Astrophysical Masers:
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Progress toward an accurate Hubble Constant

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Abstract. The Hubble constant is a key cosmological parameter that sets the present-day expansion rate as well as the age, size, and critical density of the Universe. Intriguingly, there is currently a tension in the measurements of its value in the standard flat ΛCDM model – observations of the Cosmic Microwave Background with the Planck satellite lead to a value of the Hubble constant that is lower than the measurements from the local Cepheids-supernovae distance ladder and strong gravitational lensing. Precise and accurate Hubble constant measurements from independent probes, including water masers, are necessary to assess the significance of this tension and the possible need of new physics beyond the current standard cosmological model. We present the progress toward an accurate Hubble constant determination.

Keywords. gravitational lensing, masers, (cosmology:) cosmic microwave background, (cosmology:) cosmological parameters, (cosmology:) distance scale

1. Introduction

The standard cosmological model "flat ΛCDM", consisting of dark energy (with density characterized by a cosmological constant Λ) and cold dark matter (CDM) in a spatially flat Universe, has emerged in the past decade. This simple model has yielded excellent fit to various cosmological observations, including the temperature anisotropies in the cosmic microwave background (CMB) and galaxy density correlations in baryon acoustic oscillations (BAO). Recent CMB experiments, particularly the Wilkinson Microwave Anisotropy Probe (WMAP; Komatsu *et al.* 2011, Hinshaw *et al.* 2013) and the Planck satellite (Planck Collaboration 2014, 2016), and BAO surveys (e.g., Anderson *et al.* 2014, Ross *et al.* 2015, Kazin *et al.* 2014) have provided stringent constraints on cosmological parameters in the flat ΛCDM model.

The Hubble constant (H_0) is a key cosmological parameter that sets the present-day expansion rate as well as the age, size, and critical density of the Universe. Intriguingly, Planck's value of $H_0 = 67.8 \pm 0.9\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Planck Collaboration 2016), from Planck temperature data and Planck lensing under the flat ΛCDM model, is lower than recent direct measurements based on the distance ladder, of $73.24 \pm 1.74\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Riess *et al.* 2016) and of $74.3 \pm 2.1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Freedman *et al.* 2012). Planck does not directly measure H_0, but rather enables its indirect inference through measurements of combinations of cosmological parameters given assumptions of the background cosmological model. On the other hand, Planck's H_0 value is similar to the results of some of the megamaser measurements (e.g., $H_0 = 68.9 \pm 7.1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from Reid *et al.* 2013, and $H_0 = 66.0 \pm 6.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from Gao *et al.* 2016).

A 1% *direct* measurement of the Hubble constant would help address the possible tension with the CMB value which, if significant, would point towards deviations from the standard flat ΛCDM and new physics. For example, when one relaxes the flatness or Λ assumption in the CMB analysis, strong parameter degeneracies between H_0 and other cosmological parameters appear, and the degenerate H_0 values from the CMB become compatible with the local H_0 measurements from the distance ladder (Planck Collaboration 2016, Riess *et al.* 2016). Thus, a 1% measurement of H_0 is important for understanding the nature of dark energy, neutrino physics, the spatial curvature of the Universe and the validity of General Relativity (e.g., Hu 2015, Suyu *et al.* 2012, Weinberg *et al.* 2013). For example, the dark energy figure of merit of any survey that does not directly measure H_0 improves by $\sim 40\%$ if H_0 is known to 1%.

In the following, we describe a few of the various ways of measuring the Hubble constant, and refer the readers to recent reviews on the Hubble constant for a more comprehensive overview.

2. Cosmic Microwave Background

The CMB radiation has a thermal black body spectrum, with small temperature fluctuations in different directions of the sky. The power spectrum of the CMB temperature anisotropies displays acoustic peaks, and the shape of the power spectrum provides information on our cosmological model.

In particular, the ratios of the peak heights, such as from the first three peaks, place constraints on $\Omega_{\rm m} h^2$ and $\Omega_{\rm b} h^2$ (e.g., Hu *et al.* 1997), where $\Omega_{\rm m}$ is the total matter density, $\Omega_{\rm b}$ is the baryon density, and h is the dimensionless parameter of the Hubble constant $H_0 = 100h\,{\rm km\,s^{-1}\,Mpc^{-1}}$. Without further model assumptions, one cannot extract h precisely as it is not directly constrained by the CMB observations and is thus degenerate with other cosmological parameters.

