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Clustering of Local Group Distances: Publication Bias or Correlated Measurements? VI. Extending to Virgo Cluster Distances

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Abstract

We have established an internally consistent Local Group distance framework, using the Galactic Center, the Large Magellanic Cloud, and Messier 31 (M31) as important stepping stones. At greater distances, few distance benchmarks are available. As a consequence, M87 and/or Virgo cluster distances are often invoked as the next rung on the ladder to more distant objects such as the Fornax and Coma clusters. Therefore, we extensively mined the published literature for independently derived distance estimates to either M87 or the center of the Virgo cluster. Based on our newly compiled, comprehensive database of 213 such distances, published between 1929 and 2017 July, we recommend an outward extension to our distance framework, $(m - M)_0^{\rm M87} = 31.03 \pm 0.14$ mag ($D = 16.07 \pm 1.03$ Mpc; where the uncertainty represents the Gaussian σ of the distribution), based on a subset of recent (post-1990) M87/Virgo cluster distance measurements. The most stable distance tracers employed here were derived from analysis of both primary and secondary distance indicators. Among the former, we preferentially rely on Cepheid period–luminosity relations and red-giant-branch terminal magnitudes; our preferred secondary distance tracers are surface brightness fluctuations. Our updated distance modulus to M87 implies a slightly reduced black hole mass of $(5.9 \pm 0.6) \times 10^9\,M_\odot$ with respect to that determined by the Event Horizon Telescope collaboration.

Unified Astronomy Thesaurus concepts: Astronomical reference materials (90); Astronomy databases (83); Distance measure (395); Galaxy distances (590); Virgo Cluster (1772)

1. Beyond the Local Group: Messier 87 and the Center of the Virgo Cluster

Triggered by the suggestion that published distance measurements to the Large Magellanic Cloud (LMC) may have been subject to confirmation or publication bias (Schaefer 2008), earlier this decade we set out to explore that concern in great depth. Although we were unable to confirm Schaefer's (2008) suggestion on the basis of the most comprehensive database of LMC distance moduli collected at the time (de Grijs et al. 2014, henceforth Paper I), we managed to put Freedman et al.'s (2001) canonical LMC distance modulus of $(m - M)_0^{\rm LMC} = 18.50 \pm 0.10$ mag on a much more robust statistical footing, i.e., yielding $(m - M)_0^{\rm LMC} = 18.49 \pm 0.09$ mag (independently confirmed by Crandall & Ratra 2015, using the same data set).

Next, we decided to take our analysis of possible publication bias in distance estimates to Local Group galaxies to the next level. We expanded our scope to include Messier 31 (M31) and a number of its larger and better-studied companion galaxies, i.e., M32, M33, NGC 147, NGC 185, NGC 205, IC 10, and IC 1613 (de Grijs & Bono 2014: Paper II), and the Small Magellanic Cloud (SMC; de Grijs & Bono 2015: Paper III; see for independent confirmation based on the same data set, Crandall & Ratra 2015). The latter revealed significant difficulties related to the definition of "the" SMC center, given the galaxy's irregular morphology, as well as important depth effects reflected differently by different distance tracers.

We proceeded to tie this updated Local Group distance scale to one of the most important and nearest galactic-scale distances, the distance to the Galactic Center (de Grijs & Bono 2016: Paper IV), for which we recommended $R_0 = 8.3 \pm 0.2$ (statistical) $\pm$ 0.4 (systematic) kpc (equivalent to $(m - M)_0^{\rm Gal.C.} = 14.60 \pm 0.05$ mag, where the uncertainties reflect the statistical uncertainties only), with an associated Galactic rotation constant at the solar Galactocentric radius, $\Theta_0 = 225 \pm 3$ (statistical) $\pm$ 10 (systematic) km s^{-1} (de Grijs & Bono 2017: Paper V). In very recent developments, the Gravity Collaboration et al. (2019) published an updated geometric distance determination to the Galactic Center based on 27 yr of orbital measurements for the star S2, yielding $R_0 = 8178 \pm 13$ (statistical) $\pm$ 22 (systematic) pc. Our multiple-tracer statistical determination from 2016 remains fully commensurate with this latest geometric distance determination.

Thus, through careful meta-analysis of published distance measures, we established an internally consistent and statistically supported Local Group distance framework, using the Galactic Center, the LMC, and M31—$(m - M)_0^{\rm M31} = 24.46 \pm 0.10$ mag (Paper II)—as important stepping stones. In addition, we advocated the use of NGC 4258 as the next step in the distance hierarchy on account of its water-maser-based geometric distance determination (see the discussion in Paper II).

