance derivation in this paper, for reasons discussed in the text.

Additional, although likely small, systematic uncertainties pertain to the calibration approaches adopted, with more recent analyses using a Fourier light-curve decomposition method (Jurcsik & Kovács 1996) to derive metallicities (e.g., Deb & Singh 2010; Kapakos et al. 2010, 2011; Kapakos & Hatzidimitriou 2012), followed by absolute-magnitude calibration based on either theoretical models (e.g., Weldrake et al. 2004) or robust observational analysis (e.g., Clementini et al. 2003). The latter authors explored a range of different M_V–[Fe/H] luminosity–metallicity relations to calibrate the absolute magnitudes of the 77 RRab, 38 RRc, and 10 RRd variables in their sample of LMC RR Lyrae stars, as well as cross-calibrations with other distance indicators. Their recommended calibration relation is characterized by a slope of $\Delta M_V\,(\mathrm{RR})/\Delta[\mathrm{Fe/H}] = 0.214 \pm 0.047$, which is consistent with the concensus value (cf. Paper I). The LMC zero point resulting from their RR Lyrae analysis, combined with BW calibration and the statistical parallax method, is consistent with the "short" distance scale, although use of RC stars and contemporary reddening estimates move their LMC distance modulus closer to the canonical value recommended in Paper I. Nevertheless, and in view of the systematic uncertainties affecting these calibration relations, we have opted to use relative LMC–SMC distance moduli where provided, combined with $(m-M)_0^{\mathrm{LMC}} = 18.50$ mag, since relative distance moduli are significantly less affected by lingering systematic effects.

Finally, except where specifically indicated in our database, most authors base their RR Lyrae distance estimates on RRab-type stars. A small number of authors (Smith et al. 1992; Weldrake et al. 2004; Szewczyk et al. 2009) base their results on a mixture of RRab and FO pulsators (RRc stars), where they fundamentalize the RRc stars. To calculate the weighted mean distance implied by field RR Lyrae in the SMC, we combine RRab and RRc-based distance estimates and their statistical uncertainties ; we include only the "mean" distances given by (Deb & Singh 2010, see the database notes for details), which thus leaves us with a final sample of 16 distance measurements. Table 3 provides an overview of our homogenized RR Lyrae-based SMC distances data set published between 1990 and 2015, adopting the canonical LMC distance modulus, $(m-M)_0^{\mathrm{LMC}} = 18.50$ mag where relevant. The distance moduli highlighted in italic font were not used for the determination of the weighted mean field RR Lyrae-based SMC distance. The latter is

$$(m-M)_0^{\mathrm{RR}} = 18.96 \pm 0.02 \text{ mag}, \tag{4}$$

with a standard deviation of 0.06 mag.

Figure 2(b) provides a summary of our final RR Lyrae data set. We have indicated the distances resulting from analysis of the NGC 121 RR Lyrae (Reid 1999) as well as those in the 47 Tuc field (Weldrake et al. 2004) separately, using red data points. Since these measurements relate to specific observational fields, they do not necessarily accurately reflect the distance to the SMC's center. We will discuss distance determinations to the SMC's star clusters in detail in Section 5.

4. STELLAR POPULATION TRACERS

Next, we will discuss the distance determinations resulting from careful analysis of well-defined stellar population features

