DETERMINATION
OF
THE HUBBLE CONSTANT

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Introduction

Cosmology is a rapidly maturing field, and it is currently experiencing a healthy confrontation between theory and experiment. This rapid progress in many different areas of cosmology has not removed the longstanding interest in measuring many of the fundamental cosmological parameters: the expansion rate or Hubble constant, $H_0$, the average mass density of the Universe, $\Omega_0$, the age of the oldest objects in the Galaxy, $t_0$, and the issue of whether or not there is a non-zero value for the vacuum energy density, or cosmological constant, $\Lambda$. Rather, the increasingly detailed predictions of current theory call further attention to the critical importance of accurately measuring the cosmological parameters which define the basic model for the dynamical evolution of the Universe.

For instance, accurate knowledge of the Hubble constant is required to set the time and length scales at the epoch of equality of the energy densities of matter and radiation. In turn, the scale at the horizon plays a role in fixing the peak in the perturbation spectrum of the early universe and an accurate knowledge of the Hubble constant will allow a quantitative comparison of anisotropies in the cosmic microwave background and theories of the large-scale structure of galaxies. In addition, while a factor of two uncertainty persists in the determination of $H_0$, constraints on the density of baryons in the early Universe from nucleosynthesis are limited to that same factor of 2 uncertainty. Coupled with the current best estimates of the ages of the oldest stars in globular clusters in our Galaxy, a value of the Hubble constant at the high end of the range of values currently being published, would indicate a non-zero value for the cosmological constant, and therefore require new physics not predicted a priori in the current standard particle-physics-cosmology model. It is therefore imperative to improve the accuracy in the value of the Hubble constant and overcome the “factor-of-two” uncertainty that has persisted in this field for so long.

Primarily as a result of new instrumentation at ground-based telescopes, and most recently with the successful refurbishment of the Hubble Space Telescope (HST), the extragalactic distance scale field has been evolving at a rapid pace. For this reason, during the session on the Hubble constant, I chose not to debate many of the details that have been (historically) central to the controversy. Many of the disagreements that I have with Dr. Tammann are, in fact, based on the analysis and interpretation of data that are rapidly being superseded. To illustrate the kinds of issues involved for those outside the field, some examples of the areas of dispute in the published literature are listed below.

- The choice of methods for distance determination. For example, can photographic measurements of the angular diameters of spiral galaxies give distances to the required precision to distinguish between the currently debated values of $H_0$? Sandage (1993) recently concluded that $H_0 = 43 \pm 11$ km/sec/Mpc on this basis. However, there is no evidence that the angular diameters of spiral galaxies are good standard candles; in fact, the first test of this method with a determination of a Cepheid distance to M100, a spiral galaxy in the Sandage sample, yielded a distance a factor of almost 2 less than predicted by him on the basis of its angular diameter (Freedman et al., 1994).

- A dispute over the exact value of the recession velocity of the nearest massive cluster, the Virgo cluster. This topic could be debated ad infinitum, but it is clear that due to the proximity of this cluster, both its physically-extended nature, and an additional uncertainty due to its potential motion with respect to the cosmic microwave background frame, will preclude a determination of $H_0$ to better that a precision of about ±20%. Few astronomers would disagree that the determination of $H_0$ to higher accuracy requires an extragalactic distance scale that extends at least an order of magnitude more distant than the Virgo cluster, and a calibration that is independent of the Virgo cluster distance. (Nevertheless, the distance to the Virgo cluster can provide an independent consistency check to ±20%.)

- Large (≥ 25%) scale errors in photographic photometry that was used (almost exclusively) until the 1980’s and, in some cases, continues until the present day (e.g., Cepheids: Tammann & Sandage 1968; Sandage 1983; Sandage and Carlson 1983; type Ia supernovae: Sandage and Tammann 1993; Sandage et al. 1994).