Not surprisingly, published distance measurements to galaxies beyond the Local Group become sparser with increasing distance. A notable exception in this context are distances to the Virgo cluster and its dominant giant elliptical galaxy, Messier 87 (M87). At this distance, we have access to few (if any) alternative distance benchmarks, and as a consequence M87/Virgo cluster distances are often invoked as stepping stone to more distant objects such as the Fornax and Coma clusters. (We will return to this latter aspect in Section 4.) Therefore, in this paper we set out to obtain a firm distance estimate to M87 or, alternatively, to the center of the Virgo cluster, based on a similar meta-analysis of published distance measures (and Galactic rotation constants) as we undertook for Papers I through V.

Before we set out to mine the literature, however, we needed to consider the three-dimensional (3D) spatial distribution of the galaxies in the Virgo cluster. It is well established that the cluster's mass distribution is not smooth but distributed across a number of subclumps. Most notably, NGC 4697 is the central elliptical galaxy in the foreground "NGC 4697 group," which also includes NGC 4731 and a number of smaller galaxies in the Virgo Southern Extension. On the other hand, the W′ group is located behind the main body of the Virgo cluster (e.g., Cantiello et al. 2018; their Table 2). The majority of Virgo cluster member galaxies are distributed in the so-called A, B, and E subclusters, where subclump B is thought to be located 0.4–0.5 mag (in distance modulus) behind subclumps A (e.g., Yasuda et al. 1997; Federspiel et al. 1998; Feldmeier et al. 1998)—which is associated with M87 (e.g., Gavazzi et al. 1999)—and E (Gavazzi et al. 1999; Neilsen & Tsvetanov 2000).

Current consensus suggests that M87 is located near the physical center of the Virgo cluster (e.g., Ciardullo et al. 1998; Mei et al. 2007; Blakeslee et al. 2009; Bird et al. 2010), despite the well-known radial velocity discrepancy of $\sim$200 km s^{-1} between M87 and the Virgo cluster mean (Binggeli et al. 1987), with M87 exhibiting the higher velocity, and its projected $\sim 1°$ distance from the center of the Virgo cluster's isopleths. Ciardullo et al. (1998), following Bird (1994), argued that such velocity and positional offsets are common in central elliptical galaxies in dynamically young galaxy clusters—including the Virgo cluster.

Nevertheless, it is not straightforward to define the Virgo cluster's center even when using only galaxies associated with the main subclusters tracing the Virgo cluster's potential well. Elliptical and early-type galaxies are more spherically distributed than the cluster's complement of spiral galaxies. The latter are distributed in an elongated structure extending from 13 to 30 Mpc (Planck Collaboration et al. 2016) along the line of sight. This affects the determination of average cluster distance moduli based on diagnostics typical of either late- (Tully–Fisher relation) or early-type (Faber–Jackson/$D_n - \sigma$ analysis) differently (e.g., Fukugita et al. 1993).

In Section 2, we outline our approach to obtaining our data set of published distance moduli to our target region. Then, in Section 3 we consider the statistics of the resulting distance measurements for individual tracer populations, which we discuss in Section 4. We also summarize and conclude the paper in Section 4.

2. Data Mining

To compile a comprehensive database of distances to either M87 or the center of the Virgo cluster, we extensively perused the NASA/Astrophysics Data System (ADS). As of 2019 September 3, a search for "M87" returned 7922 hits. Our manual perusal resulted in an overall tally of 213 independently derived distance values, spanning the period from Hubble's (1929) determination based on a comparison of galaxy luminosities to Hartke et al.'s (2017) reanalysis of the planetary nebulae population associated with Messier 49, published in 2017 July.

The NASA/ADS database contains all articles published in the main astrophysics journals since 1975. Its coverage of historical records is continuously increasing. In this paper, we will focus predominantly on the most modern M87/Virgo cluster distance determinations. In practice, this means that our analysis will be based on post-1985 measurements. We are confident that we have tracked down the vast majority of such measurements published in the literature.

