Summary

Advancing the Physics of Cosmic Distances
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Advancing the physics of cosmic distances: Conference summary

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Abstract. Knowing the distance of an astrophysical object is key to understanding it. However, at present, comparisons of theory and observations are hampered by precision (or lack thereof) in distance measurements or estimates. Putting the many recent results and new developments into the broader context of the physics driving cosmic distance determination is the next logical step, which will benefit from the combined efforts of theorists, observers and modellers working on a large variety of spatial scales, and spanning a wide range of expertise. IAU Symposium 289 addressed the physics underlying methods of distance determination across the Universe, exploring the various approaches employed to define the milestones along the road. The meeting provided an exciting snapshot of the field of distance measurement, offering not only up-to-date results and a cutting-edge account of recent progress, but also full discussion of the pitfalls encountered and the uncertainties that remain. One of the meeting's main aims was to provide a roadmap for future efforts in this field, both theoretically and observationally.

Keywords. gravitational lensing, masers, stellar dynamics, methods: statistical, techniques: interferometric, astrometry, binaries: eclipsing, stars: distances, stars: oscillations, Cepheids, galaxies: distances and redshifts, Local Group, Magellanic Clouds, cosmological parameters, distance scale, large-scale structure of universe

1. Introduction

Knowing the distance of an astrophysical object is key to understanding it: without an accurate distance we do not know how bright it is, how large it is, or even (for long distances) when it existed. But astronomical distance measurement is a challenging task, since the only information we have about any object beyond our solar system is its position (perhaps as a function of time) and its brightness (as a function of wavelength and time).

In 1997, the *Hipparcos* space mission provided (for the first time) a significant number of absolute trigonometric parallaxes at milliarcsec (mas)-level precision across the whole sky, which had a major impact on all fields of astrophysics. In addition, during the past ten years, the use of ground-based 8–10 m-class optical and near-IR telescopes (*Keck, VLT, Gemini, Subaru*) and space observatories (the *Hubble Space Telescope [HST], Spitzer, Herschel, Chandra, XMM-Newton*) have provided an unprecedented wealth of accurate photometric and spectroscopic data for stars and galaxies in the local Universe. Radio observations, particularly with the Very Long Baseline Array (*VLBA*) and the Japanese *VERA* array, have achieved 10 micro-arsecond astrometric accuracy. Moreover, stellar models and numerical simulations are now providing accurate predictions of a broad range of physical phenomena, which can in principle be tested using accurate spectroscopic and astrometric observations. However, at present, comparisons of theory and observations are mainly hampered by precision (or lack thereof) in distance measurements/estimates.

IAU Symposium 289 highlighted the tremendous amount of recent and continuing research into a myriad of exciting and promising aspects of accurately pinning down the cosmic distance scale. Putting the many recent results and new developments into the broader context of the physics driving cosmic distance determination is the next logical step, which will benefit from the combined efforts of theorists, observers and modellers working on a large variety of spatial scales, and spanning a wide range of expertise.

This is a very exciting time in the context of this Symposium. Very Long Baseline Interferometry (VLBI) sensitivity is being expanded, allowing, for example, direct measurement of distances throughout the Milky Way and even slightly beyond Local Group galaxies. The field will benefit from expert input to move forward into the era of *Gaia*, optical-interferometer- and Extremely Large Telescope-driven science, which (for example) will allow us to determine Coma-cluster distances without having to rely on secondary distance indicators, thus finally making the leap to accurate distance measurements well beyond the Local Group of galaxies.

In this Symposium, we managed to bring together experts on various aspects of distance determinations and (most importantly) the underlying physics enabling this (without being restrictive in areas where statistical and observational approaches are more relevant), from the solar neighbourhood to the edge of the Universe, exploring on the way the various methods employed to define the milestones along the road. We aimed at emphasising, where possible, the physical bases of the methods and recent advances made to further our physical insights. We thus aimed to provide a snapshot of the field of distance measurement, offering not only up-to-date results and a cutting-edge account of recent progress, but also full discussion of the pitfalls encountered and the uncertainties that remain. We ultimately aimed to provide a roadmap for future efforts in this field, both theoretically and observationally.

Although our focus was on techniques of distance determination, this is intimately linked to many other aspects of astrophysics and cosmology. On our journey from the solar neighbourhood to the edge of the Universe, we encountered stars of all types, alone, in pairs and in clusters, their life cycles, and their explosive ends: binary stars, in particular, play an important role in this context, e.g. in pinning down accurate distances to the Pleiades open cluster and Local Group galaxies, as well as in future ground- and space-based surveys; the stellar content, dynamics, and evolution of galaxies and groups of galaxies; the gravitational bending of starlight; and the expansion, geometry and history of the Universe. As a result, the Symposium offered not only a comprehensive study of distance measurement, but a tour of many recent and exciting advances in astrophysics.