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Neglect of the effect of dimming due to dust within galaxies (e.g., Sandage 1983; Sandage 1988). Corrections for the effects of dust in addition to corrections for errors in the photographic photometry resulted in very large (in some cases, 40 - >100%) modifications to the distances to galaxies measured with Cepheids (e.g., Freedman & Madore 1993).

Historically, measuring accurate extragalactic distances has been enormously difficult; in retrospect, the difficulties have been underestimated and systematic errors have dominated. And still, the critical remaining issue is to identify and reduce any remaining sources of systematic error. Rather than delve into and debate the details of the historical difficulties in measuring $H_0$, during my talk I raised a number of general critical issues that need to be addressed (by practitioners on both sides of the “debate”) before this problem can be resolved satisfactorily.

1. What is required to measure an accurate value of $H_0$?

2. Given the wide range of $H_0$ values quoted in the current literature, is there any reason to believe that the situation has changed very much at all in the last couple of decades? From the perspective of someone working outside the field, with new (discrepant) values for the Hubble constant continually being published, it is a fair question to ask if any progress is being made.

3. Is a measurement of $H_0$ accurate to 10% feasible with current observational tools?

These three questions are considered in turn in Sections 2, 3, and 4, respectively.

What is required to measure an accurate value of $H_0$?

In principle, the answer to this first question is very simple: measure the recession velocities and the distances to galaxies at sufficiently large distances where deviations from the smooth Hubble expansion are small, and the Hubble constant follows immediately from the slope of the correlation between velocity and distance. In practice, however, the difficulty in measuring distances to galaxies has been longstanding, and unfortunately, the answer to this question is likely to vary amongst theorists and observers; moreover, any two observers are likely to hold different opinions about the accuracy of a given method. However, in a very broad sense, both observers and theorists would likely be satisfied with a method that:

- is based upon well-understood physics,
- operates well out into the smooth Hubble flow (velocity-distances greater than 10,000 km/sec),
- can be applied to a statistically significant sample of objects and be empirically established to have high internal accuracy, and
- be demonstrated empirically to be free of systematic errors.

The above list of criteria applies equally well to classical distance indicators as to other physical methods (in the latter case, for example, the Sunyaev Zel’dovich effect or gravitational lenses). Many distance indicators have had only an empirical basis; however, where there is an understanding of the physical mechanism, the residuals in an underlying correlation can be understood and perhaps corrected. At large distances, the uncertainties due to bulk flows and peculiar velocities become an insignificant component of the total error budget; unfortunately very few methods currently meet the second and third criteria. All methods require large, statistically significant samples. This is not yet the case for the Sunyaev Zel’dovich or gravitational lens methods, for example, where samples of only a few or 2 objects, respectively, are currently available. The last point, of course, (ideally) requires that several distance indicators meeting the first three criteria be available.
At the present time, an ideal distance indicator or other method meeting all of the above criteria does not exist, and measurement of $H_0$ as high as 1% accuracy is clearly a goal for the future. However, this brings us to questions number 2) and 3): what is the current status of the field, and is a value of $H_0$ accurate to 10% feasible with current observational tools? A brief review of recent progress is given in Section 3).

Lastly, the Hubble Space Telescope Key Project on the Extragalactic Distance Scale has been designed to measure $H_0$ to 10% accuracy. A review of the goals of this project will be given, and recent results presented in Section 4).

Progress Over the Last Decade

Dramatic progress has been made recently in measuring both absolute and relative distances. Moreover, quantitative comparisons of individual indicators allow numerous cross-checks and estimates of the external, in addition to internal, errors. Before 1980 the extragalactic distance scale was based almost entirely on photographic data with large photometric errors. With CCDs and near-IR arrays more accurate photometry has become available, with corrections for reddening, and tests for effects of metallicity now being feasible. Several new, independent methods for measuring relative distances have also been developed and tested extensively. These issues are discussed in more detail in other recent reviews (e.g., see the proceedings from the STScI May 1996 Symposium on the Extragalactic Distance Scale edited by Livio & Donahue 1997; van den Bergh 1994; Jacoby et al. 1992).