We have kept careful track of the provenance of our distance estimates, whether based on M87 measurements or pertaining to the Virgo cluster more broadly. Where possible, we have only retained Virgo cluster measures that relate to the M87 subcluster, or which were centered on M87, for further analysis. Our final database, sorted by year and by tracer, is available online through http://astro-expat.info/Data/pubbias.html,[6] Figure 1(a) shows the overall data set in black; published weighted average values are overplotted in red. Panels (b) through (g) show our sample of distance measurements split by tracer. Where available, we have included the published 1σ error bars (random errors only in case systematic errors were also published) as well as horizontal dotted lines to guide the eye, located at $(m - M)_0 = 31.0$ mag. At first glance, none of the tracers, nor the data set as a whole, exhibit any systematic trends. However, it is clear that some tracers are subject to significantly greater scatter than others, and systematic differences in mean levels are seen when comparing different tracers. We will discuss these issues in the next section.

3. Differences among Tracers

Figure 1 shows that for a number of tracers we only have access to rather old (pre-1990) data. Tracers in this category include distance determinations based on group membership, Hubble's velocity–distance law, color–magnitude analysis and related methods, H II region sizes, and also supernova (SN)-based distances. Others show spreads that significantly exceed the published statistical error bars (thus suggesting the presence of unaccounted-for systematics), including distance determinations based on the globular cluster luminosity function (GCLF) and dynamical distance estimates (e.g., those based on the Tully–Fisher or Faber–Jackson relations and the $D_n - \sigma$ projection of the Fundamental Plane of elliptical galaxies). Only five data sets appear internally consistent, leading to fairly tight averages: those based on Cepheids, the planetary nebulae luminosity function (PNLF), surface brightness variations (SBF), the tip of the red giant branch (TRGB) magnitude, and novae (although the error bars associated with the latter are large).

We carefully examined the procedures followed by the original authors to arrive at each individual distance estimate for these latter tracers. In addition, we adjusted the published distances to conform with the distance framework established in the previous papers in this series, in essence tied to $(m - M)_0^{\rm LMC} = 18.49$ mag. In practice, these adjustments were primary calibration offsets of order a few hundredths of a magnitude only, in most cases; see Table 1 for the full adjusted data set. The resulting homogenized distance measurements are shown in Figure 2 as a function of distance indicator, where we have added a constant $C \in [0, 4]$ mag to offset the individual tracers from one another for reasons of clarity. Note that the distance moduli for M87 and the

[6] A permanent link to this page can be found at http://web.archive.org/web/20160610121625/ http://astro-expat.info/Data/pubbias.html; members of the community are encouraged to send us updates or missing information.

