The measurement of the Hubble Constant: beyond the cosmic ladder

Z0962251
Submitted: 17th March 2019

A precisely determined Hubble's constant H_0 would have an overarching effect on any feature of cosmological theory, from the age or critical density of the Universe to cosmic structure formation. Producing a conclusive value for H_0 is difficult as absolute distances on the cosmic scale are difficult to measure. Inhomogeneous gravitational acceleration generates motions which do not follow the simple expansion described by Hubble's Law $v = H_0 d$. An uncertainty arises due to the discrepancy between the methods which connects local distances to the smooth large-scale Hubble flow (Fukugita et al. 1993).

Several approaches for cosmic distance measurement should be utilised to reduce systematic errors. These measurements form the "rungs" of a *cosmic distance ladder*, where large extragalactic distances ($>$ 1000 Mpc) are informed and calibrated by techniques with smaller ranges (Carroll and Ostlie 2007). Astronomers often employ a variety of methods in tandem, therefore the ladder could instead be expressed as several pathways (Figure 1).

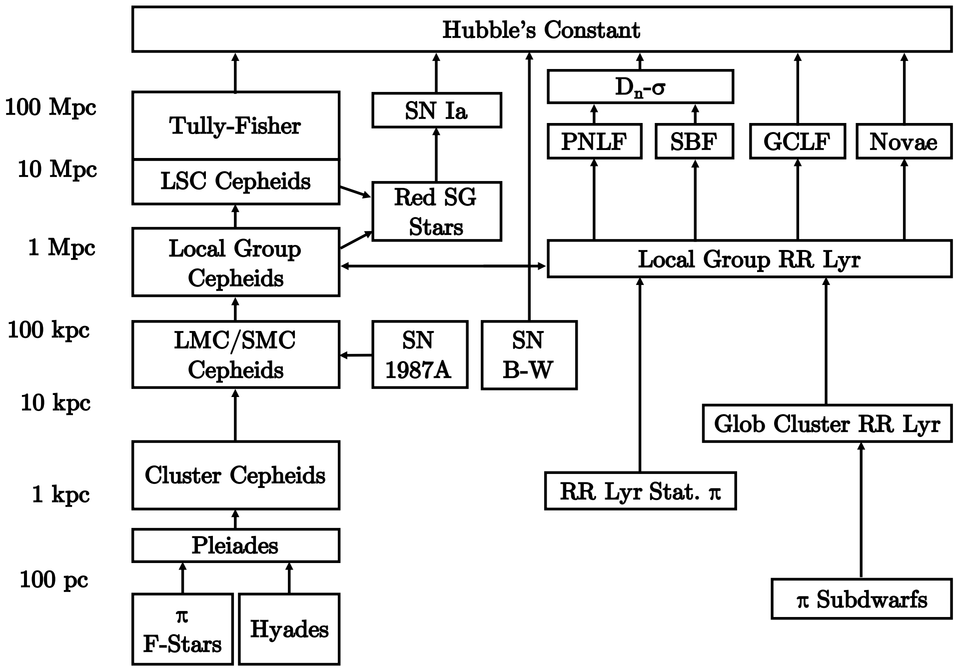

Figure 1: Adapted from Jacoby et al. (1992), this diagram illustrates the various approaches to calculate H_0, each technique is roughly placed at the approximate range it operates at. One can see that there is not one strict "cosmic ladder", rather multiple pathways to achieve H_0. For reference, the acronyms used are: B-W - Baade-Wessenlink; GCLF - Globular-Cluster Luminosity Function; LSC - Local Super Cluster; PNLF - Planetary Nebula Luminosity Function; SBF - Surface-Brightness Fluctuations; SG - Super Giant; SN - Supernovae; π - parallax.

The Hubble Space Telescope (HST) H_0 Key Project was an effort in the early 2000s to determine H_0 by calculating distances to Cepheid variables in local galaxies ($\leq$ 20 Mpc) which were then applied as a calibration to 5 secondary independent distance indicators. Described by Freedman et al. (2001), four of the methods (Type Ia supernovae, Tully-Fisher relation, surface-brightness fluctuations, and Type II supernovae) were able to produce $70 \leq H_0 \leq 72$ km s^{-1} Mpc^{-1} and the remaining technique (fundamental plane for elliptical galaxies) $H_0 \approx 82$ km s^{-1} Mpc^{-1}. Over the next decade, the methodology would be refined and the sample of Cepheids and Type Ia supernovae improved (better observations) so $H_0 = 73.48 \pm 1.66$ km s^{-1} Mpc^{-1} (Riess et al. 2018, 2011, 2016). These results set a standard benchmark for H_0 as they were found by stepping along the cosmic ladder, but whilst they are precise results, it would be beneficial to directly calculate H_0 at large distances without the need for Cepheid-based calibrations.