By assuming that our Universe is the standard spatially-flat 6-parameter ΛCDM cosmology, then the (angular) locations of the acoustic peaks allow the determination of the acoustic scale, θ_*, which is the ratio of the comoving size of the sound horizon at the time of last-scattering ($r_{\rm s}$) and the angular diameter distance at which we are observing the fluctuations ($D_{\rm A}$), i.e., $\theta_* = r_{\rm s}/D_{\rm A}$. Since $D_{\rm A}$ and $r_{\rm s}$ depend on cosmological model parameters, the measurement of θ_* places tight constraint on the following combination of parameters:

$$\Omega_{\rm m} h^{3.2} (\Omega_{\rm b} h^2)^{-0.54} \tag{2.1}$$

(e.g., Percival *et al.* 2002, Planck Collaboration 2014).

By combining equation (2.1) with the $\Omega_{\rm m} h^2$ and $\Omega_{\rm b} h^2$ constraints, the Planck Collaboration obtained a precise measurement of the Hubble constant of $h = 0.678 \pm 0.009$ (Planck Collaboration 2016). We stress that this assumes the flat ΛCDM model (for which equation (2.1) is derived), and the value of H_0 from the CMB changes markedly when the assumption of the flat ΛCDM model is relaxed.

3. Megamasers

Water masers in orbit around an active galactic nucleus (AGN) provide a geometric approach to measuring the Hubble constant. By observing the Doppler shifts in the maser lines, one could measure the velocity $v_{\rm r}$ of the masers in orbit around the AGN, and also their angular positions $\theta_{\rm r}$ from the central AGNs. Furthermore, by observing the change in velocities of the "systemic masers" (which are the masers located in front of the AGN for nearly edge-on maser disks), the acceleration $a_{\rm r}$ could be determined. This provides a measurement of the physical size of the disk r, since $a_{\rm r} = v_{\rm r}^2/r$. This physical size could then be compared to the angular size, to derive the angular diameter distance to the maser: $D = r/\theta_{\rm r} = v_{\rm r}^2/(a_{\rm r}\theta_{\rm r})$. Through the distance-redshift relation, the angular diameter distance then provides a measurement of H_0.

The Megamaser Cosmology Project (MCP) aims to determine H_0 precisely via measurements of geometric distances to galaxies in the Hubble flow. The Hubble constant based on the analysis of four megamaser galaxies in the MCP is $H_0 = 69.3 \pm 4.2\,{\rm kms^{-1}\,Mpc^{-1}}$, from UGC 3789 with $H_0 = 76 \pm 8\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (Reid *et al.* 2013 with updates), NGC 6264 with $H_0 = 68 \pm 9\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (Kuo *et al.* 2013), NGC 6323 with $H_0 = 73 \pm 26\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (Kuo *et al.* 2015) and NGC 5765b with $H_0 = 66 \pm 6\,{\rm km\,s^{-1}\,Mpc^{-1}}$ (Gao *et al.* 2016). There are several more megamaser galaxies in the MCP sample that are being analysed. We refer to the contributions by J. Braatz for more details on the MCP.

4. Extragalactic Distance Ladder

The distance ladder has provided precise measurements of the Hubble constant. In fact, it was the method used in the *Hubble Space Telescope* (*HST*) Key Project that yielded the Hubble constant with 10% uncertainty (Freedman *et al.* 2001), resolving the "factor-of-two" controversy in the Hubble constant that lasted decades.

By measuring distances (d) to faraway objects in the Hubble flow (where peculiar velocities are negligible) and also their recessional velocities (v) via redshifts, the Hubble constant can be inferred through Hubble's law $v = H_0 d$. However, distance measurements to such faraway objects are difficult to obtain directly. Thus, a practical approach is to measure absolute distances to nearby objects (e.g., through parallax), and then use methods to measure relative distances (such as supernovae) to further away objects. This builds a "ladder" to obtain distances to faraway object in the Hubble flow.