Table 4
Homogenized RC-based SMC Distances

Publ. Date (mm/yyyy)	$(m-M)_0$[a] (mag)	Reference	Notes
1998 Jan	18.56 ± 0.03	Udalski et al. (1998) [b]	Systematic uncertainty 0.06 mag
1998 Apr	18.63 ± 0.07	Uldalski (1998a)[b]	…
1998 Jun	18.82 ± 0.07	Cole (1998)	Systematic uncertainty 0.13 mag
1998 Sep	18.65 ± 0.08	Udalski (1998b) [b]	Clusters
1999 Apr	$18.91^{+0.18}_{-0.16}$	Twarog et al. (1999)	…
1999 Sep	18.97 ± 0.10	Udalski et al. (1999)	…
2000 Jan	18.77 ± 0.08	Popowski (2000)	…
2000 Sep	18.95 ± 0.05	Udalski (2000)	…
2000 May	18.85 ± 0.06	Girardi & Salaris (2001)	…
2000 Jul	18.71 ± 0.06	Crowl et al. (2001)	5 clusters,[c] Schlegel et al. (1998) reddening
2000 Jul	18.82 ± 0.05	Crowl et al. (2001)	5 clusters,[c] Burstein & Heiles (1982) reddening
2000 Mar	19.11 ± 0.2	Alcaino et al. (2003)	NGC 458 (cluster located far to the NE of the SMC body)
2000 May	18.967 ± 0.018	Pietrzyński et al. (2003)	*K*
2008 Oct	18.90 ± 0.07	Glatt et al. (2008b)	NGC 416 (main-body cluster)
2009 Mar	18.9	Cignoni et al. (2009)	NGC 602 (Wing cluster)
2009 Sep	18.89 ± 0.45	Sabbi et al. (2009)	Field SFH1
2009 Sep	18.97 ± 0.27	Sabbi et al. (2009)	Field SFH4

Notes.
[a] Distance moduli rendered in italic font were not used for the determination of the weighted mean RC-based SMC distance derivation in this paper (see the text, Notes, and these footnotes).
[b] The earlier values published by Udalski's team were ignored given that they continuously updated their numbers based on improved input physics.
[c] Based on five clusters associated with the SMC's main body, i.e., NGC 152, NGC 361, NGC 411, NGC 416, and Kron 28.

along the RGB, including the magnitude of the RC and the tip of the red giant branch (TRGB).

4.1. The RC as a Standard Candle

RC stars are the low- to intermediate-mass ($\sim$0.7–2 $M_\odot$, depending on chemical composition) analogs of the helium-burning horizontal-branch stars typically seen in old globular clusters. Theoretical models imply that their absolute luminosity depends only weakly or even negligibly on age and metallicity, particularly at wavelengths longward of the *I* band (Paczyński & Stanek 1998: *I*; Alves 2000; Grocholski & Sarajedini 2002; Alves et al. 2002; Sarajedini et al. 2002: *J*, *K*; for discussions, see Pietrzyński et al. 2010; de Grijs 2011, his Chapter 3.2.2). For instance, Stanek & Garnavich (1998) found an *I*-band variance of the RC's absolute magnitude of only $\sim$0.15 mag. In the context of SMC distance measurements, Udalski (1998a) established that the absolute *I*-band RC magnitude in SMC star clusters is virtually independent of age for ages between 2 and 10 Gyr. Although RC stars span a larger age range in many stellar populations, this result implies that the RC magnitude is useful as a standard candle to a large fraction of the SMC's stellar population. Similarly, Grocholski & Sarajedini (2002) showed that for ages between $\sim$2 and 6 Gyr and $-0.5 \leqslant$ [Fe/H] $\leqslant 0$ dex, the intrinsic variation in the RC's absolute *K*-band magnitude is minimized (see also Alves 2000; but see Salaris & Girardi 2005 and Groenewegen 2008 for discussions of population corrections).

Indeed, the lack of any age dependence for these ages is not subject to debate. In the context of our database of SMC distance estimates, which span many decades, the slope of any metallicity dependence is, however. The latter is quoted as 0.19 and 0.21 mag dex^{-1} (in [Fe/H]) by Popowski (2000) and Cole (1998), respectively, while Udalski (1998a) advocates 0.09 mag dex^{-1}. Depending on a population's mean metallicity (and its uniformity), compared with that in the solar neighborhood where the *Hipparcos* calibration of the RC clump magnitude, $M_I^0 = -0.23 \pm 0.03$ mag (Stanek & Garnavich 1998), is usually taken as the baseline, this difference may lead to *systematic differences* in SMC RC magnitude of up to 0.1 mag for typical SMC star cluster metallicities ranging from [Fe/H] $= -0.7$ dex to [Fe/H] $= -1.5$ dex (Udalski 1998a).