2. Key areas of new and/or sustained progress

In 16 reviews, 16 invited and 35 contributed talks, as well as more than 50 high-quality posters, the Symposium presented an opportunity for lively debate, exciting new results and a number of potentially ground-breaking new announcements.

2.1. *Has the Pleiades distance controversy finally been resolved?*

The Pleiades open cluster is a crucial rung of the local distance ladder, whose calibration affects many fundamental aspects of stellar astrophysics. However, the original *Hipparcos* parallaxes (Mermilliod *et al.* 1997; van Leeuwen & Hansen-Ruiz 1997; Robichon *et al.* 1999; van Leeuwen 1999), as well as the recalibrated astrometry (van Leeuwen 2007a,b), yielded distances to the individual member stars and the open cluster as a whole that were systematically lower than those resulting from previous ground-based distance determinations. The latter were predominantly based on the main-sequence fitting technique, because prior to the successful *Hipparcos* mission stellar parallaxes at the distance of the Pleiades were too small to be measurable reliably with contemporary instrumentation.

Doubt was initially cast on the original *Hipparcos* analysis, which required advanced mathematical techniques to solve simultaneously for the positions, motions and distances of 118,000 stars. Although the *Hipparcos* recalibration reduced the discrepany slightly, the difference remains too large for comfort: the variation in distance modulus implied is approximately 0.2–0.3 mag (Pinsonneault *et al.* 1998), while the difference in parallax required is of order 1 mas, but note that the absolute uncertainty in *Hipparcos* parallaxes is only 0.1 mas (Arenou *et al.* 1995; Lindegren 1995).

The controversy has, thus, not been fully resolved, and all methods applied to date are affected by their own unique sets of uncertainties (see e.g. Valls-Gabaud 2007). To account for the *Hipparcos* distance, stellar models would require changes in physics or input parameters that are too radical to be reasonable, e.g. changes in the Pleiades' characteristic metallicity or helium abundance, or in the mixing length, an age differential between local and Pleiades member stars or an unusual spatial distribution (i.e. depth effects). Most models applied to resolve the Pleiades controversy include many assumptions and simplifications which may well dominate or negate the need for the proposed small evolutionary correction between the Pleiades and local stars, e.g. in terms of stellar structure (rotation, convection, magnetic fields), stellar evolution and stellar atmospheres. VLBI observations may come to the rescue in this context: 1% parallax precision for individual Pleiades stars is anticipated (0.5% for objects in Gould's Belt). The jury is thus still out on the final resolution of the Pleiades controversy, but there appears to be light at the end of the tunnel.

2.2. *Further refinements of the distance to the Galactic Centre*

The exact distance from the Sun to the Galactic Centre, R_0, serves as a benchmark for a variety of methods used for distance determination, both inside and beyond the Milky Way. Many parameters of Galactic objects, such as their distances, masses and luminosities, and even the Milky Way's mass and luminosity as a whole, are directly related to R_0. Most luminosity and many mass estimates scale as the square of the distance to a given object, while masses based on total densities or orbit modelling scale as distance cubed. This dependence sometimes involves adoption of a rotation model of the Milky Way, for which we also need to know the Sun's circular velocity with high accuracy.

Significant efforts have been expended in recent years to reduce the uncertainties in and narrow down the actual distance to the Galactic Centre, using a large variety of mostly independent methods. Detailed orbit modelling of the so-called S stars orbiting Sagittarius A* (believed to be almost coincident with the supermassive black hole in the Galactic Centre) yields $R_0 = 8.20 \pm 0.15$ (statistical) ± 0.31 (systematic) kpc (Gillessen *et al.*, in prep.) or $R_0 = 7.7 \pm 0.4$ kpc (Morris *et al.* 2012), depending on one's assumptions about the central black hole mass and the associated uncertainties. We will need to wait until at least 2019, when we will finally have high-accuracy direct astrometric measurements of a full orbit of the star S2, for significantly reduced errors in these distance estimates. The current accuracy of R_0 determinations based on orbit modelling compares well with the results from, e.g. Cepheid-based distances. Majaess (2010), using the OGLE (Optical Gravitational Lensing Experiment) fields, finds $R_0 = 8.1 \pm 0.6$ kpc, while Dambis (2009) reported $R_0 = 7.58 \pm 0.40$ kpc. An alternative distance tracer in the form of Mira variables results in $R_0 = 8.24 \pm 0.08$ (stat.) ± 0.43 (syst.) kpc (Matsunaga *et al.* 2009), based on a sample of 143 Miras. Thus, although the exact value of R_0 remains open to debate, it is clear that the IAU-recommended value of 8.5 kpc is too large, but we are not sure whether the true value should be greater or less than 8.0 kpc

