COSMIC EXPANSION AND $H_0$:
A RETRO- AND PRO-SPECTIVE NOTE

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Attempts to measure extragalactic distances over the last 90 years are briefly described. It follows a short history of the discovery of the expansion of space. Reasons are discussed for the decrease of the Hubble constant from $H_0 \approx 500$ originally to $H_0 \lesssim 60$ at present. Remaining problems with Cepheids as local distance calibrators are outlined.

1 Introduction

The conquest of the third dimension beyond the Galaxy was one of the great challenges of the 20th century. It is not possible to do justice to its fascinating and complex history in a few pages. Much of the progress during the first half of the century was made at Mount Wilson. Insight into this part of the history is provided by Sandage (1995), and his forthcoming monograph “An informal history of the Mount Wilson Observatory (1904–1950)” will be the prime reference for the subject with all its ramifications into most fields of astronomy.

2 Early Galaxy Distances

The battle about the nature of the “nebulae” was still raging (cf. Fernie 1970) when the first attempts were made to measure the distances of individual galaxies. Five steps should particularly be remembered:

- Hertzsprung’s (1914) tragedy. He had determined the distance modulus of SMC from Cepheids to be $(m - M)_{SMC} = 20.3$ (115 kpc), roughly a factor 1.8 too large. According to the custom of the time he transformed the distance into a trigonometric parallax of $0''0001$, losing a factor of 10 during the process. While transforming the parallax into light years he lost another factor of ten. Thus his published distance of 3000 light years buried his sensational result.

- Shapley’s (1915; 1918) mistake. In the following year Shapley repeated Hertzsprung’s measurement. For various reasons he now obtained a Cepheid distance of only $(m - M)_{SMC} = 16.1$ (17 kpc), which he slightly increased in 1918 and which he could take as a confirmation of his conviction that all “nebulae” were part of his very large Galactic system.

- Lundmark’s (1920) insight: He was the first to recognize supernovae as a class distinct from novae. This explained the brightness of the “nova” 1885 in M31 and led him to
a modulus of \((m - M)_{M31} = 21.3\) (180 kpc). Still much too low the value could not be accommodated within even the wildest size estimates of the Galaxy. But the result had no influence on the “Great Debate”.

- Öpik’s [1921; 1922] ingenuity. He used the rotation velocity of M31 to determine the mass-to-light ratio of the galaxy and he broke the distance degeneracy of this value by adopting a very reasonable mass-to-light ratio of the Solar neighborhood. He obtained a stunningly good value of \((m - M)_{M31} = 24.5\) (750 kpc), which he decreased in the following year by a factor of 1.7. Öpik’s papers remained unnoticed.

- Hubble’s breakthrough in 1924. The discovery of several novae in “nebulae”, first by Ritchey (1917), stimulated the search for variability and led Hubble to the discovery of a Cepheid in M31 in 1923, — the first Cepheid beyond the Magellanic Clouds. At the meeting of the Association for the Advancement of Science in December 1924 he announced the discovery of several very faint Cepheids in M31. They proved that many of the nebulae are actually “island universes”, but the proof was not generally accepted for a while, because van Maanen’s (1923) unexplained measurement from proper motions of a detectable rotation of the spirals (for a possible explanation cf. Baade 1963) stood still in the way. Hubble published his Cepheid distance of M31 only in 1929a, after he had published the Cepheids in NGC 6822 (1925) and M 33 (1926).

3 The Emergence of Cosmic Expansion

The great paradigms are often introduced on humble paths. Did Slipher (1914) realize that his first – and subsequent – radial velocities of “nebulae” would be the stepping stone of modern cosmology? The first interpretations of the surprisingly large radial velocities were made under the impression of the de Sitter (1916, 1917) effect”, which was a correct, yet unphysical solution of Einstein’s field equation, predicting a change of the clock rate with the square of the distance \(r\) in a static Universe (Wirtz 1918, 1923; Stromberg 1923; Lundmark 1925). Lundmark wrote “the smaller and presumably more distant spirals have a higher space motion”, yet his ansatz \(v = ar + br^2 + c\) betrays his preoccupation with the de Sitter effect.