Keeping this discussion in mind, we set off on a careful analysis of the RC-based distance measurements to the SMC contained in our database; see Table 4 for the RC data set considered in this paper. Early efforts were led by Udalski and his collaborators (Udalski 1998a, 1998b, 2000; Udalski et al. 1998) based on both SMC OGLE field regions (particularly scans of the low-density fields SC1, SC2, SC10, and SC11 in the outer galaxy) and the galaxy's star cluster population. At the time of these publications, the debate regarding a possible metallicity dependence of the RC's *I*-band magnitude was particularly heated, resulting in continuous updates of the SMC's distance modulus from a low value of $(m-M)_0 = 18.65 \pm 0.03$ (statistical) $\pm$ 0.06 (systematic) mag (Udalski 1998a) to a high value of $(m-M)_0 = 18.95 \pm 0.05$ mag (Udalski 2000). Intermediate and higher values, corresponding to a stronger metallicity dependence, were also favored by other contemporary authors (Cole 1998; Twarog et al. 1999; Popowski 2000), leading to a robust theoretical determination of $(m-M)_0 = 18.85 \pm 0.06$ mag by Girardi & Salaris (2001).

More recent determinations of RC-based distances have focused on distances to its star clusters. Although we will discuss the distance estimates resulting from star cluster analysis separately, here we specifically address relevant results based on their RC magnitudes. Crowl et al. (2001) explored the RC's use as a distance indicator to 12 SMC clusters, although only a subset (NGC 152, NGC 361, NGC

411, NGC 416, and Kron 28) are actually associated with the galaxy's main body (for a clear overview, see their Figure 1). The RC magnitudes of these five clusters combined, with their statistical uncertainties used as weights, lead to a weighted mean SMC distance modulus of $(m-M)_0 = 18.88 \pm 0.15$ (18.71 ± 0.11) mag, adopting Burstein & Heiles (1982) (Schlegel et al. 1998) foreground extinction estimates. We will return to the use of star cluster samples in Section 5.

Of the more recent determinations, Alcaino et al. (2003), Glatt et al. (2008b), and Cignoni et al. (2009) base their distance estimates on star clusters located well outside the SMC's main body, with the exception of NGC 416 studied by Glatt et al. (2008b), for which they determine $(m-M)_0 = 18.90 \pm 0.07$ mag. Pietrzyński et al. (2003) and Sabbi et al. (2009) focus on field regions and find, respectively, $(m-M)_0 = 18.93 \pm 0.03$ mag (which is affected by lingering systematic uncertainties in the K band) versus $(m-M)_0 = 18.89 \pm 0.45$ mag (field SFH1) and $(m-M)_0 = 18.97 \pm 0.27$ mag (field SFH4). The latter fits are calibrated using the Bertelli et al. (1994) isochrones. This is identical to the SMC distance estimate based on field RC stars of Udalski et al. (1999), $(m-M)_0 = 18.97 \pm 0.09$ mag, recalibrated for a LMC distance modulus of $(m-M)_0^{\rm LMC} = 18.50$ mag.

At the start of the period of interest considered here, the dependence of absolute RC magnitudes on ages and metallicities was not well understood and resulted in short distances to the Magellanic Clouds. Recently, Groenewegen (2008) provided updated I- and K-band calibrations in the 2MASS photometric system, $\langle M_I^{\rm RC} \rangle = -0.22 \pm 0.03$ mag and $\langle M_K^{\rm RC} \rangle = -1.54 \pm 0.04$ mag. The latter is somewhat fainter than Grocholski & Sarajedini (2002) calibration, $\langle M_K^{\rm RC} \rangle = -1.61 \pm 0.04$ mag, which Groenewegen (2008) attributed to the need to apply population corrections, caused by selection effects affecting the calibration reference stars. The weighted mean value resulting from combining all measurements pertaining to the SMC's main body (or objects associated with it) published since 1998, again adopting the individual uncertainties as weights, yields

$$(m-M)_0^{\rm RC} = 18.88 \pm 0.03 \text{ mag}, \tag{5}$$

with a standard deviation of 0.08 mag.