An alternative is measuring Cosmic Microwave Background (CMB) anisotropies. Through analysing all-sky temperature and polarisation maps, ΛCDM cosmology models can be fitted to constrain cosmological parameters. Surveys of the CMB have included those performed by the spacecraft COBE, WMAP, and more recently, Planck. The results of the latter, $H_0 = 67.5 \pm 0.5$ km s^{-1} Mpc^{-1} (Planck Collaboration et al. 2018), is important as it is discrepant when compared to the HST-based value (Riess et al. 2018). Investigations of potential systematics in either methods have concluded that some arise due to the modelling of the Cepheids (Follin and Knox 2018) and that there are residual systematics from certain spectra used in the Planck likelihood calculation (Spergel et al. 2015). However the tension between the H_0 values still exists, therefore other techniques should still be explored and tested.

Considering the Sunyaev-Zel'dovich effect (SZE), this leads to a change in the apparent brightness of the CMB towards a cluster of galaxies or for any reservoir of hot plasma (Birkinshaw 1999, Carlstrom et al. 2002). Combined with X-ray emissions from intracluster gas, the SZE can be used as a tracer for cosmological parameters. Birkinshaw (1999) describes the technique as a comparison of the angular size of a galaxy cluster with the measure of the line-of-sight size of the cluster. With spectra data at hand, the emission of the gas in a galaxy cluster can be described by the X-ray surface brightness, and the gas absorption by the measurement of the thermal SZE (an intensity change). The surface brightness and intensity change can be re-expressed in terms of physical constants and angular structure factors, this then leads to a single expression for calculating the angular diameter distance,

$$d_A = \left(\frac{N_{SZ}^2}{N_X}\right)\frac{\Lambda_{e0}}{4\pi(1+z)^3[I_0\Psi_0\sigma_T]^2}. \tag{1}$$

The full derivation and definitions for Equation 1 can be found in Holzapfel et al. (1997).

Employing this equation with cluster redshifts z and the deceleration parameter q_0, H_0 can be obtained in a direct and alternate way which is independent of the distance estimation chain. The South Pole Telescope Sunyaev-Zel'dovich (SPT-SZ) survey was a programme which made use of the SZE to detect galaxy clusters (Chang et al. 2009). Multiple analyses have been performed to constrain cosmological parameters using the SPT-SZ datasets, the majority of which tested variations of the ΛCDM model (de Haan et al. 2016, Hou et al. 2014). Hou et al. (2014) examined models which were constraining single or double parameters such as the neutrino mass. They combined external data sets (WMAP7, BAOs, previous H_0 calibrations) with their own and achieved $H_0 = 68.3 \pm 1.0$ km s^{-1} Mpc^{-1} which agrees with HST and Planck results.

The CMB can thus be utilised in multiple ways to calculate H_0. In a similar vein, gravity effects can be explored and employed to measure the constant without the need of the cosmic ladder. The two most important effects manifest in the form of gravitational lensing and gravitational waves, and through a combination of multiple methods, one can obtain a highly accurate and precise value for H_0.

Optical observations of the night sky may sometimes reveal arcs of light surrounding a central object. This effect is known as *gravitational lensing* and it occurs when light travelling towards us from a distant bright object (a quasar) is curved by the space-time of a much massive object (a galaxy cluster or hypothetical MACHOs) in the foreground which lenses and arcs the light (Carroll and Ostlie 2007). If the initial source, such as an active galactic nucleus or a supernova, varies in luminosity then this variability can be viewed in the arcs, albeit with time delays as the light takes different paths (Suyu 2017). This time delay can be related to the lens mass distribution and the "time-delay distance" $D_{\Delta t}$, where $D_{\Delta t}$ is the multiplicative combination of three angular diameter distances: observer-source distance D_s, observer-lens distance D_d, and lens-source distance D_{ds} (Shajib et al. 2018, Suyu 2017). The application to cosmology arises as $D_{\Delta t}$ is inversely proportional to H_0 plus weakly dependent on other cosmological constants.