In terms of refining our knowledge of the Galactic rotation parameters, significant progress has also been made in recent years. Based on 5000 hours of *VLBA* observations, the BeSSeL survey obtained parallaxes and proper motions of >400 sources. The BeSSeL team reports a new Galactic rotation velocity of $\Theta_0 = 243 \pm 7$ km s^{-1} (for R$_0 = 8.38 \pm 0.18$ kpc) or $\Theta_0 = 236 \pm 10$ km s^{-1} for R$_0 = 8.2 \pm 0.3$ kpc based on stellar orbits and proper motions of Sgr A*. The Japanese *VERA* team, meanwhile, obtained parallaxes of 30 objects, resulting in R$_0 = 8.05 \pm 0.45$ kpc and $\Omega_0 \equiv (\Theta_0/R_0) = 31.09 \pm 0.78$ km s^{-1} kpc^{-1}.

2.3. *Stellar distance tracers: calibration of Local Group distances*

A significant fraction of the meeting was devoted to discussions about the use, reliability and calibration of pulsating stars as distance tracers, essentially based on using their period–luminosity relations. This is an extensive field, in which much progress has been made since the Cepheid period–luminosity relation was first established by Henrietta Leavitt a century ago.

Much of the current debate centres on whether or not the relation for Cepheids exhibits a single slope or is perhaps better defined by two segments with independently determined slopes. It appears that observations at longer wavelengths, particularly in the near- and mid-IR, may bring closure to this issue. In addition to unequivocally yielding single-slope relations, the associated error bars are much reduced, hence leading to distance estimates affected by significantly reduced uncertainties compared to the use of optical period–luminosity(–colour) relations. Reddening corrections remain among the key sources of uncertainty. Additional sources of uncertainty include the alleged effects of circumstellar envelope variability, a source of error that has long been overlooked and neglected, and the maximum useful period for Cepheid period–luminosity relation applications (ultralong-period Cepheids do not seem to obey a clear-cut relationship of this type).

It was suggested that red-supergiant Mira variables may be better distance tracers than classical Cepheids under certain circumstances, given that they are brighter and associated with old(er) stellar populations. As massive stars, Cepheids are by definition confined to young stellar populations. Ideally, linking up both tracers in the same galaxy will conclusively constrain the distance debate.

Among the brightest non-variable distance tracers, recent years have seen significant improvements in the accuracy of using stars at the tip of the red giant branch. But all these methods rely on secondary calibration, i.e. on the presumption that we understand the underlying physics of both nearby and distant objects of the same type. Geometric distance methods out to the Local Group galaxies are, unfortunately, few and far between. It was therefore encouraging to note that eclipsing binary systems have been detected and used to constrain the distance to IC 1613 with encouraging accuracy. This may lead to IC 1613 eventually being designated as a new Local Group distance benchmark.

2.4. *LMC distance: the first step of the extragalactic distance ladder*

The Magellanic Clouds, and in particular the Large Magellanic Cloud (LMC), represent the first rung of the extragalactic distance ladder. The galaxy hosts statistically large samples of potential standard candles, including many types of variable stars. They are all conveniently located at roughly the same distance – although for detailed distance calibration the LMC's line-of-sight depth and 3D morphology must also be taken into account – and relatively unaffected by foreground extinction. The LMC's unique location allows us to compare and, thus, cross correlate and calibrate a variety of largely independent distance indicators, which can, in turn, be applied to more distant targets.

The distance to the LMC has played an important role in constraining the value of the Hubble constant. The *HST* Key Project on the extragalactic distance scale (Freedman *et al.* 2001; see also Freedman & Madore 2010) used a revised calibration of the Cepheid period–luminosity relation (adopting the maser-based distance to NGC 4258) and numerous secondary techniques to obtain a distance modulus to the LMC of $(m - M)_0 = 18.50 \pm 0.10$ mag – corresponding to a distance $D_{\rm LMC} = 50.1^{+1.4}_{-1.2}$ kpc – and $\rm H_0 = 72 \pm 3$ (stat.) ±7 (syst.) km $\rm s^{-1}$ $\rm Mpc^{-1}$. Trends in subsequent LMC distance determinations have been questioned by Schaefer (2008): he argued that all 31 measurements published between 2001 and early 2008 cluster too tightly around the *HST* Key Project's value and suggested that this may imply a 'bandwagon effect', i.e. publication bias.