Figure 2(c) provides an overview of our final RC data set. We have indicated the distances resulting from analyses of the NGC 121 RC stars (Crowl et al. 2001; Glatt et al. 2008a) separately, using red data points. However, note that these measurements are surrounded by some controversy. Crowl et al. (2001) used the RC determination in this cluster from Mighell et al. (1998), based on these latter authors' assumption that NGC 121 is an intermediate-age cluster. If, on the other hand, NGC 121 is indeed much older (as we argue in Section 5.1, given that it hosts >10 Gyr-old RR Lyrae stars), the cluster's "RC" stars are more likely red horizontal-branch stars, which are not known to be good standard candles. Nevertheless, Glatt et al. (2008a) argue convincingly that NGC 121 is a few billion years younger than the canonical globular cluster age in the Milky Way, so that the object may indeed be a transition-type cluster.

4.2. Giant Stars

Among red-giants-based distance determinations, those based on the TRGB, the maximum absolute luminosity reached by first-ascent red giants with ages in excess of ~1–2 Gyr, are most commonly used. The TRGB marks the onset of helium fusion in their electron-degenerate helium cores. Its absolute bolometric magnitude varies by only 0.1 mag for a wide range of metallicities and ages (Iben & Renzini 1983; Da Costa & Armandroff 1990; Salaris & Cassisi 1997; Madore et al. 2009). Although the TRGB's I-band magnitude has become firmly established as a local distance indicator, there is a systematic offset of 0.1 mag between the TRGB and Cepheid distance scales (Tammann et al. 2008). At the same time, the metallicity dependence of the Cepheid PLR has been calibrated using the TRGB method (Rizzi et al. 2007; Sanna et al. 2008), which implies a worrying degree of circular reasoning.

Only few TRGB-based distance determinations have been published for the SMC's main body. Cioni et al. (2000) used a combination of near-IR $JHK_{\rm s}$ passbands and observations from the DENIS[13] database to derive $(m-M)_0 = 19.02 \pm 0.04$ mag. Udalski (2000) and Pietrzyński et al. (2003) used the I-band TRGB magnitude and OGLE observations to derive a very similar distance to the bulk of the SMC stars,

$$(m-M)_0^{\rm TRGB} = 19.00 \pm 0.04 \text{ mag}, \tag{6}$$

while these authors quote additional systematic uncertainties $\Delta(m-M)_0 = 0.07$ mag (Udalski 2000), resulting from reddening and calibration errors, to $\Delta(m-M)_0 \simeq 0.20$ mag (Pietrzyński et al. 2003), caused by calibration differences between the I and K bands. These TRGB-based distances are somewhat larger, at the 1–2σ level, than those resulting from other giant-star-based tracers, including Mira and semi-regular variable stars (Kiss & Bedding 2004), carbon stars (Soszyński et al. 2007), and RGB pulsators (Tabur et al. 2010).

5. STAR CLUSTERS

Many of the SMC's populous star clusters are located well away from the galaxy's main body. In Section 4.1 we specifically highlighted a small number of clusters that we consider firmly associated with the bulk of the SMC's stellar population. Nevertheless, by considering the galaxy's entire star cluster population, we may gain additional insights into the most appropriate distance to its center of mass. In addition, since star clusters often contain multiple distance tracers simultaneously, distances to individual star clusters can be used to cross-validate individual methods of distance determination and identify possible systematic offsets. This is our main aim in assessing the various distance determinations to NGC 121 available in the literature. Subsequently, we will combine the individual measurements available for a sample of SMC clusters to obtain a mean distance to the galaxy's gravitational center.