Lemaître (1927) was the first to combine observations with the theory of expanding space. Extrapolating Hubble’s Cepheid distances, he derived a value of what was to become known as the “Hubble constant” of \(H_0 = 627\) \([\text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}]\). A similar analysis of the observations led Robertson (1928) to imply a value of \(H_0 = 461\).

Hubble had used his Cepheid distances to calibrate the brightest stars \((M_{pg} = -6.3)\) and the mean luminosity of bright galaxies \((M_{pg} = -15.8)\; —\; \text{either value} \; 4^m - 5^m\; \text{too faint}\). In this way he extended his distance scale out to the Virgo cluster. Hubble (1929b) plotted his distances against Slipher’s radial velocities and derived a value of \(H_0 = 500\). This is generally considered as the discovery of the expanding Universe. But he was not sure what to make of his discovery and he commented: “...the relation may represent the de Sitter [clock] effect”. Considerable weight of Hubble’s solution hinges on four Virgo cluster members, which would nowadays be excluded because of their virial motions. Hubble was lucky that Slipher had not accidentally picked the bright Virgo spiral NGC 4569 with its negative radial velocity; this galaxy would have considerably confused his first Hubble diagram. But he knew already of M. Humason’s very large velocity of NGC 7619 (3800 km s\(^{-1}\)), and in the following years he extended the Hubble diagram in collaboration with Humason beyond 40 000 km s\(^{-1}\) (Humason 1936). It is curious that Hubble, while convincing the world of the expanding Universe with his brilliant book “The Realm of the Nebulae” (1936a), died with doubts on his mind about the expansion. They were based on his unsatisfactory counts of galaxies (Hubble 1936b; cf. Sandage 1995), and his last Hubble diagram
(1953) is commented “no recession factor applied”, i.e. he did not apply the full K-correction required in an expanding Universe (cf. Sandage 1955).

de Sitter (1930) extended the Hubble diagram to 7800 km s$^{-1}$ including new redshifts by F.G Pease and M. Humason. Hubble was outraged and took it as an undue competition. de Sitter used distances by Shapley, Lundmark, and Hubble as calibrators and galaxy diameters as distance indicators. His data imply a Hubble constant just short of 500. Having discarded his clock rate effect he proved deep insight into his result, still exceptional at the time, by writing: “The only acceptable explanation ... is by the inherent expanding tendency of space which follows from the solution ... of Einstein’s differential equations for the inertia field”. Any possibly remaining doubt about the expansion of space was dispelled (it took a Fritz Zwicky to remain reluctant) by the fundamental paper by Humason, Mayall, & Sandage (1956, known as HMS). The authors presented redshifts for 920 galaxies, objectively measured magnitudes, the first correct K-corrections, and a Hubble diagram of field galaxies as well as a tight Hubble diagram of clusters.

In the following years Sandage (e.g. 1972; Sandage & Hardy 1973; Sandage, Kristian, & Westphal 1976) started a vast program to extend and to tighten the Hubble diagram of brightest cluster members with the final goal to determine the deceleration parameter $q_0$. The program came to a halt when it become clear that (cluster) galaxies undergo luminosity evolution. But the results were decisive subsequent to the discovery of the large quasar redshifts which stimulated a mysticism, even among astronomers, which is now hard to understand.

We will return to the ultimate Hubble diagram of supernovae of type Ia in Section 8, which does not only lead to the large-scale value of $H_0$, but with considerable likelihood even to a combined value of $\Omega_M$ and $\Omega_\Lambda$.

4 The Stretching of the Distance Scale

Hubble (1936b) has decreased his 1926 distances, and it became increasingly clear that they had further to be decreased to account for Galactic absorption (cf. Table 3). But Hubble gave his 1936 distances to E. Holmberg as his preferred values still in 1950.