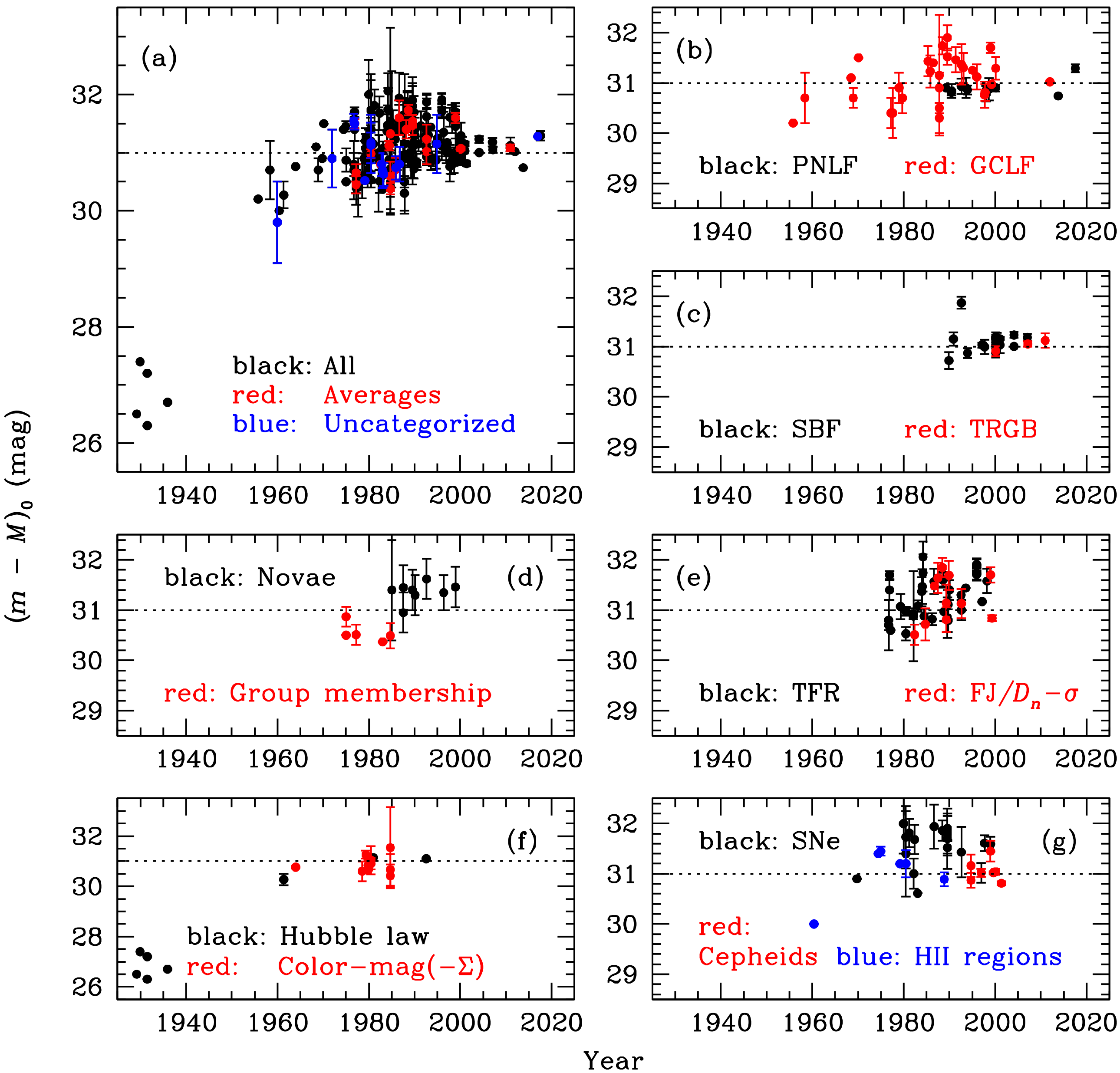

Figure 1. Published distances to either M87 or the center of the Virgo cluster as a function of publication date (original values with their original error bars, where available). The horizontal dotted lines are drawn at $(m - M)_0 = 31.0$ mag and are meant to guide the eye. $D_n - \sigma$: Edge-on projection of the Fundamental Plane of elliptical galaxies, where D_n is the diameter within which the effective surface brightness is 20.75 μ_B (B-band surface brightness) and σ is the mean velocity dispersion within the galaxy's effective radius; FJ: Faber–Jackson relation; GCLF: Globular cluster luminosity function; PNLF: Planetary nebula luminosity function; SBF: Surface brightness fluctuations; SNe: Supernovae; TFR: Tully–Fisher relation; TRGB: Tip of the red giant branch. "Averages" in panel (a) include weighted and unweighted means of different methods of distance determination to M87, as well as mean values of the distance moduli to samples of central Virgo Cluster galaxies, as published by the original authors (see Section 9 in our externally linked data table); "Uncategorized" distance moduli include any measurements that are not already included in the other panels, mostly because of the scarcity of data points for a particular measurement approach.

Virgo Cluster (see Table 1, third column, for this distinction) are statistically indistinguishable, so that henceforth we will base our analysis on the combined data set.

By comparison with the canonical $(m - M)_0 = 31.0(+C)$ mag lines included to guide the eye, it appears that our sample of novae imply systematically larger distances, while the PNLF distances are systematically shorter. However, since the latter are based on the extremely sharp bright cut in the PNLF, planetary nebulae detections are biased toward foreground objects, so that the resulting distance estimates are, in essence, lower limits.

The left-hand panel of Figure 2 shows the mean values and their 1σ uncertainties (assuming Gaussian distributions, for simplicity) of the individual tracers; see Table 2 for the numerical values. Note that the error bar associated with the mean Cepheid distance is artificially enhanced by the inclusion of an apparently outlying data point published in 1998 December. This latter value, obtained from Tammann et al. (2000),[7] is part of a data set of galaxy distances that are commonly referred to as the "long distance scale."

A "long" versus "short" distance scale debate raged in the second half of the 20th century, associated with, respectively,

[7] Note that this value was initially published in 1998 December; although the volume of conference proceedings was eventually published in 2000, we assigned this data point to its initial publication date since we are interested in tracing the evolution of Virgo Cluster/M87 distance moduli with time.