Once again, going to near- and mid-IR wavelengths may enable us to reduce the uncertainties in the distance to the LMC. At present, 2–3% distance accuracy is already achievable, and this may be improved to $\sim$ 1% in the near future! For instance, the Carnegie Hubble Program, using data from the warm *Spitzer* mission, derived $(m-M)_0 = 18.477 \pm 0.034$ mag (Freedman *et al.* 2012), while Ripepi *et al.* (2012) used *VISTA* observations to arrive at $(m - M)_0 = 18.46 \pm 0.03$ mag. These distances are comfortably close to and within the mutual uncertainties of the direct, geometric distance determination based on eclipsing binaries by Pietrzyński *et al.* (2012), $(m - M)_0 = 18.48 \pm 0.01$ (stat.) ±0.04 (syst.) mag.

2.5. *Rotational parallaxes/water masers: new standard benchmarks?*

The technique of VLBI is not only useful in the context of resolving the distance to the Pleiades, it is also increasingly used to measure extragalactic proper motions. In turn, this enables geometric distance determination out to some 100 Mpc, including to the nearby galaxies NGC 4258, M33, UGC 3789, NGC 6264, and many more. Combined with *a priori* information on a galaxy's inclination with respect to our line of sight and its rotation curve, based on radial velocity measurements, we can construct an accurate, slightly warped 'tilted-ring' model of the galaxy's dynamical structure, usually assuming circular orbits (although this assumption does not result in major systematic uncertainties). This, in turn, allows correlation of the angular proper motion measurements with the rotational velocity information obtained in linear units and, thus, provides an independent distance measurement.

Much has been made of the original application of water maser measurements in NGC 4258, but in the mean time this technique has been extended to other nearby systems. Initial efforts to determine the distance to the Local Group galaxy M33 have thus far resulted in $D_{\rm M33} = 750 \pm 140 \pm 50$ kpc, where the first uncertainty is related to uncertainties in the HI rotation model adopted for the galaxy, and the second uncertainty comes from the proper motion measurements. Participants in the meeting were told that 10% distance accuracy will be achievable eventually, provided that the team retains access to the Green Bank Telescope, which was recently slated for closure because of severe funding constraints. The prospects for application of this technique to M31 are moderately positive, although at present only two water masers have been identified in the galaxy that are potentially useful; meanwhile, Cepheid variables enable a distance estimate of $D_{\rm M31} = 752 \pm 27$ kpc (3%). The *Square Kilometre Array (SKA)* may have a major role to play in this context.

Simultaneously, the Megamaser Cosmology Project aims at using extragalactic maser sources to directly measure $\rm H_0$ in the Hubble flow, which is clearly a very challenging endeavour at distances > 100 Mpc! Their preliminary results look promising however: using NGC 6264 ($D = 137$ Mpc) as a benchmark, they find $\mathrm{H}_0 = 74 \pm 10$ km s^{-1} Mpc^{-1}.

2.6. *Nearby galaxy samples*

Beyond the distances where common geometric methods or even Cepheid period–luminosity relations offer a way to determine reasonably accurate distances, many secondary methods of distance determination have been developed. In almost all cases, their reliability depends on a proper understanding of the underlying physics. And this is where some of the key remaining problems originate, leading to 'annoying' uncertainties that are hard to reduce.

For instance, the planetary nebula luminosity function (PNLF) has long been used as a distance indicator. In the narrow-band filter centred on the [O III]λ5007Å emission line, the PNLF in nearby galaxies is defined by a universal, sharp cut-off at the bright end. This feature can be used as a standard candle, resulting in distances to the planetary nebulae's host galaxies accurate to $\sim 25\%$ or better. However, at the meeting we learnt that this sharp cut-off may, in fact, not be so sharp, particularly in giant elliptical galaxies. This implies that we really need to improve our physical understanding of the processes that lead to the establishment of the PNLF. (A serious problem in this context is that worldwide there is a trend leading to a general loss of narrow-band capabilities at major research observatories!)

Secondly, the often-used Tully–Fisher relation, which relates a galaxy's luminosity to its rotational velocity, enables us to determine highly accurate distances, but one should realise that its use is actually based on numerous simplifications, assumptions and degeneracies (e.g. on the assumption of an asymptotic value of the rotation curve, adoption of halo mass scaling relations), but it works somehow, and surprisingly well! Application of this technique yields values of H_0 in the same ballpark as those obtained from Cepheids, with uncertainties of order 10%. Expressed in worldly units, we were told that one can obtain relevant observations for large samples of galaxies at a cost ranging from US$ 200 to US$ 15,000 per galaxy.