Yet Hubble’s distance scale was challenged by Behr (1951). He noticed the large luminosity scatter of Local Group galaxies and he argued via the Malmquist effect that Hubble’s mean luminosity was too faint by $\sim 1^{m}$ 5 if applied to more distant, magnitude-selected galaxies. (This is to our knowledge the first mentioning of Malmquist statistics in extragalactic work; cf. Section 7). Citing Baade (1944) he also corrected Hubble’s magnitudes by $0^{m}$ 35 (at $18^{m}$ 3). These were Behr’s two main reasons for deriving a value of $H_0 = 260$. He would have found an even smaller value had he known of Stebbins, Whitford, & Johnson’s (1950) pioneering photoelectric photometry which proved Hubble’s photometric scale error to be even larger.

The revision received much more weight when Baade (1952) announced that work in M 31 had shown, that either the zero point of the Cepheids or of the RR Lyr stars must be in error. Since Sandage’s (published 1953) color-magnitude diagram of M 3 had shown that the RR Lyr stars are correct, the Cepheid luminosities had to be increased, as Mineur (1945) had already suggested. Baade concluded that “previous estimates of extragalactic distances ... were too small by as much as a factor of 2”, which led him to $H_0 \sim 250$.

Accounting for the first four years of research with the 200′′ telescope, Sandage (1954) summarized the evidence for $H_0$ and concluded $125 < H_0 < 276$.

HMS (1956) estimated $H_0 = 180$ on two grounds: (1) They showed that what Hubble had considered as brightest stars of NGC 4321, a member of the Virgo cluster, were actually HII regions. The brightest stars set in only $\sim 2^{m}$ fainter. (2) The absolute magnitude of M 31, resulting from its apparent Cepheid modulus of $(m – M) = 24.25$ (Baade & Swope 1954), could be used by the authors to calibrate the upper-envelope line of their Hubble diagram of
Table 1: Distances of nearby galaxies from 1936–2002.

|       | Hubble 1936* | 1950 $(m - M)^0$ | Sandage 1958*** | 1962 | 2002† | Factor |
|-------|-------------|-----------------|-----------------|------|-------|--------|
| LMC   | 17.1        | 17.1            | 16.7            | 19.2 | 18.4  | 18.56  | 1.08 |
| SMC   | 17.3        | 17.3            | 17.0            | 19.2 | 18.78 | 19.00  | 1.11 |
| M 31  | 21.6        | 22.4            | 21.8            | 24.6 | 24.16 | 24.47  | 1.14 |
| NGC 2403 | 24.0       | 23.6            | 27.6            | 27.6 | 27.65 | 1.02   |
| M 101 | (25.5)      | 24.0            | 23.6            | 27.7 | 29.36 | 2.1    |
| Virgo | 26.7        | 26.8            | 26.8            | 30.8 | 31.6  | 1.4    |

$H_0 = 526, 75, 77 \pm 20, 58 \pm 6$

* Hubble's 1926 distances are 0.5'5 larger
** corrected for galactic absorption
*** from Novae
† as compiled by Tammann et al. (2001b)

field galaxies on the assumption that the luminosity of M 31 must be matched by at least some galaxies.

The confusion between brightest stars and HII regions was elaborated by Sandage (1958). The corresponding correction together with the correction of Hubble's photometric scale led him to conclude that the 1936 distance scale was too short by 4.6 and consequently that $H_0 = 75$. He noted that if the brightest stars had $M_{pg} = -9.5$ (which is now well demonstrated) $H_0$ would become 55. He also concluded from novae that Hubble’s Local Group distances were more nearly correct, i.e. too small by “only” 2.3 on average (cf. Table 1). Sandage’s paper has become a classic for not only having given the first modern values of $H_0$, but also because it contains the first physical explanation of the instability strip of Cepheids.

The situation in mid-1961 was summarized by Sandage (1962) at the influential 15th IAU Symposium (cf. Table 1). While he cited values of $H_0 \sim 110$ by Sérsic (1960), van den Bergh (1960), and Holmberg (1958), his own values — based, in addition to Cepheids and brightest stars, on the size of HII regions — were 75–82. F. Zwicky pleaded in the discussion for $H_0 = 175$ from supernovae.

