An internally consistent distance framework in the Local Group

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Abstract. Accurate and precise astronomical distance determinations are crucial for derivations of, among others, the masses and luminosities of a large variety of distant objects. Astronomical distance determination has traditionally relied on the concept of a ‘distance ladder.’ Here we review our recent attempts to establish a highly robust set of internally consistent distance determinations to Local Group galaxies, which we recommend as the statistical basis of an improved extragalactic distance ladder.

1. Establishing the distance ladder

Distance determination is among the most fundamental tasks of the astronomer. Accurate and precise distances allow us to derive a multitude of basic physical parameters of objects as diverse as stars, galaxies, active galactic nuclei, and even of cosmological large-scale structures. Yet, to determine the distances to the nearest galaxy clusters, for instance, we must understand the physics of the galaxies in the nearby Universe. Distances to galaxies in the Local Group, in turn, often rely on our detailed understanding of the physics of a range of stellar tracers. This goes to show that the process of distance determination to increasingly distant target objects relies on accurate and precise knowledge of the distances to their more local counterparts, with each rung of the so-called ‘distance ladder’ depending for its calibration on equally good or better calibration of the previous, closer rung (e.g., de Grijs 2011).

Whereas geometric distances can be obtained to a range of objects in our own Milky Way galaxy and even to the nearest galaxies in the Local Group, provided that one chooses one’s tracers carefully (e.g., Pietrzyński et al. 2013), individual tracers do not always provide robust measurements for the purposes of distance calibration. Yet, the Local Volume, and the Local Group in particular, represents the single most important environment to calibrate our distance zero point.
For at least a century, numerous authors have derived distances to one or more galaxies in the Local Group (see, e.g., de Grijs et al. 2014; de Grijs & Bono 2014, 2015, 2016; and references therein), characterized by a range in accuracy and precision. Over the course of the past four years, we have attempted to establish a highly robust set of internally consistent distance determinations to Local Group members (de Grijs et al. 2014; de Grijs & Bono 2014, 2015), including to the centre of the Milky Way (de Grijs & Bono 2016), which we hope can serve as the long-targeted distance zero point and form the basis of an improved extragalactic distance ladder. As we will see below, we have opted to tie our distance scale to the distance to the Large Magellanic Cloud (LMC), for which we have adopted a distance modulus of \((m - M)_0 = 18.49\) mag (Pietrzyński et al. 2013; de Grijs et al. 2014; note that since this value is our adopted distance modulus, we do not include an uncertainty) throughout.

1.1. Distance to the Galactic Centre

As our starting point in the Local Group, we take the Milky Way’s centre as our initial benchmark. The distance to the Galactic Centre is indeed used as a reference value for a variety of methods of distance determination, both inside and outside the Milky Way. Its actual value has a direct impact on the distances, masses, and luminosities one can derive for many Galactic objects, as well as on the mass, size, and rotation characteristics of the Milky Way as a whole. Most luminosities and masses scale as \((\text{distance}^2)\), while masses based on total densities or orbital modelling scale as \((\text{distance}^3)\). Higher-accuracy distance determinations allow for improved calibration of the zero points of many secondary distance tracers, including of the often-used Cepheid and RR Lyrae period–luminosity relations. In turn, this leads to improved estimates of globular cluster ages, the Hubble constant, and the age of the Universe. In addition, improved calibration of the local distance scale carries the potential to yield better constraints on a range of cosmological scenarios.

We perused the extensive literature on the Galactic Centre and embarked on a careful analysis of a large number of tracer populations (de Grijs & Bono 2016). We included both those populations defining a ‘centroid’ with the Galactic Centre at its centre (e.g., globular clusters, red clump stars, as well as Cepheid, RR Lyrae and Mira variables) and kinematic tracers (including variable stars, open clusters, maser sources, and objects tracing the Galactic disk). We thus arrived at a recommended Galactic Centre distance of \(R_0 = 8.3 \pm 0.2\) (statistical) \pm 0.4 (systematic) kpc, corresponding to \((m - M)_0 = 14.60 \pm 0.05\) (statistical) \pm 0.10 (systematic) mag.

Compare and contrast this recommendation with the current-best determinations based on geometric considerations, including the orbits of the Galactic Centre’s ‘S stars’ and statistical parallax determinations of the central population of stars in the Milky Way. The S stars have yielded values for the Galactic Centre distance ranging from \(R_0 = 8.0 \pm 0.3\) kpc (Ghez et al. 2008a,b) to \(R_0 = 8.2 \pm 0.34\) kpc (Gillessen et al. 2013). Similarly, statistical parallax measurements resulted in \(R_0 = 8.24 \pm 0.12\) kpc (Rastorguev et al. 2016). By contrast, Matsunaga et al.’s (2011) determination of \(R_0 = 7.9 \pm 0.2\) kpc (based on application of the period–luminosity relation to three Cepheid variables in the Galactic nucleus) is systematically smaller.