Table 1
Adopted "Adjusted" Distance Moduli Used in This Paper

Publ. date (mm/yyyy)	$(m-M)_0$ (mag)	M87 ("M") or Virgo ("V")	Reference	Notes
		1. Cepheids		
12/1996	31.01 ± 0.08	V	van den Bergh (1996)	
12/1998	31.44 ± 0.21	V	Tammann et al. (2000)	
08/1999	31.01 ± 0.03	V	Macri et al. (1999)	
02/2000	31.03 ± 0.06	M	Ferrarese et al. (2000)	
05/2001	30.80 ± 0.04	V	Freedman et al. (2001)	Recalibration
		2. PNLF		
03/1989	30.87 ± 0.	V	Jacoby et al. (1989)	
06/1990	30.81 ± 0.14	V	Jacoby et al. (1990)	
06/1990	30.78 ± 0.06	M	Jacoby et al. (1990)	
08/1992	30.90 ± 0.15	V	Jacoby et al. (1992)	
08/1993	30.93 ± 0.2	V	Méndez et al. (1993)	
12/1993	30.89 ± 0.09	V	Ciardullo et al. (1993)	
01/1998	30.82 ± 0.16	M	Ciardullo et al. (1998)	
01/1998	30.88 ± 0.09	M	Ciardullo et al. (1998)	Rescaled Jacoby et al. (1990) value
08/1998	30.94 ± 0.22	M	Feldmeier et al. (1998)	
02/2000	30.89 ± 0.07	M	Ferrarese et al. (2000)	
01/2013	30.80 ± 0.	M	Longobardi et al. (2013)	
		3. SBF		
11/1989	30.86 ± 0.17	V	Tonry et al. (1989)	
11/1990	31.35 ± 0.13	V	Tonry et al. (1990)	I
08/1992	30.90 ± 0.12	V	Jacoby et al. (1992)	
12/1993	30.87 ± 0.10	V	Ciardullo et al. (1993)	
02/1997	31.06 ± 0.05	M	Tonry et al. (1997)	
09/1997	31.06 ± 0.14	M	Neilsen et al. (1999)	
02/2000	31.18 ± 0.04	M	Ferrarese et al. (2000)	I
02/2000	31.08 ± 0.06	M	Ferrarese et al. (2000)	F814W
02/2000	30.86 ± 0.09	M	Ferrarese et al. (2000)	K_s
02/2000	31.17 ± 0.10	M	Ferrarese et al. (2000)	K'
02/2000	31.14 ± 0.03	V	Tonry et al. (2000)	
02/2000	31.02 ± 0.16	M	Tonry et al. (2000)	
06/2000	31.18 ± 0.12	V	Neilsen & Tsvetanov (2000)	
01/2001	31.14 ± 0.03	V	Tonry et al. (2001)	
01/2001	31.02 ± 0.16	M	Tonry et al. (2001)	
02/2004	31.19 ± 0.06	V	Jerjen et al. (2004)	
02/2004	30.96 ± 0.	M	Jerjen et al. (2004)	
		4. TRGB		
02/2000	30.89 ± 0.10	M	Ferrarese et al. (2000)	
02/2007	30.89 ± 0.05	V	Williams et al. (2007)	
12/2010	31.09 ± 0.14	M	Bird et al. (2010)	
		5. Novae		
01/1985	31.26 ± 1.0	M	Pritchet & van den Bergh (1985)	$30.4 < (m-M)_B < 32.4$ mag
07/1987	31.31 ± 0.44	V	Pritchet & van den Bergh (1987)	
07/1987	30.81 ± 0.4	V	Pritchet & van den Bergh (1987)	Using the Cohen (1985) Galactic calibration
07/1989	31.12 ± 0.4	V	van den Bergh (1989)	
02/1990	31.30 ± 0.40	V	Capaccioli et al. (1990)	
08/1992	31.62 ± 0.40	V	Jacoby et al. (1992)	
05/1996	31.35 ± 0.35	V	Livio (1997)	
12/1998	31.34 ± 0.40	V	Tammann et al. (2000)	

low and high values of the Hubble constant (for a review, see, e.g., de Grijs 2011). However, since the publication of Freedman et al.'s (2001) seminal study on the extragalactic distance scale, consensus has been reached that the short distance scale is closer to reality. If we were to remove the Tammann et al. (2000) data point, the Cepheid average value for M87 would be reduced to $(m-M)_0 = 30.96$ $(\sigma = 0.11)$ mag.