5.1. NGC 121

NGC 121 is the oldest populous star cluster in the SMC; its metallicity is the lowest among the SMC's cluster population, [Fe/H] = -1.71 ± 0.10 dex (e.g., Udalski 1998b; Crowl et al. 2001). It has been studied extensively and is host to a number of different distance tracers. This makes the cluster a suitable testbed for our assessment of the importance of any systematic effects among the latter. Table 5 includes the "best"

[13] Deep Near Infrared Survey of the Southern Sky; http://cds.u-strasbg.fr/denis.html.

Table 5
"Best" Distance Measures to the Old SMC Cluster NGC 121

$(m-M)_0$ (mag)	Tracer	Reference
18.98 ± 0.07	RR Lyrae	Reid (1999)
18.88 ± 0.06	RC[a]	Crowl et al. (2001)
18.91 ± 0.06	RC[b]	Crowl et al. (2001)
19.0 ± 0.4	TRGB	Dolphin et al. (2001)
18.98 ± 0.10	HB level	Dolphin et al. (2001)
18.96 ± 0.04	CMD fit	Dolphin et al. (2001)
18.96 ± 0.02	CMD fit	Glatt et al. (2008a)
19.06 ± 0.03	RC	Glatt et al. (2008a)

Notes.
[a] Burstein & Heiles (1982) extinction adopted.
[b] Schlegel et al. (1998) extinction adopted.

distance moduli to NGC 121, based on our perusal of the relevant literature.

Most tracers tend toward a larger distance modulus of around $(m-M)_0 \sim 19.0$ mag, although a spread of order 0.1 mag is clearly implied. We only have access to multiple measurements for distance determinations to the cluster based on the use of RR Lyrae stars and fits to its CMD. The difference between the RR Lyrae-based distances suggested by Nemec et al. (1994) and that of Reid (1999) is sufficiently large so as to warrant a detailed examination. Nemec et al. (1994) included two such distance estimates, based on two different sets of photometric measurements. They point out, following Walker & Mack (1988), that the earlier photographic-plate measurements of four RR Lyrae stars by Graham (1975) are systematically fainter by ~0.2 mag in both the B and V bands than the CCD-based observations of Walker & Mack (1988). For the SMC field, Nemec et al. (1994) could only compare their estimate with that of Graham (1975). The distance modulus to NGC 121 based on B-band photometry reported by Walker & Mack (1988) is, to within their mutual 1σ photometric uncertainties of 0.03 mag, fully consistent with the SMC field distance of Graham (1975). Udalski (1998b) also concluded from a comparison with newly obtained CCD data that the Graham (1975) SMC field photometry is in excellent agreement with their new measurements. In view of these considerations, and given the difficulty of deriving accurate photographic photometry in crowded fields which most likely affected Graham (1975) cluster photometry, Reid (1999) used the Walker & Mack (1988) cluster photometry to base his distance determination on.

The main physical difference between the Nemec et al. (1994) and Reid (1999) distance estimates to NGC 121 is found in their use of calibration object. Nemec et al. (1994) base their distance calibration on the distance to the Galactic globular cluster M15, while Reid (1999) reports a differential distance modulus with respect to the LMC. Reid (1999) quotes a mean V-band magnitude of LMC cluster RR Lyrae of $\langle V_0 \rangle = 18.98$ mag (Walker 1994), which he compared with the equivalent value for NGC 121 RR Lyrae in the SMC, $\langle V_0 \rangle = 19.46 \pm 0.07$ mag (Walker & Mack 1988), to derive $\Delta\mu_0 = 0.48 \pm 0.07$ mag (irrespective of any calibration relations adopted), and hence $(m-M)_0^{\rm SMC} = 18.98 \pm 0.07$ mag. A careful assessment of the choices made by Nemec et al. (1994) implies that their distance calibration corresponds to an LMC distance modulus of $(m-M)_0^{\rm LMC} = 18.35$ mag. Correcting the resulting distance modulus to the canonical LMC distance modulus results in an updated distance to NGC 121 of $(m-M)_0^{\rm NGC\ 121} = 18.78$ mag (no individual uncertainties quoted, although the authors provide an upper limit of 0.2 mag). For consistency with Papers I and II, as well as with the choices made in this paper, we adopt Reid (1999) estimate.