A promising alternative method of distance determination out to galaxy clusters in the Hubble flow is found in the technique of surface brightness fluctuations (SBFs). The relative SBF distance to the Coma cluster with respect to the Virgo and Fornax clusters is well determined: $(m - M)_{0,\mathrm{Coma}} = 34.98 \pm 0.06/34.96 \pm 0.07$ mag, or $\Delta(m - M)_0 = 3.89 \pm 0.06$ mag relative to the Virgo cluster. This leads to a robust distance estimate to the Coma cluster of $D_{\mathrm{Coma}} = 99 \pm 3$ Mpc.

2.7. *In the Hubble flow and beyond*

Type Ia supernovae (SNe Ia) remain excellent distance indicators out to moderate redshifts, despite many lingering uncertainties as regards the underlying physics, including those related to the apparent progenitor diversity. However, we are approaching systematic limits hampering efforts to further reduce the associated uncertainties. These systematic effects include, e.g. the precision of photometric calibrations and the fairly limited numbers of observations of SNe Ia.

Current values of H_0 based on measuring gravitational-lens time delays range from approximately 50 to 85 km s^{-1} Mpc^{-1}. Most of the uncertainties originate from sometimes poorly constrained model assumptions, e.g. adopton of isothermal profiles, sometimes in the presence of external tidal fields, the central concentration degeneracy, environmental density distributions or multiple lenses. One particularly interesting quadruple gravitational lens, B1608+656, long held the distinction of allowing the most straightforward application of time delay measurements. The value of H_0 resulting from these observations was $H_0 = 70.6 \pm 3.1$ km s^{-1} Mpc^{-1}. Derivation of this result was all but straightforward, however. It required adoption of the currently favoured cosmological parameters, *HST* pixel-by-pixel photometry, *Keck* low-resolution spectroscopy, cosmological N-body simulations, and assumption of a proper, extended source intensity distribution. Combined with the *Wilkinson Microwave Anisotropy Probe (WMAP)* five-year results and assuming a flat geometry, $H_0 = 69.7^{+4.9}_{-5.0}$ km s^{-1} Mpc^{-1} and the equation of state, $w = -0.94^{+0.17}_{-0.19}$ (68% confidence; Suyu *et al.* 2010).

More recently, Suyu *et al.* (2012) improved these cosmological parameter determinations using a second, well-understood lens, RXJ1131–1231. The current-best cosmological parameters resulting from gravitational-lens time-delay measurements are $H_0 = 75.2^{+4.4}_{-4.2}$ km s^{-1} Mpc^{-1} and $w = -1.14^{+0.17}_{-0.20}$.

On scales of (and distances to) distant galaxy clusters, the Sunyaev–Zel'dovich effect offers a suitable handle on determinations of H_0. Current determinations depend on the assumptions adopted; they include $H_0 = 76.9^{+3.9}_{-3.4}$ (stat.) $^{+10.0}_{-8.0}$ (syst.) versus $H_0 = 73.7^{+4.6}_{-3.8}{}^{+9.5}_{-7.6}$ km s^{-1} Mpc^{-1}, adopting hydrostatic equilibrium versus an isothermal cluster model (Bonamente *et al.* 2006), $H_0 = 77.6^{+4.8}_{-4.3}{}^{+10.1}_{-8.2}$ km s^{-1} Mpc^{-1} if one attempts to avoid the cool cluster cores, and $H_0 = 73.2^{+4.3}_{-3.7}$ and $H_0 = 71.4^{+4.4}_{-3.4}$ km s^{-1} Mpc^{-1} for a standard ΛCDM cosmology versus a flat Universe with constant w (Holanda *et al.* 2010).

Other H_0 values determined in recent years using up-to-date techniques and competitive data sets include measurements done as part of the Carnegie Hubble Program: $H_0 = 74.3 \pm 0.4$ (stat) ± 2.1 (syst.) km s^{-1} Mpc^{-1} (based on calibration in the Local Group) and $H_0 = 74.3 \pm 2.6 \pm 3.5$ km s^{-1} Mpc^{-1} using > 400 galaxies based on mid-IR (3.6μm) data. In this regard, observations with the *James Webb Space Telescope (JWST)* offer exciting prospects to reach unprecedented 1% accuracy!

The 6dF Galaxy Survey of local, low-z baryon acoustic oscillations (BAOs) yields $H_0 = 67 \pm 3.2$ km s^{-1} Mpc^{-1}, a 5% result, with exciting prospects for further improvement, to approximately 1%. More importantly, BAO distances are comparable to SNe Ia distances, which implies that this would allow a crucial cross check of results. On large scales, *WMAP* has made significant contributions; based on seven years of observations (*WMAP*-7), $H_0 = 70.4 \pm 2.5$ km s^{-1} Mpc^{-1}. Note that these results rely on many priors and are not independent. In particular, they assume a flat geometry, but the value of H_0 is degenerate with the total curvature of the Universe, k. If these constraints are relaxed, H_0(*WMAP*-7) $= 53^{+15}_{-13}$ km s^{-1} Mpc^{-1}, although the meeting was also told that adoption of Modified Newtonian Dynamics would lead to lower values of H_0 too, by $\sim 20\%$.