By combining the 28 data points for the Cepheids, TRGB, and SBF measurements, which are all well-calibrated and independently determined, the resulting true distance modulus

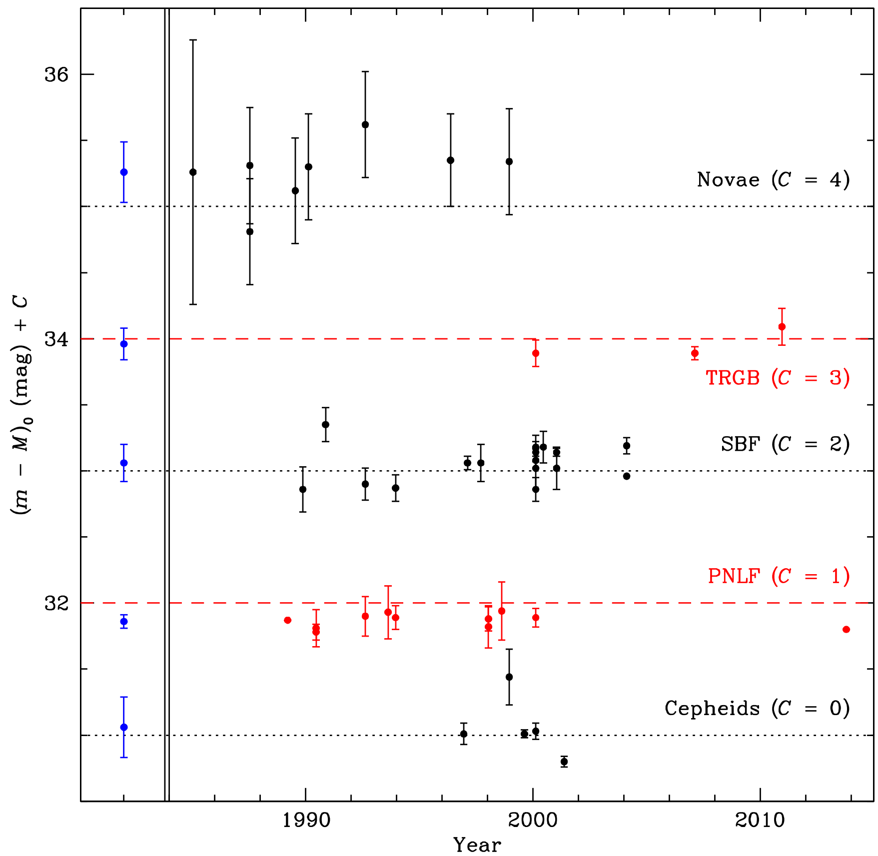

Figure 2. "Cleaned" M87/Virgo cluster distances and their published 1σ error bars for five data sets that include the most recent determinations available, offset by constants steps C for clarity. Individual distances have been corrected, where necessary, to a common distance scale, i.e., tied to $(m-M)_0^{\rm LMC} = 18.49$ mag. The blue data points in the left-hand panel represent the mean values and their 1σ uncertainties (assuming Gaussian distributions, for simplicity) of the individual tracers. The horizontal dotted and dashed lines are drawn at $(m-M)_0 = 31.0 + C$ mag, and are meant to guide the eye.

Table 2
Mean, Post-1985 Published Distance Measures to M87 and the Center of the Virgo Cluster as a Function of Tracer Population

Tracer	N	Mean (mag)	σ (mag)
Cepheids[a]	5	31.06	0.23
PNLF	11	30.86	0.05
SBF	17	31.06	0.14
TRGB	3	30.96	0.12
Novae	8	31.26	0.23

Note.
[a] If we were to ignore the Tammann et al. (2000) data point, published in 1998 December, the mean Cepheid distance modulus reduces to $(m-M)_0 = 30.96$, $\sigma = 0.11$ mag.

for the Virgo cluster center is $(m-M)_0 = 31.05$ mag, with a Gaussian spread of $\sigma = 0.16$ mag ($D = 16.2 \pm 1.2$ Mpc). The equivalent values for the data set without the Tammann et al. (2000) measurement are $(m-M)_0 = 31.03$ mag and $\sigma = 0.14$ mag. None of these tracers suggest any trend as a function of publication date, and hence taking a straight average seems justified, also in view of the relatively small number of data points available.

Our recommended final value is, in fact, fully consistent with almost all of the weighted average distance moduli to either M87 or the center of the Virgo cluster published since 1990, with the notable exception of the Tammann et al. (2000) value, $(m-M)_0 = 31.60 \pm 0.09$ mag. Jacoby et al. (1992) considered seven of the most reliable extragalactic distance tracers—the GCLF, novae, SNe Type Ia, the TFR, the PNLF, SBF, and the $D_n - \sigma$ relation—to derive a weighted average of $(m-M)_0 = 31.02 \pm 0.22$ mag for the Virgo cluster.