Koopmans et al. (2003) presents mass models which were developed to reduce known systematics such as the radial mass profile, dust extinction, etc. Three particular mass models (SIE, SPLE1, SPLE2) were tested which considered only the gravitational lensing constraints and so examined no stellar dynamics. This resulted in H_0 ranging from 71–74 km s^{-1} Mpc^{-1} and a best value of $H_0 = 74^{+10}_{-11}$ km s^{-1} Mpc^{-1}. It is clear that whilst the uncertainties are large, the general H_0 value agrees with the Cepheid/Planck results. Introducing additional constraints would improve the precision, Courbin et al. (2011) demonstrates that parameters such as the baryonic fraction in the Einstein radius and the velocity dispersion of the lensing galaxy could be found by combining spatially deconvolved HST F160W images with VLT spectroscopic data, hence further constraining the results.

Gravitational lensing is therefore a highly viable method in the measurement of H_0. However it has the limitation of requiring long-periods of photometric observations to observe the time delays. A more suitable strategy would be to utilise gravitational waves as a standard siren as observatories have been purposely built for their detection. Waves originating from the decaying orbit of an ultra-compact, binary neutron star system would be the most likely to be registered by Earth based detectors (Schutz 1986).

LIGO Scientific Collaboration et al. (2017) describes their approach used to calculate H_0 for object GW170817 detected by the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) (LIGO Scientific Collaboration et al. 2015) and the Virgo detector (Acernese et al. 2015). The gravitational wave (GW) data is used to infer the distance d to the source through constraining a posterior probability in a Bayesian framework model. An initial posterior distribution for the observed data x_{GW} can be converted into a posterior on the inclination angle $\cos i$ and $H_0 = v_H/d$, where v_H is the Hubble flow velocity. $\cos i$ is important as it was found that d is strongly correlated with the inclination of the binary orbital plane. Obtaining v_H for the source, the host galaxy's measured recessional velocities can be corrected for local peculiar motions. Together, this method does not require the Hubble flow velocities of any local calibrating galaxies which have been estimated using the distance ladder.

Applying $v_H = 3017 \pm 166$ km s^{-1} to the model produces a maximum a posteriori value of $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1} which is consistent with the known results. The precision of the GW method could be improved by employing more detectors in the observation network. KAGRA is a Japanese GW telescope which is currently under construction, it features cryogenic cooling and it is based underground (Akutsu and collaboration 2015), both of these will reduce the thermal and seismic noise therefore improving the data signal-to-noise ratio. Alternatively, the precision could be refined by simply incorporating alternative data-sets. Recent work by Hotokezaka et al. (2018) demonstrates that the uncertainty in the LIGO Scientific Collaboration et al. (2017) H_0 value is dominated by the degeneracy in the GW signal between the source distance and the "weakly constrained" viewing angle. They provide an alternative analysis which makes use of a collection of radio images for GW170817's superluminal jets to restrict the inclination angle. Employing analytical modelling, full hydro-dynamic numerical simulations and semi-analytic calculations of synthetic jet models, the new constraints resulted in an improved measurement of $H_0 = 68.9^{+4.7}_{-4.6}$ km s^{-1} Mpc^{-1}.

Method	$\boldsymbol{H_0}$ **(km s^{-1} Mpc^{-1})**
HST Key Project with Cepheids+secondary	73.48 ± 1.66
Planck observations of the CMB	67.5 ± 0.5
Sunyaev-Zel'dovich Effect and SPT-SZ data	68.3 ± 1.0
Gravitational lensing and mass modelling	74^{+10}_{-11}
Gravitational waves with LIGO and Virgo	$70.0^{+12.0}_{-8.0}$
Gravitational waves plus radio data for jets	$68.9^{+4.7}_{-4.6}$

Table I: Summarised results from the various methods used to calculate Hubble's Constant. All values are in general agreement, however there is tension between the results found from Cepheid calibrated values and the CMB Planck results. The alternative methods appear to support the Planck value for H_0.

In conclusion, this discussion has detailed three alternative methods which can be used to measure Hubble's constant H_0 without the need to climb the cosmic ladder in the local Universe. Exploiting and measuring the Sunyaev-Zel'dovich effect, gravitational lensing, and gravitational waves leads to accurate values for H_0 which agree with those found with the traditional standard candle techniques. If used in tandem, one could potentially produce an extremely accurate and precise H_0 value. Measuring Hubble's constant beyond the cosmic ladder is a promising field of research and with more observations and analysis there is no doubt that eventually a single unifying value for H_0 will be found.

Final word count: 1487

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