3. Concluding thoughts

Significant recent progress has been achieved in establishing an increasingly firm and robust distance ladder, where possible based on well-understood physics. Nevertheless, uncertainties – both systematic and statistical – persist, even for the nearest and presumably best understood rungs of the distance ladder, resulting from different observational or technical approaches, as well as from our incomplete theoretical understanding of relevant physical aspects. An example of such lingering systematic uncertainties and the associated controversy is related to the role of the Pleiades open cluster as a crucial nearby rung of the cosmic distance ladder. Reconciliation of these systematic differences and uncertainties may require further advances in theoretical research, e.g. in terms of a more detailed and improved understanding of the late stages of stellar evolution, stellar atmospheric and pulsation physics, horizontal-branch morphologies, and mass-loss processes, among others, as a function of stellar mass.

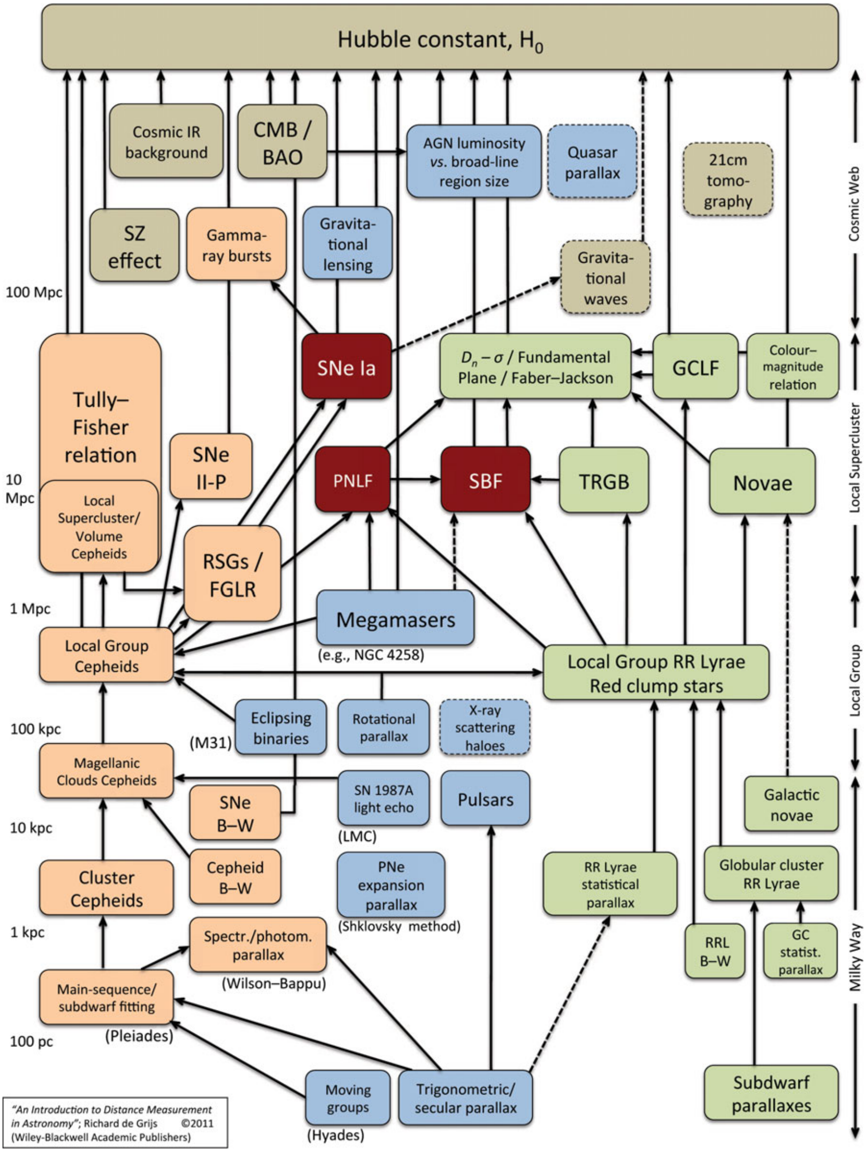

Figure 1. Updated, present-day distance ladder, based on an original idea by Ciardullo (2006). Light orange: Methods of distance determination associated with active star formation ('Population I', intermediate- and high-mass stars). Light green: Distance tracers associated with 'Population II' objects/low-mass stars. Blue: Geometric methods. Red: Supernovae (SNe) Ia, the planetary nebulae (PNe) luminosity function (PNLF) and surface-brightness fluctuations (SBF) are applicable for use with both Populations I and II. Light brown: Methods of distance or H_0 determination which are not immediately linked to a specific stellar population. Dashed boxes: Proposed methods. Solid, dashed arrows: Reasonably robust, poorly established calibrations. B–W: Baade–Wesselink. RRL: RR Lyrae. RSGs/FGLR: Red supergiants/flux-weighted gravity–luminosity relationship. TRGB: Tip of the red-giant branch. GCLF: Globular cluster (GC) luminosity function. SZ: Sunyaev–Zel'dovich. CMB/BAO: Cosmic microwave background/baryon acoustic oscillations. Colour–magnitude relation: Refers to galactic colours and magnitudes. *(adapted from de Grijs 2011)*

From an observational perspective, the future looks bright across the entire observable wavelength range. Although much current focus is on designing ever larger telescopes, the astronomical community must carefully consider whether the field is best served by having access to the next-generation of these extremely large telescopes at optical/near-IR wavelengths and the *SKA* in the radio domain or if significant progress can still be made with dedicated 2–4 m-class optical telescopes and upgraded current-generation radio interferometers. Clearly, although they will have small fields of view, larger optical and near-IR telescopes will have larger light-collecting areas and we will, thus, be able to apply current techniques to objects at greater distances: think of e.g. eclipsing-binary analysis potentially at Virgo cluster distances, monitoring Cepheid variables spanning a reasonable period distribution in Coma cluster galaxies and RR Lyrae variables in both spirals and ellipticals in the Virgo cluster, thus providing an independent calibration of SN Ia distances and finally linking the different stellar-population tracers.