5 A New Start on the Distance Scale 1960–1990

The still unchallenged (within the errors) Cepheid distance of M 31 of $(m - M)^0 = 24.20 \pm 0.14$ (Baade & Swope 1963), derived by H.H. Swope after W. Baade’s death from his 200''-plates and from H.C. Arp’s photoelectric sequence, may be considered as the beginning of a new era. (For the history of the time cf. also Sandage 1998, 1999a).

By the same time the “direct” (i.e. non-spectroscopic) staff members at the Mount Wilson and Palomar observatories (W. Baade, E. Hubble, M. Humason, A. Sandage, and others) had accumulated many 200''-plates of a few galaxies outside the Local Group for work on the Cepheids. In addition, A. Sandage had set up photoelectric sequences around these galaxies, whose faintness and quality has remained unsurpassed until the advent of CCD detectors.

Although the first Cepheid distance of NGC 2403 to come out of this program confirmed Sandage’s 1962 value (Tammann & Sandage 1968), using the then latest version of the Cepheid period-luminosity (P-L) relation (Sandage & Tammann 1968), it was criticized as being (much) too large (e.g. Madore 1976, de Vaucouleurs 1975, Hanes 1982). The modern value is actually
marginally larger (Freedman et al. 2001).

The second galaxy of the program, NGC 5457 (M 101), came as a great surprise: its distance was found twice the value of Sandage’s (1962) estimate (Sandage & Tammann 1974a), i.e. \((m - M)^0 = 29.3\). The distance of M 101 and its companions was based on brightest stars, HII region sizes, and van den Bergh’s (1960) luminosity classes of spiral galaxies, but also heavily on the absence of Cepheids down to the detection limit. The faint Cepheids were eventually found with HST, yielding \((m - M)^0 = 29.34\) (Kelson et al. 1996). In the mean time the distance had been denounced as being too large (e.g. de Vaucouleurs 1978; Humphreys & Strom 1983).

The new distance of M 101 made clear that the brightest spirals of luminosity class (LC) I are brighter than anticipated and that the luminosity of their brightest stars and the size of their largest HII regions had to be increased. This led immediately to a distance of the Virgo cluster of \((m - M) = 31.45\) (Sandage & Tammann 1974b), — a value probably only slightly too small (cf. Tammann et al. 2001b). The ensuing luminosity calibration of LC I spirals could then be applied to a specially selected, distance-limited sample of 36 such galaxies, bounded by 8500 km s\(^{-1}\). The conclusion was that \(H_0 = 55 \pm 5\) “everywhere” (Sandage & Tammann 1973).

The largest contribution to the systematic errors was attributed to the calibration through Cepheids (cf. Section 9).

The main antagonist of this solution became G. de Vaucouleurs. Having started with \(H_0 = 50\) from brightest globular clusters (de Vaucouleurs 1970), he switched to \(H_0 \sim 100 \pm 10\) (de Vaucouleurs 1977; de Vaucouleurs & Bollinger 1979). By assuming rather short local distances and by turning a blind eye to all selection effects, he managed to maintain this value — eventually with strong directional variations — until his last paper on the subject (de Vaucouleurs & Peters 1985).

In the mean time new distance indicators were proposed which correlate global galaxian observables with the total luminosity or the diameter of a galaxy. An extrapolation of Öpik’s (1921) method was to use the 21cm HI-line width (a measure of the rotational velocity) as a mass and hence luminosity indicator, i.e. the so-called Tully-Fisher relation (Tully & Fisher 1977; Sandage & Tammann 1976). It followed the L-\(\sigma\) (Minkowski 1962; Faber & Jackson 1976), \(D_n-\sigma\) (Dressler et al. 1987), or fundamental plane (Djorgovski & Davis 1987) method and the surface brightness fluctuation (SBF) method (Tonry & Schneider 1988). Since these relations have considerable intrinsic scatter their discussion is deferred to Section 7.