The differences in NGC 121 distance moduli based on stellar population tracers are generally less than 0.10 mag, with the exception of the distance estimates based on measurements of the RC magnitude (Crowl et al. 2001; Glatt et al. 2008a, but see the caveat mentioned in Section 4.1). Crowl et al. (2001) applied a correction of +0.093 mag to the theoretical M_V(RC) values of Girardi et al. 2000, see also Girardi & Salaris 2001). This explains the systematic difference between the Crowl et al. (2001) and Glatt et al. (2008a) NGC 121 distance moduli. Since we adopted the Girardi et al. RC calibration in Section 4.1, for reasons of internal consistency we will adopt the Glatt et al. (2008a) RC-based distance.

Based on these considerations, the resulting weighted mean distance modulus to NGC 121 is $(m-M)_0 = 18.98 \pm 0.02$ mag. In terms of differential distance moduli, Udalski (1998b) suggests that NGC 121 is located 0.08 ± 0.04 mag behind the SMC's center, thus leading to

$$(m-M)_0^{\rm NGC\ 121 \rightarrow SMC} = 18.90 \pm 0.04 \text{ mag}. \quad (7)$$

5.2. The SMC Cluster Population

Finally, it is instructive to determine the mean distance to the SMC's cluster population. Although most of the galaxy's star clusters are located well outside its main body, their mean distance gives us additional insights into the relevant distance scale. Among our database of SMC distance determinations, three groups of studies provide homogeneous sets of cluster distances (Crowl et al. 2001; Glatt et al. 2008a; Dias et al. 2014). We strongly prefer to use a homogeneous baseline for our analysis of the ensemble of SMC clusters.

Table 6 includes the full set of 25 SMC clusters for which individual distance determinations are available in the literature, based on a variety of tracers. We first checked for duplicates in distance estimates to these sample objects. (Note that we did not include NGC 121 in this analysis, give that we addressed the distance to this cluster in the previous section.) Most importantly, Crowl et al. (2001) and Glatt et al. (2008b) have five clusters in common, i.e., NGC 339, NGC 416, Lindsay 1, Lindsay 38, and Kron 3. From the Crowl et al. (2001) results, we considered their distance estimates using both the Burstein & Heiles (1982) and the Schlegel et al. (1998) estimates of the foreground extinction. These authors offer the choice of adopting either a constant absolute RC magnitude, independent of age or metallicity, or adoption of the assumption that the absolute RC magitude is a function of both age and metallicity. We adopted the latter assumption and used the individual cluster distance moduli as tabulated by Crowl et al. (2001). As pointed out by these authors, the distances based on the Schlegel et al. (1998) extinction estimates are systematically shorter; a comparison between the Glatt et al. (2008b) distances and the Crowl et al. (2001) values using Burstein & Heiles (1982) extinction estimates shows that the Crowl et al. (2001) distances tend to be somewhat shorter than those of Glatt et al. (2008b), which is owing to the different RC-magnitude calibrations adopted by the two

