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).

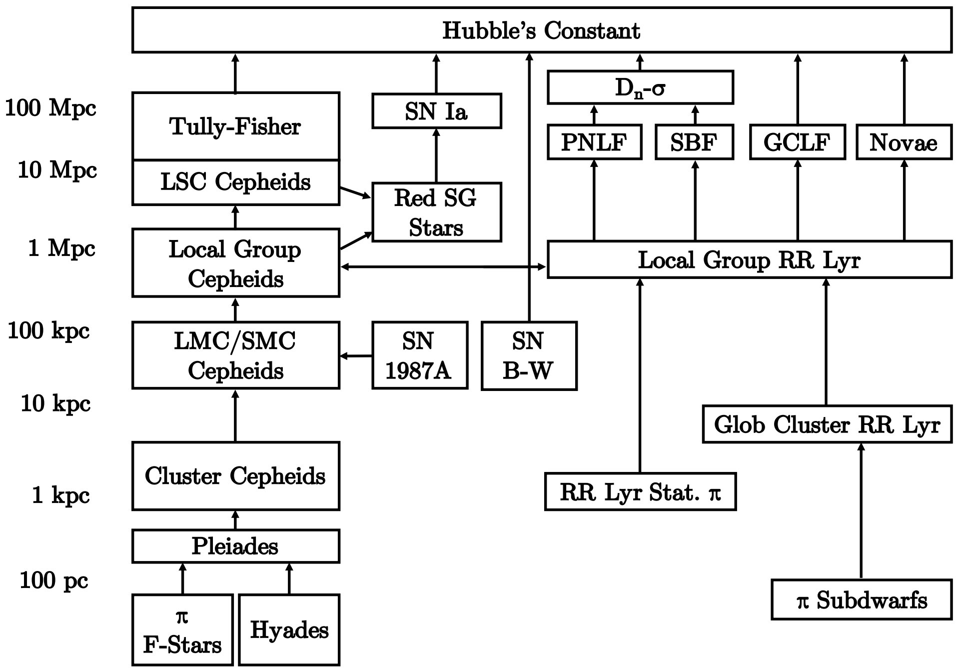

Figure 1: Adapted from Jacoby et al. (1992), this diagram illustrates the various approaches to calculate H_0, each technique is roughly placed at the approximate range it operates at. One can see that there is not one strict "cosmic ladder", rather multiple pathways. For reference, the acronyms used 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 temperature and polarisation maps, ΛCDM cosmology models can be applied 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) which 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 code (Spergel et al. 2015). However the tension between the H_0 values still exists, therefore it would be beneficial to explore other potential methods for calculating the constant.

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