The turnover point of the bell-shaped luminosity function of globular clusters has been used as a distance indicator (van den Bergh, Pritchet, & Grillmair 1985). The successes and failures of the method are discussed elsewhere (Tammann & Sandage 1993). Following a proposal by Ford & Jenner (1978) also brightest planetary nebulae have been widely used as distance indicators. But the method seems to depend on population size (Bottinelli et al. 1991; Tammann 1993), chemical composition, and age (Méndez et al. 1993).

6 A Complication: Peculiar Motions

Peculiar motions, addressed already by de Sitter (1934), may camouflage the true value of \(H_0\), the negative velocity of M 31 being a clear warning. Moreover Zwicky (1933) had pointed out the enormous virial motions in high-density clusters. But in the 1930’s the one-dimensional peculiar motions of field galaxies were estimated to be \(\lesssim 200\) km s\(^{-1}\) (Hubble & Humason 1931, 1934). Later work has shown that they are rather \(\lesssim 50\) km s\(^{-1}\) on average at a local scale of 5 Mpc (Yahil, Tammann, & Sandage 1977; Sandage 1986; Ekholm et al. 2001; Karachentsev et al. 2002) or even of 10 Mpc (Tammann & Kraan-Kortweg 1978). Yet the size of the peculiar motions increases with the scale length.

The first physically motivated detection of a significant streaming velocity, viz. towards the Virgo cluster center, is due to Peebles (1976; Davis & Peebles 1983). Later work showed that the
Virgocentric flow amounts to \(\sim 220 \pm 50 \text{ km s}^{-1}\) at the position of the Local Group (Tammann & Sandage 1983; Kraan-Korteweg 1986). Much larger streaming velocities have since been proposed over still larger scales, but it has never become clear, whether they are not due to Malmquist bias of poorly defined galaxy samples (Section 7).

The total (three-dimensional) vector of \(\sim 630 \text{ km s}^{-1}\) of all peculiar motions the Local Group partakes in, is reflected in the CMB dipole (Corey & Wilkinson 1976; Smoot, Gorenstein, & Muller 1977). A significant fraction of the dipole is probably generated on scales within \(< 6000 \text{ km s}^{-1}\) (Dale et al. 1999; da Costa et al. 2000), although some authors still favor higher values. As a consequence a reliable large-scale value of \(H_0\) should be determined at \(> 6000 \sim 10000 \text{ km s}^{-1}\) (Section 8).

Notwithstanding the presence of large bulk motions the mean value of \(H_0\) turns out to be surprisingly scale-invariant. Within \(v \sim 1200 \text{ km s}^{-1}\) (excluding the Virgo region) \(H_0\) is only insignificantly different from the large-scale value by \(\Delta H_0 = 1.8 \pm 2.7\) (Tammann et al. 2001b, Fig. 9). Note that the local and distant values of \(H_0\) are about equally affected by any errors of the underlying Cepheid calibration (cf. Section 9).

7 Yet Another Problem: Selection Bias

The lesson of Malmquist (1920) was only slowly incorporated by extragalactic workers and is still not fully accounted for in some modern work. The essence is that the mean luminosity of objects drawn from an (apparent-) magnitude-limited sample increases with distance, and that one overestimates \(H_0\) as a consequence of this, if one applies a local calibration to distant objects.

The influence of the Malmquist bias was greatly exacerbated when distance indicators came into use which use global galaxian parameters as distance indicators, like the LC, TF, \(D_n-\sigma\) (or fundamental-plane), or SBF methods. These methods have important luminosity scatter in the order of \(\sigma_M > 0^{m}3\), and since the bias is strongly dependent on the size of the true intrinsic scatter \(\sigma_M\) (which is difficult to determine), they are highly susceptible to Malmquist bias. Non-allowance for Malmquist bias leads always, of course, to too high values of \(H_0\).

The literature abounds with \(H_0\) determinations by means of the above relations as applied to (complete or even incomplete) magnitude-limited samples. They typically lead to incorrect values of 70 \(\sim H_0 \sim 80\).