Table 6
SMC Clusters With Published Distance Estimates

Cluster	$(m-M)_0$ (mag)	Tracer	Reference[a]
47 Tuc field	18.93 ± 0.24	RR Lyrae	Weldrake et al. (2004)
AM 3	18.99 ± 0.16	CMD fits	Dias et al. (2014)
BS 90	18.85 ± 0.1	CMD fits	Rochau et al. (2007)
BS 196	18.95 ± 0.05	CMD fits	Bica et al. (2008)
HW 1	18.84 ± 0.16	CMD fits	Dias et al. (2014)
HW 40	19.08 ± 0.14	CMD fits	Dias et al. (2014)
ICA 16	19.05 ± 0.05	CMD fits	Demers & Battinelli (1998)
Kron 3	18.80 ± 0.05	RC	Weighted average (C01, G08)
Kron 28	18.78 ± 0.09	RC	Weighted average (C01)
Kron 44	18.92 ± 0.04	RC	Weighted average (C01)
Lindsay 1	18.67 ± 0.06	RC	Weighted average (C01, G08)
Lindsay 2	18.68 ± 0.14	CMD fits	Dias et al. (2014)
Lindsay 3	18.64 ± 0.14	CMD fits	Dias et al. (2014)
Lindsay 38	19.03 ± 0.04	RC	Weighted average (C01, G08)
Lindsay 113	18.47 ± 0.07	RC	Weighted average (C01)
NGC 121	18.98 ± 0.02	Multiple	This paper
NGC 152	18.96 ± 0.19	RC	Weighted average (C01)
NGC 330	18.82 ± 0.03	Cepheids	Weighted average[b]
NGC 339	18.78 ± 0.02	RC	Weighted average (C01, G08)
NGC 361	18.61 ± 0.12	RC	Weighted average (C01)
NGC 411	18.57 ± 0.14	RC	Weighted average (C01)
NGC 416	18.89 ± 0.07	RC	Weighted average (C01, G08)
NGC 419	18.50 ± 0.12	RC	Glatt et al. (2008b)
NGC 602 A	18.7	RC	Cignoni et al. (2009)
Unnamed cluster	18.8	CMD fits	McCumber et al. (2005)

Notes.
[a] C01: Crowl et al. (2001), G08: Glatt et al. (2008b).
[b] Weighted average of two distance estimates based on different stellar models, one without and one with moderate overshooting (Sebo & Wood 1994).

different teams. In other words, this is a systematic effect. Since one of our aims is to understand the systematic uncertainties involved in Local Group distance determinations, we decided to calculate weighted average values for those clusters with both Crowl et al. (2001) and Glatt et al. (2008b) distances, without any pre-selection.

Three additional clusters were found to have duplicate distance determinations. The distance to AM 3 was determined by both Da Costa (1999) and also recently by Dias et al. (2014). We chose to retain the latter value because of its inclusion in the homogeneous set of distance determinations of Dias et al. (2014), although the more recent estimate is essentially identical to the earlier determination. Second, Dias et al. (2014) published an updated distance estimate for Lindsay 2, which supersedes their earlier, significantly larger value from Dias et al. (2008). We selected the more recent determination for further analysis. (In addition, their earlier value originated from a conference contribution while the more recent distance was published in a peer-reviewed article.) Finally, NGC 361 was analyzed by both Smith et al. (1992) and Crowl et al. (2001). For reasons of homegeneity, we opted to use the Crowl et al. (2001) values, while we also noted that the Smith et al. (1992) distance related to a field near the cluster rather than to NGC 361 itself.

The projected geometric mean center position of the entire star cluster system thus selected is found at R.A. (J2000) $= 00^{\rm h}$ $52^{\rm m}\ 41^{\rm s}$, decl. (J2000) $= -72°40'28''$, which coincides with a location in the densest stellar region of the SMC's main body. Note that we did not set out to select an unbiased cluster sample, although we also point out that our final sample of 25 clusters is not necessarily biased in any way in relation to the resulting set of distances. The weighted mean distance to this arbitrary set of 25 SMC clusters is

$$(m-M)_0^{\rm clusters} = 18.81 \pm 0.03 \text{ mag}, \tag{8}$$

with a standard deviation of 0.17 mag. The latter value includes both depth effects and systematic uncertainties.