Separately, we arrived at the conclusion that \(R_0 = 8.3\) kpc implies that the circular rotation speed at the solar circle, \(\Theta_0\), as traced by the Galaxy’s mass-bearing components is \(\Theta_0 = 225\) (statistical) \pm 3 \pm 10 (systematic) km s\(^{-1}\), so that \(\Theta_0/R_0 = 27.12 \pm 0.39\) (statistical) \pm 1.78 (systematic) km s\(^{-1}\) kpc\(^{-1}\) (de Grijs & Bono 2017).
1.2. The Large Magellanic Cloud

The distance to the LMC is truly the first rung on the extragalactic distance ladder. The galaxy hosts statistically large samples of so-called ‘standard candles,’ so that it represents a great benchmark object for distance calibration. Because of its disk-like geometry, all standard candles are located at roughly the same distance (but note that depth effects are not completely negligible). In addition, they are affected by only little extinction. The LMC offers us a great opportunity to cross calibrate many tracers simultaneously, and possibly even link them to their Galactic counterparts.

It also hosts a number of geometric distance tracers, including the supernova (SN) 1987A and a good number of eclipsing binary systems. The systematic uncertainty in the LMC distance was singled out by the Hubble Space Telescope (HST) Key Project (HSTKP) on the Extragalactic Distance Scale (Freedman et al. 2001) as being of key importance for determining the precision of the Hubble constant, \( H_0 \), and until recently contributed most of the remaining systematic uncertainty. The HSTKP team determined \( H_0 = 72 \pm 3 \) (statistical) \( \pm 7 \) (systematic) \( \text{km s}^{-1} \text{Mpc}^{-1} \).

En passant, the HSTKP team determined a distance modulus for the LMC, \( \left( m - M \right)_0 = 18.50 \pm 0.10 \) mag, corresponding to \( D_{\text{LMC}} = 50.1_{-1.4}^{+1.4} \) kpc. Freedman et al. (2001) based these determinations on a revised calibration of the Cepheid period–luminosity relation (adopting the maser-based distance to NGC 4258 as their distance calibration) and numerous secondary techniques. At the same time, this result finally resolved the long-standing ‘short’ versus ‘long’ LMC distance debate, which had been raging in the community for a number of decades.

However, trends in subsequent LMC distance determinations were questioned by Schaefer (2008), who claimed that “all 31 measurements since 2001 seem to cluster too tightly around the HST Key Project’s value.” Schaefer (2008) attributed his findings to the presence of ‘publication bias’ or a potential bandwagon effect. In de Grijs et al. (2014) we set out to redo this latter analysis based on the most comprehensive data mining approach of the literature carried out until that time.

We concluded that we could not support Schaefer’s (2008) claims. For instance, his suggestion that the uncertainties in the post-2002 measures were not distributed like a Gaussian assumes that the pre-2002 uncertainties were Gaussian-like. They are not. This also assumes that conditions have remained comparable, which again is not justified. Schaefer (2008) did not undertake a detailed assessment of the systematic uncertainties, while his statistical tests were in essence based on application of the Kolmogorov–Smirnov test. This latter test assumes a Gaussian distribution of LMC distance measurements, as well as a sample of independent and identically distributed values. Neither assumption is applicable to the body of LMC distance measurements. By virtue of our significantly enlarged database of LMC distance measurements, which avoided the pitfalls associated with the earlier incomplete database where the presence of gaps was found to hide correlations, we found that we could not conclude that publication bias significantly affected the published LMC distance determinations.

Having perused more than 16,000 articles, we eventually collected 233 post-1990 derivations of the LMC distance modulus. In our subsequent analysis, we had to make a number of choices and assumptions. For multiple measurements published in the same paper, we included them separately if they comprised ‘final’ results (after all, any differences show the effects of systematic uncertainties). We therefore did not only consider weighted means. If correlated results were provided in a given paper, we considered these representative of the systematic uncertainties. Such effects included variations
in extinction corrections, metallicities or $\alpha$ abundances, and $p$ (‘projection’) factors. In some papers, the same tracer populations were used but applied at different wavelengths or they adopted different calibration methods. Again, this provided us with a handle on the systematic uncertainties; only 47 articles included their own assessments of these systematic effects.

