The Hubble constant and new discoveries in cosmology

S. H. Suyu\textsuperscript{1,2}, T. Treu\textsuperscript{1}, R. D. Blandford\textsuperscript{2}, W. L. Freedman\textsuperscript{3}, S. Hilbert\textsuperscript{2}, C. Blake\textsuperscript{4}, J. Braatz\textsuperscript{5}, F. Courbin\textsuperscript{6}, J. Dunkley\textsuperscript{7}, L. Greenhill\textsuperscript{8}, E. Humphreys\textsuperscript{9}, S. Jha\textsuperscript{10}, R. Kirshner\textsuperscript{8}, K. Y. Lo\textsuperscript{5}, L. Macri\textsuperscript{11}, B. F. Madore\textsuperscript{3}, P. J. Marshall\textsuperscript{7}, G. Meylan\textsuperscript{6}, J. Mould\textsuperscript{4}, B. Reid\textsuperscript{12}, M. Reid\textsuperscript{8}, A. Riess\textsuperscript{13,14}, D. Schlegel\textsuperscript{12}, V. Scowcroft\textsuperscript{3}, L. Verde\textsuperscript{15}

\textsuperscript{1}University of California Santa Barbara, email: suyu@physics.ucsb.edu, tt@physics.ucsb.edu, \textsuperscript{2}Kavli Institute for Particle Astrophysics and Cosmology, \textsuperscript{3}Carnegie Observatories, \textsuperscript{4}Swinburne University of Technology, \textsuperscript{5}National Radio Astronomy Observatory, \textsuperscript{6}École Polytechnique Fédérale de Lausanne, \textsuperscript{7}University of Oxford, \textsuperscript{8}Harvard-Smithsonian Center for Astrophysics, \textsuperscript{9}European Southern Observatory, \textsuperscript{10}Rutgers University, \textsuperscript{11}Texas A&M University, \textsuperscript{12}Lawrence Berkeley National Laboratory, \textsuperscript{13}Johns Hopkins University, \textsuperscript{14}Space Telescope Science Institute, \textsuperscript{15}University of Barcelona

Abstract.

We report the outcome of a 3-day workshop on the Hubble constant ($H_0$) that took place during February 6-8 2012 at the Kavli Institute for Particle Astrophysics and Cosmology, on the campus of Stanford University. The participants met to address the following questions. Are there compelling scientific reasons to obtain more precise and more accurate measurements of $H_0$ than currently available? If there are, how can we achieve this goal? The answers that emerged from the workshop are (1) better measurements of $H_0$ provide critical independent constraints on dark energy, spatial curvature of the Universe, neutrino physics, and validity of general relativity, (2) a measurement of $H_0$ to 1% in both precision and accuracy, supported by rigorous error budgets, is within reach for several methods, and (3) multiple paths to independent determinations of $H_0$ are needed in order to access and control systematics.

Keywords. cosmology: distance scale – cosmology: cosmological parameters – cosmology: dark energy – galaxies: distances and redshifts

Are there compelling scientific reasons to obtain more precise and more accurate measurements of $H_0$ than currently available? A measurement of the local value of $H_0$ to 1% precision (i.e., random errors) and accuracy (i.e., systematic errors) would provide key new insights into fundamental physics questions and lead to potentially revolutionary discoveries. These include the nature of dark energy and its evolution, the curvature of the Universe as a test of inflationary models, the mass of neutrinos and the total number of families of relativistic particles (e.g., Freedman & Madore 2010, Riess et al. 2011, Weinberg et al. 2012, Reid et al. 2010, Sekiguchi et al. 2010). For example, Figure 1 (extracted from Weinberg et al. 2012) illustrates the dependence of the Figure of Merit (FoM, for dark energy parameterized by $w(a) = w_p + w_a(a_p - a)$), introduced by the Dark Energy Task Force (DETF; Albrecht et al. 2006), on the accuracy of additional measurements of the Hubble constant that would be used as a prior in Stage III and Stage IV experiments. In all cases, adding a prior from an independent measurement of $H_0$ with accuracy that matches the uncertainty one would have in the

\textsuperscript{†} More details of the workshop are given at the website: http://web.physics.ucsb.edu/~suyu/H0KIPAC/Home.html
absence of the prior (1.3% for Stage III, and 0.7% for Stage IV) increases the FoM by \(\sim 40\%\). Measuring \(H_0\) therefore raises the value of current Stage III and future Stage IV experiments for relatively small incremental cost. In an unparameterized model of \(w\) (e.g., in redshift bins), Stage IV Cosmic Microwave Background (CMB), Baryon Acoustic Oscillation (BAO), Supernovae (SN) and Weak Lensing (WL) surveys will only constrain \(H_0\) to \(\gtrsim 10\%\) (Weinberg et al. 2012); thus an independent measurement of \(H_0\) provides the only knowledge of the Hubble constant. This highlights that probes at \(z > 0\) (e.g., CMB and BAO) do not measure \(H_0\); they provide derived \(H_0\) constraints only within a given and well-specified cosmological model. In addition, accurate determinations of distances to objects that are needed for local \(H_0\) measurements provide an invaluable opportunity to learn about gravitational physics of an inhomogeneous Universe. Therefore, a 1% measurement of \(H_0\) in combination with higher redshift probes provides a fundamental test of the foundations of cosmological models, including possible departures from general relativity.

**Figure 1.** Dependence of the FoM from the DETF on the accuracy of independent measurements of the Hubble constant that would be used as priors in Stage III and IV forecasts from Weinberg et al. (2012). The fiducial Stage IV program with FoM = 664 is marked by an open circle. In all cases, adding a prior from an independent measurement of \(H_0\) with \(\sim 1%\) accuracy increases the FoM by \(\sim 40\%.\) The figure was extracted from Weinberg et al. (2012).

