The measurement of the Hubble Constant: beyond the cosmic ladder

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

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

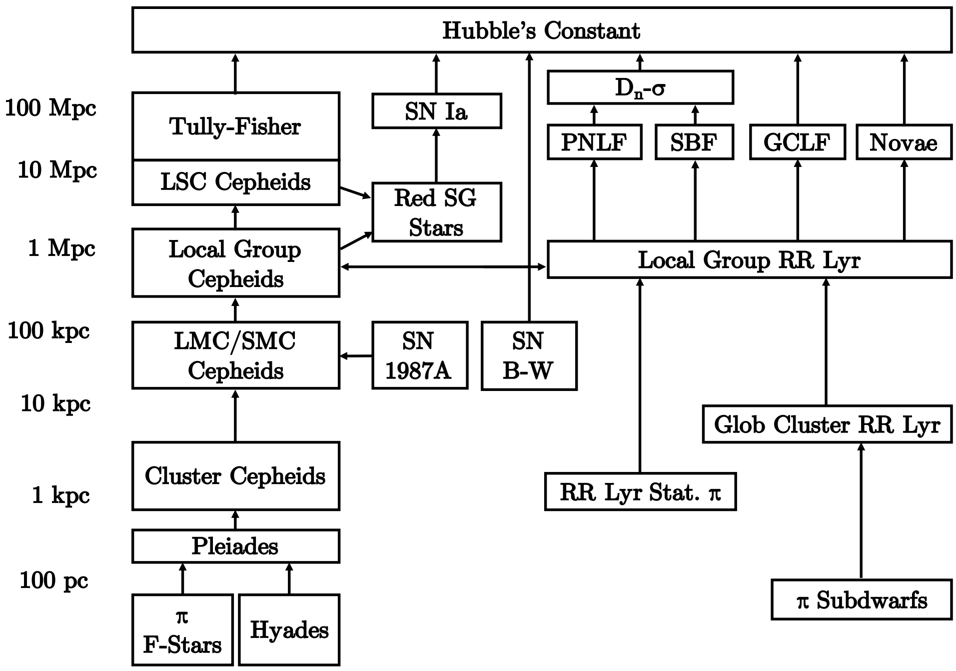

Figure 1: Adapted from Jacoby et al. (1992), this diagram illustrates the various approaches to calculate H_0, each technique is roughly placed at the approximate range it operates at. One can see that there is not one strict "cosmic ladder", rather multiple pathways. For reference, the acronyms used 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) then applying them 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 $70 \leq H_0 \leq 72$ kms^{-1} Mpc^{-1} and the remaining technique (fundamental plane for elliptical galaxies) $H_0 \approx 82$ kms^{-1} Mpc^{-1}. Over the next decade, the methodology would be refined and the sample of Cepheids and Type Ia supernovae improved (better observations and other data types) $H_0 = 73.48 \pm 1.66$ kms^{-1} Mpc^{-1} (Riess et al. 2018, 2011, 2016). These results set a standard benchmark for H_0, they were found by taking steps along the cosmic ladder and whilst they have high accuracy, it would be beneficial to directly calculate H_0 at large distances without the need for Cepheid-based calibration.

One alternative is measuring Cosmic Microwave Background (CMB) anisotropies. Through analysing all-sky temperature and polarisation maps, ΛCDM cosmology models can be fitted which 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 include $H_0 = 67.5 \pm 0.5$ kms^{-1} Mpc^{-1} (Planck Collaboration 2018), this is of particular importance as it is discrepant when compared to the most recent HST-based result (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 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 it would be beneficial to explore other methods for calculating the constant.

Still considering the CMB, the Sunyaev-Zel'dovich effect (SZE) 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 emission from intracluster gas, the SZE can be used as a tracer for cosmological parameters. Birkinshaw (1999) describes the technique to be a comparison of the angular size of a galaxy cluster with a measure of the line-of-sight size of the cluster. With spectra data at hand, the emission of 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 final equation with values for cluster redshifts z and the deceleration parameter q_0, H_0 can be obtained in this direct alternative way which is independent of the chain of distance estimators. The SPT-SZ is an instrument which makes use of the SZE to detect galaxy clusters (Chang et al. 2009). Multiple attempts have been made to constrain cosmological parameters using SPT-SZ datasets. In the work by de Haan et al. (2016) Hou et al. (2014)

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