On the other hand, one only has to consider the tremendous success of surveys with small telescopes, such as OGLE and the Sloan Digitial Sky Survey (SDSS), to realize that smaller, dedicated telescopes still have an important role to play in the overall context of astrophysical distance measurement. After all, in many cases currently unresolved questions benefit from being allocated significant amounts of observing time rather than access to the deep Universe. In this context, the European Southern Observatory's *VISTA* telescope (Emerson *et al.* 2004) will likely play an important role in e.g. achieving firmer zero points for period–luminosity relations at near-IR wavelengths by surveying the Magellanic Clouds as well as the Galactic Centre region and the inner disk through the *VISTA* near-IR YJK_s survey of the Magellanic System (VMC; Cioni *et al.* 2008, 2011) and the *VISTA* Variables in the Vía Láctea (VVV; Minniti *et al.* 2010) public surveys, respectively.

Looking beyond the immediate future, many new ground-based observatories, including the *Large Synoptic Survey Telescope (LSST)* and *Pan-STARRS* (Panoramic Survey Telescope & Rapid Response System), and space-based missions are currently in the design, construction or early operations phases, at wavelengths across the electromagnetic spectrum, from the very-high-frequency X-rays (e.g. in the context of improving Sunyaev–Zel'dovich-effect measurements) to low-frequency radio waves. In addition, let me highlight one of the key forthcoming space-based missions of relevance to the field of astrophysical distance measurement. The Milky Way's structure will be characterized to unprecedented levels of accuracy within a few years of the launch of *Gaia*.

Somewhat further afield, the *JWST* will give us an unprecedentedly high-resolution mid-IR view of the Universe, promising e.g. significant reduction of the uncertainties in mid-IR Cepheid period–luminosity relations (e.g. Madore *et al.* 2009a,b) and red-giant-branch-bump validation as a distance indicator (e.g. Valenti *et al.* 2004), among others. Observations at IR wavelengths hold significant promise in relation to improved or alternative methods of distance determination.

Remarkable and significant progress as regards the accuracy and robustness of cosmic distances at any scale has been made in the past few decades. The launch of the *HST* in the early 1990s proved a pivotal event in reducing the uncertainties in the Hubble constant, predominantly through carefully calibrated Cepheid-based extragalactic distances. *WMAP* has allowed determination of the prevailing cosmological parameters as well as the Hubble constant at high redshift to unprecedented accuracy and precision, provided that the cosmological-model-dependent assumptions at the basis of these results retain their validity as ever more precise and larger-scale measurements are becoming available. Lower rungs of the distance ladder have also seen (at least partial) convergence of their absolute levels through cross calibration with independent methods of distance determination. Nevertheless, establishing a fully robust distance ladder – or, as proposed at the meeting, rather a *network of distance tracers* – remains a lofty goal and may, in fact, be but an unreachable dream, given the significant uncertainties affecting many of the contributing methods, even the most robust techniques (cf. the Pleiades controversy).