The obvious way to overcome the Malmquist bias is to use distance-limited samples. Examples are TF distances of a complete galaxy sample bounded by 1000 km s\(^{-1}\) (avoiding the wider Virgo region as being too noisy for velocities to represent a good distance cutoff; Federspiel 1999; cf. Tammann et al. 2001b, Fig. 5a) and giving \(H_0 = 59 \pm 3\), or a complete sample of Virgo cluster spirals yielding a TF modulus of \((m - M)_\text{Virgo} = 31.58 \pm 0.24\) (Federspiel 1999).

But complete distance- or volume-limited samples are restricted to quite local regions. Several authors have therefore developed various methods how to derive unbiased values of \(H_0\) from (complete) magnitude-limited samples of field galaxies (Teerikorpi 1984, 1997; Bottinelli et al. 1986; Federspiel, Sandage, & Tammann 1994); for a tutorial see Sandage 1995; for a parameter-free method see Hendry 2002). Also cluster samples are affected by Teerikorpi Cluster Population Incompleteness Bias (Teerikorpi 1987; Sandage, Tammann, & Federspiel 1994). The original hope that the inverse TF relation was bias-free has not substantiated (Teerikorpi et al. 1994).

Bias-corrected samples of field galaxies give typical values of \(H_0 \lesssim 60\), e.g. from LC (Sandage 1996, 1999, 2003; Patrul et al. 1998), from TF (Theureau et al. 1997; Theureau 2000; Ekholm et al. 1999; Hendry 2002), from galaxy diameters (Goodwin et al. 1997), and from the \(D_n-\sigma\) method (Federspiel 1999).
Figure 1: The Hubble diagram in $V$ for the 35 SNe Ia of the fiducial sample with magnitudes $m_{V}^{\text{corr}}$, i.e. corrected for decline rate $\Delta m_{15}$ and color $(B-V)$. The solid line is a fit to the 26 SNe Ia with $A_V \leq 0^{.2}$ (closed circles) assuming a flat universe with $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$; the dashed line is a linear fit with a forced slope of 0.2 (corresponding approximately to $\Omega_M = 1.0$ and $\Omega_{\Lambda} = 0.0$).

All these solutions reach hardly beyond 5000 km s$^{-1}$, even in the best cases. The determination of the large-scale value of $H_0$ is therefore deferred to the next Section.

8 The Golden Route to the Large-Scale Value of $H_0$

Two developments have opened a simple and reliable way for the determination of $H_0$ out to distances of $\sim 30,000$ km s$^{-1}$.

1) Following an early suggestion by Kowal (1968) it has become increasingly clear that SNe Ia are the most powerful standard candles to date. The scatter of their Hubble diagram decreased steadily as it became possible: a) to remove non-type Ia SNe from the sample, b) to obtain good photometry of their magnitudes at maximum, many of which are due to a specific program at Cerro Tololo, c) to allow for the dependence of $m_{\text{max}}$ on the decline rate of the light curve, — a correction which turned out to be smaller than originally proposed by Phillips (1993), and d) to correct for a dependence of $m_{\text{max}}$ on the intrinsic color of the SN Ia (Tammann & Sandage 1995, Tripp 1998). Parodi et al. (2000) have compiled a complete fiducial sample of 35 blue SNe Ia, which fulfill the conditions $(B-V)^{0} \leq 0.10$ and $1200 < v < 30,000$ km s$^{-1}$ (the lower limit is imposed to reduce the effect of peculiar velocities, the upper limit is to minimize the effect of $\Omega_M$ and $\Omega_{\Lambda}$). This sample allows to determine good dependencies of $m_{\text{max}}$ on decline rate and intrinsic color. The resulting $m_{\text{corr max}}$ in $B$, $V$, and $I$ define very tight Hubble diagrams (cf. Parodi et al. 2000). As an example only the Hubble diagram in $V$ is shown here (Fig. 1). The solution for the Hubble line, shown in the Figure, excludes the nine SNe Ia which have a Galactic absorption of $A_V > 0^{.2}$ according to Schlegel et al. (1993). They appear to be somewhat bright and their absorption may be overestimated.