The correspondence between our final distance modulus and that advocated by Jacoby et al. (1992) is perhaps somewhat surprising, given that the calibrations used for the tracers in common are somewhat divergent; in practice, however, this divergence results in canceling out most of the differences. For instance, Jacoby et al. (1992) based their Cepheid distance calibration on an adopted LMC distance modulus of $(m-M)_0 = 18.57$ mag, 0.08 mag larger than our preferred value; on the other hand, their SBF calibration assumes a distance to M31 of 770 kpc, some 10 kpc closer (corresponding to a difference of 0.03 mag in distance modulus) than the distance of 780 kpc we recommend to render the Local Group distances internally consistent.

Ferrarese et al. (2000) found $(m-M)_0 = 31.07 \pm 0.03$ mag using a wide variety of distance indicators, including Cepheids, the PNLF, the GCLF, SBF, and the TRGB. Finally, Bird et al. (2010) published a mean value of the distance modulus to M87 based on the TRGB, the PNLF, globular cluster sizes and SBF/Cepheid distances, of $(m-M)_0 = 31.06 \pm 0.06$ mag. These latter authors adopted calibration conventions for the tracers in common with our study that are indeed very close (within 0.01–0.02 mag in terms of the resulting distance moduli) to our adopted values.

Considering the overall distribution of distance measures (Figure 1(a)), at first glance it appears that the intrinsic spread has narrowed considerably since the turn of the millennium. This is indeed reflected in the small $\sigma = 0.14$ mag obtained for our combined sample, which is dominated by more recent measurements. However, this apparent tightening of the overall distribution is not a manifestation of publication bias, nor even of any sustained trends. It is caused by a shift in focus of the community from one subset of distance indicators to another. As discussed above, the post-2000 measurements we have considered to reach our final recommendation included distance estimates based on Cepheid period–luminosity relations, SBF, and the TRGB magnitude. Where such measures were available prior to 2000, none of the tracers suggest a significant broadening of their distribution toward earlier times.

Before 2000, important subsets of our data points included measurements that exhibited significant scatter, e.g., GCLF-, novae-, and SNe-based distance measurements, and distances based on galaxy dynamics (the Tully–Fisher and $D_n - \sigma$ relations). In addition, the mean distance modulus implied by our subset of group membership-based distances is systematically closer, while the distances resulting from novae, SNe, TFR, and $D_n - \sigma$ analysis all appear to straddle around means that are systematically more distant than the canonical $(m - M)_0 = 31.0$ mag level. All of these latter data points come from our pre-2000 data set, and so these systematic offsets contribute to the appearance of a broadening of the overall distribution prior to 2000 compared with more recent measurements.

Finally, although we have considered the full set of data points post-2000, including distance estimates to M87 and the center of the Virgo cluster, there is no evidence of any systematic offsets for any of our tracer populations at more recent times.

4. Implications

Armed with our recommended M87 distance modulus, $(m - M)_0 = 31.03$ mag ($\sigma = 0.14$ mag, equivalent to 1.03 Mpc at the galaxy's distance of 16.07 Mpc), we are now well placed to extend our previously established local distance framework to the nearest galaxy clusters. Our internally consistent distance estimates to the Galactic Center, the LMC, and M31, combined with the geometric water-maser-based distance determination to NGC 4258, represent a tight framework to tie the local distance scale to. Table 3 provides a summary of our preferred reference distances.

This will allow us to assign absolute distances and realistic uncertainties to galaxies in the greater Virgo cluster environment, while also enabling us to use the robust Virgo cluster core distance as a stepping stone to even greater distances, all constrained to conform with the overall distance framework. Few galaxies beyond the largest ellipticals in the Virgo cluster have sizeable numbers of published distance moduli available. However, many can be placed within the 3D environment of the Virgo cluster by reference to any of the collections of relative distance moduli compiled to date (e.g., Mei et al. 2007; Blakeslee et al. 2009). Most of the latter result from relative comparisons of SBF magnitudes obtained based on homogeneous analyses, hence constituting their own internally consistent distance framework.

Perhaps more interesting would be an extension of the Galactic Center–LMC–M31–(NGC 4258)–M87 reference distance ladder out to the Fornax and Coma clusters. These clusters have been studied extensively, but few direct, absolute distance measurements are available. However, a not insignificant fraction of the published distances to the Fornax and Coma clusters are relative distance moduli with respect to that of the Virgo cluster (e.g., Blakeslee et al. 2009; Villegas et al. 2010; and references therein). This seems an opportune time, therefore, to extend our internally consistent distance framework to the ~20–100 Mpc scales of Fornax and Coma cluster-like distances. We will pursue this in Paper VII; at the present time (2019 November 8) a NASA/ADS object search for "Fornax cluster" returns 1869 references. A search for "Coma cluster" returned 5358 hits.