In an attempt at summarising this vast field, Figure 1(†) visualises the applicability, distance range, mutual dependences and robustness of many of the most common methods of distance determination.

References

Arenou, F., Lindegren, L., Froeschle, M., Gomez, A. E., Turon, C., Perryman, M. A. C., & Wielen, R. 1995, *A&A*, 304, 52

Bonamente, M., Joy, M. K., LaRoque, S. J., Carlstrom, J. E., Reese, E. D., & Dawson, K. S. 2006, *ApJ*, 647, 25

Ciardullo, R. 2006, In *Planetary Nebulae Beyond the Milky Way* (Stanghellini, L., Walsh, J. R., & Douglas, N., eds.), ESO Astrophys. Symp., p. 79

Cioni, M.-R. L., Bekki, K., Clementini, G., *et al.* 2008, *Publ. Astron. Soc. Aus.*, 25, 121

Cioni, M.-R. L., Clementini, G., Girardi, L., *et al.* 2011, *A&A*, 527, A116

Dambis, A. K. 2009, *MNRAS*, 396, 553

de Grijs, R. 2011, *An Introduction to Distance Measurement in Astronomy*, Wiley–Blackwell Acad. Publ.

Emerson, J. P., Sutherland, W. J., McPherson, A. M., Craig, S. C., Dalton, G. B., & Ward, A. K. 2004, *ESO Messenger*, 117, 27

Freedman, W. L. & Madore, B. F., 2010, *ARA&A*, 48, 673

Freedman, W. L., Madore, B. F., Gibson, B. K., *et al.* 2001, *ApJ*, 553, 47

Freedman, W. L., Madore, B. F., Scowcroft, V., *et al.* 2012, *ApJ*, 758, 24

Holanda, R. F. L., Lima, J. A. S., & Ribeiro, M. B. 2010, *ApJ*, 722, L233

Lindegren, L. 1995 *A&A*, 304, 61

Madore, B. F., Rigby, J., Freedman, W. L., Persson, S. E., Sturch, L., & Mager, V. 2009a, *ApJ*, 693, 936

Madore, B. F., Freedman, W. L., Rigby, J., Persson, S. E., Sturch, L., & Mager, V. 2009b, *ApJ*, 695, 988

Majaess, D. J. 2010, *Acta Astron.*, 60, 55

Matsunaga, N., Kawadu, T., Nishiyama, S., Nagayama, T., Hatano, H., Tamura, M., Glass, I. S., & Nagata, T. 2009, *MNRAS*, 399, 1709

Mermilliod, J.-C., Turon, C., Robichon, N., Arenou, F., & Lebreton, Y. 1997, *ESA Spec. Publ.*, 402, 643

Minniti, D., Lucas, P. W., Emerson, J. P., *et al.* 2010, *New Astron.*, 15, 433

Morris, M. R., Meyer, L., & Ghez, A. M. 2012, *Res. Astron. Astrophys.*, 12, 995

Pietrzyński, G., Thompson, I. B., Gieren, W., *et al.* 2012, *Nature*, 484, 75

Pinsonneault, M. H., Stauffer, J., Soderblom, D. R., King, J. R., & Hanson, R. B. 1998, *ApJ*, 504, 170

Ripepi, V., Moretti, M. I., Marconi, M., *et al.* 2012, *MNRAS*, 424, 1807

Robichon, N., Arenou, F., Mermilliod, J.-C., & Turon, C. 1999, *A&A*, 345, 471

Schaefer, B. E. 2008, *AJ*, 135, 112

Suyu, S. H., Marshall, P. J., Auger, M. W., Hilbert, S., Blandford, R. D., Koopmans, L. V. E., Fassnacht, C. D., & Treu, T. 2010, *ApJ*, 711, 201

Suyu, S. H., Auger, M. W., Hilbert, S., *et al.* 2012, *ApJ*, submitted (arXiv:1208.6010)

Valenti, E., Ferraro, F. R., & Origlia, L. 2004, *MNRAS*, 351, 1204

Valls-Gabaud, D. 2007, *Proc. IAU Symp.*, 240, 281

van Leeuwen, F. 1999, *A&A*, 341, L71

van Leeuwen, F. 2007a, *Astrophys. Space Sci. Libr.*, 350

van Leeuwen, F. 2007b, *A&A*, 474, 653

van Leeuwen, F. & Hansen-Ruiz, C. S. 1997, *ESA Spec. Publ.*, 402, 689

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