This mean distance compares well with previous determinations of the star cluster centroid distance, although based on smaller numbers of clusters. Crowl et al. (2001) RC-based distance determinations to their small sample of 12 clusters led to a mean distance of $(m-M)_0 = 18.82 \pm 0.05$ mag (18.71 ± 0.05 mag) assuming Burstein & Heiles (1982) (Schlegel et al. 1998) foreground extinction, while the average RC-based distance to the six clusters studied by Glatt et al. (2008b) was found at $(m-M)_0 = 18.87 \pm 0.03$ mag.

Table 7
Mean Distances to the SMC Based on a Range of Distance Indicators

$(m-M)_0$ (mag)	σ (mag)	Tracer
18.93 ± 0.03	0.26	Early-type EBs
18.965 ± 0.025	0.048[a]	Late-type EBs
19.00 ± 0.02	0.08	FU Cepheids
19.01 ± 0.02	0.06	FO Cepheids
18.96 ± 0.02	0.06	RR Lyrae
18.88 ± 0.03	0.08	RC stars
19.00 ± 0.04	…	TRGB
(18.90 ± 0.04	…	NGC 121)
(18.81 ± 0.03	0.17	Star clusters)

Note.
[a] The standard deviation given for the late-type EBs is the systematic uncertainty reported by Graczyk et al. (2014).

6. FINAL RECOMMENDATION

In an effort to provide a firm mean distance estimate to the SMC, and thus place it within the internally consistent Local Group distance framework we established recently, we performed extensive analysis of the published literature to compile the largest database available to date containing SMC distance estimates.

We highlight the need for such an effort by pointing out that almost all authors who derive either "short" or "long" distances[14] to the SMC based on their chosen distance indicator and tracer sample selectively refer to a subset of recent (and not-so-recent) distance estimates that support their result. The danger of this habit persisting in the literature is that one loses sight of the global picture. We aim at remedying this situation by providing estimates of the mean SMC distance based on a large number of distance tracers. Table 7 offers a summary of the mean distances determined in this paper.

[14] Note that the terms "short" and "long" used in this context simply refer to the extremes of the published SMC distance range, and not to the "short" and "long" distance scales used to refer to LMC distances in previous decades (cf. Paper I).

Throughout the paper, we have emphasized the important role attributed to systematic uncertainties. In addition to the corrections for geometric and depth effects required because of the galaxy's complex nature, we also pointed out lingering systematic uncertainties in the absolute distance calibrations using a variety of stellar tracers, as well as those owing to uncertain extinction corrections. Nevertheless, if we take the simple weighted mean of the distances given in Table 7, except for the bracketed values pertaining to the SMC's star clusters, we obtain our final recommendation for the "mean" SMC distance,

$$(m - M)_0^{\rm SMC} = 18.96 \pm 0.02 \text{ mag}. \tag{9}$$

This value is fully consistent with the recommendation by Graczyk et al. (2014) based on their analysis of both etEBs and ltEBs, the distance indicator thought to be least affected by systematic uncertainties owing to poorly understood physics. It is indeed encouraging to note that the most recent SMC distance determination, which is based on mid-IR PLR analysis of FU Cepheids, also yields $(m - M)_0^{\rm mid-IR} = 18.96 \pm 0.01$ (statistical) $\pm$ 0.03 (systematic) mag (Scowcroft et al. 2015).

Although this is our final, recommended value based on the full body of SMC distance estimates published during the past 2–3 decades, we caution that an acute awareness of systematic effects possibly exceeding 0.15–0.20 mag is of the utmost importance when using such a generic mean value for practical purposes. Indeed, despite decades of progress, we are still dealing with distance diagnostics that show standard deviations of order 0.10 mag or more in the resulting distance moduli. This means that more detailed analyses of both the SMC's geometry and possible sources of systematic errors are still urgently required (cf. Rubele et al. 2015; V. Ripepi et al. 2015, in preparation).

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