Table 3
Recommended Local Distance Framework Out to the Virgo Cluster

Target	$(m - M)_0^{\rm rec.}$ (mag)	Reference
Gal. Center[a]	14.60 ± 0.05	Paper IV
LMC	18.49 ± 0.09	Paper I
SMC	18.96 ± 0.02	Paper III
M31	24.45 ± 0.10	Paper II
NGC 4258	29.29 ± 0.08	Herrnstein et al. (1999)
M87/Virgo	31.03 ± 0.14	This paper

Note.
[a] Random (statistical) uncertainties only.

It is also interesting to briefly explore the impact of our updated, statistically supported distance modulus to M87 on the recent determination of that galaxy's black hole mass (Event Horizon Telescope Collaboration et al. 2019). Most luminosity and many mass estimates scale with D^2 (where D is the distance), while masses based on total densities or orbital modeling scale as D^3. The M87 distance modulus derived here corresponds to a distance of 16.07 ± 1.03 Mpc; the Event Horizon Telescope Collaboration et al. (2019) adopted $D_{\rm M87} = 16.8 \pm 0.8$ Mpc. Although both distance values are consistent with each other within the respective 1σ uncertainties, our derived central value is ~4% smaller than theirs. Given the $D_{\rm M87}^2$ scaling of the M87 black hole mass, this implies that with our updated distance modulus, the galaxy's black hole mass may have to be downsized from $M_{\rm BH}^{\rm EHT} = (6.5 \pm 0.7) \times 10^9 M_\odot$ to $M_{\rm BH}^{\rm new} = (5.9 \pm 0.6) \times 10^9 M_\odot$.

Finally, thus far we have predominantly considered the random (statistical) uncertainties associated with our set of distance estimates. Although we briefly discussed the nature of any differences between the distance to M87 and that to the Virgo cluster more broadly, the systematic uncertainties affecting our results are harder to quantify. These uncertainties mostly originate from the calibration choices made for any given distance indicator, many of which trace back to the intrinsic uncertainty in the Cepheid period–luminosity calibration. The latter has been reduced from ~0.15 mag (Freedman et al. 2001; Macri et al. 2006) to ~0.10 mag (Freedman & Madore 2010), or ~0.8 Mpc at the distance of M87, in recent years. The advent of *Gaia*-based distances has the potential to reduce these uncertainties even further (e.g., Ripepi et al. 2019 but see Groenewegen 2018). In addition, the tie from the Cepheid distance scale to the SBF (Tonry et al. 2001), TRGB, PNLF, or novae calibrations used more commonly in recent years introduces an additional systematic uncertainty, rendering the overall systematic uncertainty affecting our results at

$\sim$0.2 mag (e.g., Bird et al. 2010), despite all being based on a robust Local Group distance framework.

These levels of systematic uncertainties are corroborated by studies using multiple tracers to determine the same "best" distance to either M87 or the Virgo cluster center. For instance, Ferrarese et al. (2000) considered five different tracers, some covering multiple wavelengths, resulting in a weighted average distance modulus to the center of the Virgo cluster of $(m - M)_0 = 31.07 \pm 0.03$ mag. However, the 1σ spread among their eight individual distance estimates is of order 0.15 mag. Similarly, the spread among the five values published by Tammann et al. (2000) is of order 0.11 mag.

In this context, it is instructive to consider distance estimates that are not directly tied to any of the calibration scales we have discussed so far. One of those stands out, in particular. The Planck Collaboration et al. (2016) published a novel distance to the Virgo cluster as a whole based on the Sunyaev–Zel'dovich method, $(m - M)_0 = 31.28$ mag (no uncertainty quoted). Compared with our preferred distance modulus of 31.03 mag, this provides a good quantitative handle on the remaining systematic uncertainties affecting secondary distance indicators at this distance range. Note that this is a lower limit to the error budget, since it is not yet clear whether the difference is only caused by a difference in the zero-points of the different distance scales or if it may also be affected by the environment. The Large Synoptic Survey Telescope will play a key role in this context, since homogeneous multipassband optical data will provide an important opportunity to tie distances to Local Group and Local Volume galaxies using the same empirical framework.

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