With the exception of a small number of independent methods for measuring $H_0$ applied at large distances (for example, the Sunyaev-Zel’dovich method for clusters or the gravitational lens time-delay method), most routes to the extragalactic distance scale rely on the calibration of an additional tier of (secondary) methods using the Cepheid period-luminosity relation (e.g., the type Ia supernovae, Tully-Fisher relation for spiral galaxies, or surface brightness fluctuations). In principle, the type II supernova expanding atmosphere method is independent of the Cepheid distance scale, but also may be calibrated by Cepheids as an external check on systematics. Other indicators (for example, the planetary nebula luminosity function (PNLF), and tip of the red giant branch (TRGB)) do not currently operate beyond the distance to the Virgo cluster, and hence need to be tied into other methods that can be applied at greater distances where peculiar velocities are a smaller component of the overall expansion velocity. Nevertheless, the PNLF and TRGB methods provide an essential check on the consistency of Cepheid-plus-other-distance methods in the range of overlap. Since the absolute scale of most current distance indicators is obtained using Cepheids, it is clearly imperative to eliminate significant systematic errors in the Cepheid distance scale.

Cepheid Distances to Galaxies

Significant progress in the application of Cepheid variables to the extragalactic distance scale has been made over the past decade or so. Many of the improvements have become possible due to advances in detector technology: in particular, the arrival of linear detectors sensitive over a broad range of wavelengths from the visible to the near-infrared (see the reviews by Madore & Freedman 1991; Jacoby et al. 1992; Freedman & Madore 1996). The discussion below briefly summarizes that given in Freedman & Madore (1996).

The areas where the most dramatic improvements have been made include:

1) Correction for significant (typically 0.5 mag) scale errors in the earlier photographic photometry.
2) Observations of Cepheids beyond the Magellanic Clouds at BVRI and in some cases, JHK wavelengths, enabling...
3) ... Corrections for interstellar reddening, and
4) Empirical tests for the effects of metallicity.

During his talk, Dr. Tammann stressed the remarkable consistency of the $H_0$ determinations undertaken by himself and Dr. A. Sandage over the past 20 years that yield a value of $H_0 = 55 \text{ km/sec/Mpc}$. This consistency is truly remarkable. The interested reader is referred to a discussion by Freedman & Madore (1993) of the changes to the local Cepheid distance scale over the period from 1974 to 1993. For example, for the nearby galaxies M31 and M33, the published (apparent blue) distance moduli changed by 1.24 mag (!) and 0.48 mag, respectively. In the case of M81, the distance was changed twice (by a factor of almost two) from 3.3 Mpc in 1974, to 5.8 Mpc in 1984, and back down to 3.6 Mpc in 1994. It is thus even more...
remarkable that despite these enormous (up-and-down) changes to the zero point of the Cepheid distance scale over this same 20-year period, the value of \( H_0 \) remained at 55.

In the subsequent two sections, the effects of reddening and metallicity on the Cepheid distance scale are discussed.

**Reddening**

Twenty years ago photoelectric BVI photometry for Magellanic Cloud Cepheids had been obtained by a number of authors (see Feast & Walker 1987; Madore 1985 for reviews). However, for more distant galaxies where generally only \( B \)-band photographic photometry was available, corrections were made only for *foreground* reddening, but not for reddening of the Cepheids internal to the parent galaxy under study (*e.g.*, Tammann & Sandage 1968; Sandage 1983, Sandage and Carlson 1983; however, see Madore 1976).

![Figure n6822, BVR photometry for Cepheids in NGC 6822. The filled triangle marks the true modulus = intercept of the fit at the origin \( 1/\lambda = 0.0 \) for \( E(B-V) = 0.21 \pm 0.03 \) mag (from Gallart & Aparicio 1996). The broken line is a fit of a standard Galactic extinction law to the data.](image.png)