**How can we achieve 1% precision and accuracy?** The value of \(H_0\) has long been controversial because of many systematic effects in any given method that need to be understood, controlled and quantified. Nonetheless, similar to the much better publicized advances in measuring \(\Omega_m\) and \(\Omega_\Lambda\), “precision cosmology” has taken place in measuring \(H_0\) as observations improve, errors are controlled and independent methods are employed. We critically assessed the following range of methods at the workshop, focusing on their strengths, weaknesses and prospects for measuring \(H_0\) to 1%; Cepheids, Tip of the Red Giant Branch (TRGB), Type Ia Supernovae, Surface Brightness Fluctuations (SBF), Masers, and Gravitational Lens Time Delays. Recent reviews on these topics can be found in Freedman & Madore (2010), Ud (2005), Treu (2010), and Weinberg et al. (2012). All of these methods currently measure \(H_0\) to within 10%, finding it to be in the range 68 to 79 km s\(^{-1}\) Mpc\(^{-1}\), a remarkable consistency given the well-known history of this constant (e.g., Riess et al. 2011; Freedman et al. 2011; Hislop et al. 2011; Mager et al. 2008; Blakeslee et al. 2010; Braatz et al. 2010; Suyu et al. 2010). Advances in reconstructing peculiar velocities (e.g., Lavaux et al. 2010) should help reduce the uncertainties in future local measurements of \(H_0\).

We summarize the current status of each method below.

- Recent progress in observing Cepheids in the infrared leads to 0.1 mag dispersion (5% in distance) for a single Cepheid. A 1% \(H_0\) measurement should be achievable in
principle from this technique, and requires a reduction of uncertainties due to crowding and metallicity of stars together with an increase in the number of calibrators.

- TRGB can measure 0.1 mag (5% in distance), which appears to be the limit in accuracy. This approach is restricted to nearby galaxies and provides a valuable independent check of Cepheids.
- Infrared observations of SN Ia yield distances with 10% precision. These in combination with Cepheid and maser distances lead to a ~3% measurement in $H_0$ [Riess et al. 2011]. The biggest challenge for improvement is the slow increase in the number of calibrators nearby enough to detect Cepheids in the host (one every 2–3 years). Future work to reduce the uncertainty to 1% includes characterizing the population, studying the dependence in metallicity and understanding the theory of SN Ia explosions.
- Recent SBF study by Blakeslee et al. (2010) suggests a scatter of only 1.5% in distance for a small sample; the approach is promising but requires more study to quantify biases and systematics.
- There are currently ~10 known maser galaxies whose geometric distances can be measured at the ~10% level. An updated distance measurement to NGC 4258 with 2.5% precision was presented. Getting to the 1% level in $H_0$ would need both discovery of more systems (NGC 4258 is unfortunately a rare nearby system), which would be challenging before the SKA, and better modeling/understanding of disk physics. A factor of ~2 reduction in uncertainty for NGC 4258 and an identification of a second NGC-4258-like maser in a galaxy with detectable Cepheids are both valuable as they would advance calibrations of other indicators.
- Gravitational lens time delays can measure time-delay distances to ~5% for a single lens system. The distance is primarily sensitive to $H_0$, and the 5% translates to ~7% in $H_0$ assuming uniform prior distributions of $\Omega_\Lambda$, $w$, and $H_0$. A comparison of multiple systems is crucial to test for any residual systematic errors in the correction of the line of sight effects. There are currently tens of time-delay lenses from Cosmograil, and future samples of hundreds make 1% an achievable goal when systematics are under control.

We also investigated CMB and BAO, both of which do not measure directly $H_0$, but can predict it within the context of a model. Upcoming CMB data (e.g., from Planck) should be able to break the degeneracy between the number of relativistic neutrino species and $H_0$ that is present in current CMB data. However, an independent measurement of $H_0$ is needed to extract from the CMB information on dark energy and spatial curvature of the Universe. BAO provides a standard ruler on the sky, but will be limited by cosmic variance at low $z$. Measurements of $D_A$ and $H(z)$ at ~1% in various bins of $z$ appear feasible with current and planned large-scale BAO surveys (e.g., BOSS and BigBOSS). Independent analyses using different approaches by separate groups and independent galaxy samples probing various galaxy populations are needed to offer consistency checks and tests for any unknown systematic uncertainties. We also examined differential ages of cosmic chronometers (old passive elliptical galaxies) as a probe of $H(z)$. At present, this technique produces measurements of $H$ at $z \sim 0$ with a 6% uncertainty and of $H(z)$ up to $z \lesssim 1$ with a ~13% uncertainty. It remains to be explored if the method can achieve 1% in accuracy with targeted data.

Concluding Remarks

All approaches can gain by both developing novel analysis techniques and increasing the sample size (though the $\sqrt{N}$ gain is only obtained when systematics are under control). A good physical understanding is highly desirable for all methods (progenitors of

† COSmological MOonitoring of GRAvItational Lenses
supernovae, structure/dynamics of water masers, etc.). As most of the methods are limited by systematics, it becomes ever more important to provide rigorous error budgets for each approach, make data available to others, and perform cross checks via, e.g., public challenges and blind tests that would substantiate the independence. Furthermore, several distance indicators with comparable 1% precision are required to provide a robust estimate of $H_0$ to 1% accuracy. Each of the above-mentioned methods is currently worth pursuing, and extensive work is needed in the next several years to beat down the systematics to these levels; it is not clear that all methods will achieve it. The multiple paths of independent $H_0$ determination are crucial for understanding whether the current indications of tension between direct local measurements of $H_0$ and BAO/CMB are signaling new physics.

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