In the Carnegie Hubble Program, Freedman *et al.* (2012) calibrated the Cepheid distance scale using mid-infrared observations. Combining this with data from the *HST* Key Project, Freedman *et al.* (2012) obtained $H_0 = 74.3\,{\rm km\,s^{-1}\,Mpc^{-1}}$ with a systematic uncertainty of $\pm 2.1\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

In the SH0ES program, Riess *et al.* (2016) more than doubled the sample of reliable Type Ia supernovae (SNe Ia) having a Cepheid-calibrated distance, allowing a reduction in the systematic uncertainties in the H_0 measurement. Using the distance measurement to the maser galaxy NGC 4258, Cepheids in the Large Magellanic Cloud, the Milky Way and M31, and ~ 300 SNe Ia at $z < 0.15$, Riess *et al.* (2016) obtained $H_0 = 73.24 \pm 1.74\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

As an alternative to the traditional Cepheids distance ladder, Beaton *et al.* (2016) are carrying out the Carnegie-Chicago Hubble Program with the goal of reaching a 3% measurement of H_0. This distance ladder uses RR Lyrae variables, the tip of the red giant branch and SNe Ia, providing an independent cross-check of the traditional Cepheids distance ladder.

5. Strong lensing time delays

Strong gravitational lensing occurs when there is a chance alignment of a massive object along the line of sight to a background source. The light from the background source gets deflected by the gravitational field of the foreground object such that multiple distorted images of the background source appear around the foreground lens. When the source is one that varies in its luminosity, such as an activie galactic nucleus or supernova, the variability of the source manifests in each of the multiple images but delayed in time due to the different light paths (e.g., Vanderriest *et al.* 1989, Kochanek *et al.* 2006, Courbin *et al.* 2011).

Strong gravitational lenses with measured time delays between the multiple images provide a competitive approach to measuring the Hubble constant, completely independent of the distance ladder (Refsdal 1964). The time delay (Δt) depends on the "time-delay distance" ($D_{\Delta t}$) and the lens mass distribution. This time-delay distance is a combination of the three angular diameter distances in lensing (observer-source distance $D_{\rm s}$, observer-lens distance $D_{\rm d}$, and lens-source distance $D_{\rm ds}$). As a result, $D_{\Delta t}$ is inversely proportional to H_0 and depends weakly on other cosmological constants. In addition to $D_{\Delta t}$, the angular diameter distance to the lens $D_{\rm d}$, which is more sensitive to dark energy parameters, can be extracted from the lens system if the velocity dispersion of the foreground lens galaxy is measured and combined with the time delays (Jee *et al.* 2015).

The H0LiCOW collaboration (Suyu *et al.* 2017) obtained exquisite imaging and spectroscopic observations on 5 lensed quasars with time delays from the COSMOGRAIL collaboration (e.g., Courbin *et al.* 2011, Tewes *et al.* 2013) and radio monitoring (Fassnacht *et al.* 1999, 2002). Using the time-delay monitoring/measurements (Bonvin *et al.* 2017), lens environment studies with wide-field imaging and spectroscopy (Rusu *et al.* 2017, Sluse *et al.* 2017), and lens mass modeling with *HST* observations, Wong *et al.* (2017) measured the time-delay distance to the lens system HE0435−1223 with a precision of 7.6% via a blind analysis. Combining this with two other time-delay distance measurements (to B1608+656 and RXJ1131−1231; Suyu *et al.* 2010, 2013, 2014) and considering flat ΛCDM cosmology, Bonvin *et al.* (2017) measured $H_0 = 71.9^{+2.4}_{-3.0}\,{\rm km\,s^{-1}\,Mpc^{-1}}$. In addition, the exquisite data sets obtained on the H0LiCOW lenses allow studies of the lens galaxies and quasars, including the connection between black holes and their host galaxies (Ding *et al.* 2017a, 2017b).

There are two more lenses in the H0LiCOW sample that are currently being analyzed. Four more with time delays from COSMOGRAIL are getting follow-up observations. Wide-field imaging surveys including the Dark Energy Survey (Dark Energy Survey Collaboration 2005, 2016) and the Hyper-Suprime Cam Survey (Aihara *et al.* 2017) are yielding new lensed quasar systems (e.g., Agnello *et al.* 2015, Lin *et al.* 2017, Ostrovski *et al.* 2017, Sonnenfeld *et al.* 2017), with the first one being monitored and its delays measured (Courbin *et al.* 2017). With hundreds of new lens systems expected from current and future surveys, a 1% measurement of H_0 from lensing time delays will be achievable (Jee *et al.* 2016, Shajib *et al.* 2017).

6. Summary

Stakes are high to assess the significance of the current tension in the H_0 values from some of the cosmological probes. Independent methods to measure H_0 with 1% precision and accuracy are necessary to overcome systematic effects for verifying or falsifying the standard cosmological paradigm.

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