The very small scatter of $\sigma_m = 0^{.2}$ in Fig. 1 could be entirely due to observational errors (in magnitude and color), to which peculiar velocities may contribute to some extent. The lumi-
nosity variation of homogenized, blue SNe Ia is therefore below the detection limit. Their unique rôle as standard candles and their insensitivity against Malmquist bias are unquestionable.

The conclusion is that SNe Ia open the golden route to the large-scale value of $H_0$ if “only” their absolute magnitude $M_{\text{corr}}$ can be determined.

2) The advent of HST made it possible — as a pilot program had shown (Sandage & Tammann 1982) — that the required luminosity calibration of SNe Ia could be achieved. A special HST program was mounted with the aim of determining Cepheid distances of nearby galaxies which have produced a well observed SN Ia in the past. This has now led to the distances of seven standard SNe Ia, which were augmented by two additional objects from external sources. The data are compiled in Saha et al. (2001). The mean absolute magnitude of the nine SNe Ia, after correction for decline rate and color, becomes $M_{\text{corr}}^V = -19.53 \pm 0.06$.

If this value is combined with the equation of the corresponding Hubble line, as shown at the bottom of Fig. 1 one obtains

$$H_0 = 56.9 \pm 2.3.$$  

Very similar solutions are obtained from the $B$ and $I$ magnitudes (cf. Tammann et al. 2001f).

The value of $H_0$ could be increased by 1.6 units if the LMC distance modulus, i.e. the zero point of the Cepheid distance scale, were adopted to be 18.50, instead of 18.56 used here. It could also be increased by 1.3 units if all 35 SNe Ia were included in the solution. $H_0$ decreases by 0.8 units for an $\Omega_M = 1$, $\Omega_\Lambda = 0$ Universe. (Note the non-vanishing effect which $\Lambda$ has already at $v = 30,000 \text{ km s}^{-1}$).

An important feature of the present solution is that the calibrating SNe Ia and the distant sample of SNe Ia have the same absorption-corrected mean colors. Solutions which do not fulfill this condition betray an inconsistent treatment of the two sets.

Equation (1) reflects only statistical errors. The systematic errors are discussed by Saha et al. (2004) and Tammann et al. (2001f). The conclusion is that the systematic error of $H_0$ is $\lesssim 10\%$, the slope of the magnitude dependence on decline rate and color contributing somewhat, but the main source of error being the Cepheid distances discussed in the next Section.

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A note is here in place on the equally tight Hubble diagram from relative TF distances of clusters (Giovanelli et al. 1997; Dale et al. 1999; cf. Tammann, Reindl, & Thim 2001a, Fig. 2), where the cluster distances are based on the mean of about 15 subjectively selected spirals per cluster. The formidable problem is, however, how to calibrate the diagram. One possibility is to adopt the distance of one or more clusters. Sakai et al. (2000) have applied instead the local calibration of the TF relation (derived from known Cepheid distances) directly to the individual cluster galaxies, and have obtained a value of $H_0 = 71$. This procedure is of course invalid. It is well known that if one applies the TF calibration to only some bright members of the Virgo cluster or any other cluster, the mean distance becomes $\sim 0.4$ smaller than from the complete cluster spiral population (Kraan-Korteweg, Cameron, & Tammann 1988, Fig. 6). This is a typical example of the Teerikorpi Cluster Bias effect (cf. Section 7). It is therefore obvious that the value of $H_0$ by Sakai et al. must be too high by roughly 20%.

The same objection holds against the calibration of the Hubble diagram of 11 clusters, whose relative distances are based on the mean $D_n - \sigma$ distances of a few cluster E/S0 members (Kelson et al. 2000). The additional problem is here that even the local calibration of the $D_n - \sigma$ relation is shaky because there is no early-type galaxy with a primary distance determination.