Systematic uncertainties encountered in our analysis included differences in zero-point calibrations (e.g., Hipparcos, HST/Fine Guidance Sensor, or ground-based, interferometric parallaxes), as well as differences in Baade–Wesselink analyses; the functional form of the calibration relations adopted; Lutz–Kelker-type biases in parallax measurements; differences in the metallicity scale and extinction corrections; transformations between filter systems (e.g., HST versus ground-based $UBVRI$); and the location of the emission from SN 1987A as a function of wavelength.

In terms of parallax measurements, observational uncertainties cause objects which are in reality located outside the adopted lower parallax limit to scatter into the sample’s selection volume and vice versa. Since there are more objects just outside than just inside the selection boundary (at least for predominantly uniformly distributed objects), more objects will be scattered into than out of the sample, so that a systematic bias is introduced. This so-called ‘Lutz–Kelker bias’ applies to parallax measurements of any sample of objects; it does not strictly apply to individual parallaxes.

As regards the appearance of SN 1987A, the key questions requiring exploration include, Does the emission used to measure delay times at a variety of wavelengths actually originate from the same region(s) in the ring? Does emission start immediately when photons hit the gas? Is there a delay? It has been suggested that ultraviolet lines, such as N$_{III}$/N$_{IV}$ may originate from the ring’s inner edge, while the optical [O$_{III}$] lines may have come from the main body. Using the proper geometry, including a finite ring thickness, the ultraviolet light curve could then result in an underestimate of the light travel time across the optical ring diameter (and thus in the distance) of up to 7%. This scenario is unlikely, however, given the very similar ionisation potentials of [O$_{III}$] and N$_{III}$/N$_{IV}$, as well as their likely spatial distributions (e.g., Gould & Uza 1998; and references therein).

Following a careful assessment of the statistical and systematic uncertainties associated with all reported post-1990 LMC distance measurements, our final recommendation for the LMC’s distance modulus is $(m - M)_0 = 18.49 \pm 0.09$ mag. This has since been confirmed on the basis of independent statistical analysis (Crandall & Ratra 2015). It is also fully consistent with the large body of Cepheid-based distance measurements to the LMC, which resulted in $(m - M)_0 = 18.48 \pm 0.08$ mag (de Grijs et al. 2014). We note that the independent eclipsing binary distance modulus of Pietrzyński et al. (2013) provides excellent confirmation: $(m - M)_0 = 18.493 \pm 0.008$ (statistical) $\pm 0.047$ (systematic) mag, corresponding to a distance $D_{LMC} = 49.97 \pm 0.19$ (statistical) $\pm 1.11$ (systematic) kpc.

2. Beyond the Large Magellanic Cloud

We took a similar approach to derive an independent statistically justified distance modulus to the Small Magellanic Cloud. Although we noticed some tension at the $2\sigma$ level among the various tracers used in the literature, our final recommendation, $(m - M)^{SMC}_0 = 18.96 \pm 0.02$ mag (statistical uncertainty only) is adequately supported (within the uncertainties) by the majority of distance tracers.
For good measure, we proceeded to obtain statistical distances using the same data mining approach for M31, M33, and a number of smaller galaxies in their immediate vicinity. Where necessary for relative distance measurements, we used \((m - M)^{\text{LMC}}_0 = 18.49\) mag as our local benchmark for calibration purposes.

Our full set of Local Group distance measurements is included Table 1, which we offer as our final recommendations. It represents a summary of having perused tens of thousands of articles in the literature, eventually leading to a collection of statistically carefully justified local benchmark distances. In turn, these are meant to provide a useful cross calibration for Gaia and Large Synoptic Survey Telescope benchmarking.

### Table 1. Recommended benchmark distance moduli in the Local Group

| Benchmark          | \((m - M)^{\text{rec.}}_0\) (mag) |
|--------------------|----------------------------------|
| Galactic Centre    | 14.60 ± 0.11                     |
| Large Magellanic Cloud | 18.49 ± 0.09               |
| Small Magellanic Cloud | 18.96 ± 0.02               |
| NGC 185            | 24.00 ± 0.12                     |
| NGC 147            | 24.11 ± 0.11                     |
| IC 1613            | 24.34 ± 0.05                     |
| IC 10              | 24.36 ± 0.45                     |
| M32                | 24.43 ± 0.07                     |
| M31                | 24.45 ± 0.10                     |
| NGC 205            | 24.56 ± 0.15                     |
| M33                | 24.67 ± 0.07                     |

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