Purely physical methods leading directly to $H_0$, without using any astronomical distance for calibration, are steadily gaining weight. A combined solution of six gravitationally lensed double or multiple quasars yields for a $\Lambda$CDM model a well constrained value of $50 < H_0 < 60$ (Saha 2002). The physics of the light curve plateau of SNe of type IIP suggests values of $54 \lesssim H_0 \lesssim 65$ (Hamuy 2001; Nadyozhin 2002; Lasenby 2002), summarizing the data from the Sunyaev-Zeldovich effect, concludes that $H_0$ is “sixtyish”. CMB fluctuations are compatible with the same estimate (Netterfield et al. 2002; Pryke 2002), but instead of determining $H_0$ from the CMB
it should rather be used as a prior to confine other parameters of the early Universe (Durrer 2002). This is in fact the main motivation at present to determine as precise a CMB-independent value of $H_0$ as possible.

9 Back to the Beginnings

It was suggested (Freedman et al. 2001) that the absorption of LMC Cepheids, widely used as zero point for all Cepheid distances, had been overestimated so far and that Cepheids were intrinsically dimmer than anticipated; this would result in an increase of $H_0$ by $\sim 6\%$. This suggestion is not correct for long-period Cepheids (Tammann et al. 2001b), which are decisive for the luminosity calibration of SNe Ia, but the suggestion invited a closer look into the P-L and P-C relations of Cepheids in different galaxies.

The data for nearby Cepheids have dramatically increased in recent years. Berdnikov et al. (2000) have provided $B, V, I$ photometry for hundreds of Galactic Cepheids for which Fernie et al. (1995) have determined reddening values. Feast (1999) has compiled the distances of 28 Cepheids in Galactic clusters, and Gieren et al. (1998) have determined distances of 34 Galactic Cepheids by means of the Baade-Becker-Wesselink method. Udalski et al. (1999a,b) have published periods and magnitudes in the standard system, obtained in the course of the OGLE program, for many hundreds of fundamental-mode Cepheids in LMC and SMC as well as their consistent $E(B-V)$ values.

The analysis of this wealth of data is still in progress, but it is already clear that the P-L and P-C relations are different in different galaxies. In LMC neither the P-L nor the P-C relation can be fitted by a single slope (Tammann et al. 2001b), whereas the steep Galactic P-L relation shows no deviation from linearity. Cepheids in LMC are up to $0.5^m$ brighter at log $P = 0.4$ than their Galactic counterparts (somewhat dependent on the adopted distances), but the difference

![Diagram](image_url)
diminishes towards longer periods. It is a lucky coincidence that the Galactic and LMC P-L relations cross at $\log P \approx 1.5$ and that this is about the median period of the SNe Ia-calibrating Cepheids. But the choice of any specific P-L relation may influence the resulting absorption-corrected distance of external galaxies by up to 10%.

A distance-independent comparison of the Cepheids in the Galaxy, LMC, and SMC is afforded by their mean position in the color-color diagram (Fig. 2). It cannot entirely be excluded that the (large) Galactic $E(B-V)$ values are underestimated and that the Galactic Cepheids should be slid closer to the LMC Cepheids along the reddening line, but the fact that Cepheids in SMC at a given period are bluer in $(B-V)^0$ and redder in $(V-I)^0$ than those in LMC cannot be the result of incorrect reddenings. If the P-C relations are not universal then it follows by necessity that also the P-L relations must be different, at least at some wavelengths.

It comes as a surprise that the largest single source of systematic errors, which affect the luminosity calibration of SNe Ia and hence the large-scale value of $H_0$, is due to the intrinsic difference of Cepheids in different galaxies. Of course, all other distance determinations which are calibrated through Cepheids face the same problem. At present it is not known which parameter decides on the specific form of the P-L relation, but metallicity is a prime suspect. If this is so, and considering that the mean metallicity of the SNe Ia-calibrating galaxies is roughly $[\text{Fe/H}] = 0$, one should prefer the Galactic over the LMC P-L relation. In that case the galaxy distances, based on long-period Cepheids, would tend to increase.

It is a long-range program of the future to trace accurate P-C and calibrated P-L relations in a variety of nearby galaxies, to understand the physics of their being different, and then to decide about their applicability to more distant galaxies. It may take the astrometric distances from GAIA to calibrate the various P-L relations for further use as distance indicators. At present it is prudent to attribute a systematic error of at least 5% to the value of $H_0$, accounting for only the intrinsic difference of Cepheids.

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