Allan Sandage and the Cosmic Expansion

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Allan Sandage – a mentor, a collaborator, a friend for 47 years
Abstract

Allan Sandage (1926 - 2010) has published over 500 papers. Only a small part concerns directly the extragalactic distance scale and the character of the cosmic expansion field, but the problem accompanied him from the beginning to the end. His first paper (1954) on the expansion rate, a summary of the first four years with the 200” telescope, gave $125 < H_0 < 276$, but a difficulty at the time was that the variability of $H_0$ with distance (and direction?) was poorly known. Already two years later he co-authored the famous HMS paper which gave a linear expansion field – albeit with large scatter – out to $z = 0.2$ and a best value of $H_0 = 180$. Single-handedly he set out a very extended observing program, including a six-month stay in Australia, to improve and extend the Hubble diagram of first-ranked galaxies in clusters and groups to higher and lower redshifts. In at least eleven papers he laid down the results strengthening the linearity of the expansion field and decisively weakening claims for large non-cosmological redshifts. Eventually redshifts of $z = 0.4$ were reached (together with J. Kristian and J. Westphal) in 1975, but the program was terminated when it became clear that first-ranked E galaxies could not lead to a value of $q_0$ due to their important luminosity evolution. In one of his last papers he showed that the expansion rate does not vary by more than $\pm 2.3\%$ in the range from 300 to 30,000 km s$^{-1}$ once allowance is made for the attraction of the Virgo cluster center and of the mass distribution in a shell beyond 3500 km s$^{-1}$ causing the CMB dipole.

Sandage revised the expansion rate to $75 < H_0 < 82$ on the basis of Cepheids, brightest stars and well identified HII regions in 1961. A series of eight “Steps to the Hubble Constant” followed (1974-1995) where Cepheids, brightest stars, HII regions, luminosity classes, 21cm line widths and for the first time SNI were used to derive $H_0 = 50 - 60$. Already in 1990 he had formed a small HST team for the luminosity calibration of SNe Ia. The summary paper of this project (Sandage et al. 2006) yielded $H_0 = 62.3 \pm 1.3$, a value which rests on new, metal-dependent period-luminosity relations of Cepheids, and which was subsequently confirmed by a Population II distance scale based on the RR Lyr-calibrated tip of the red-giant branch. Still during Sandage’s live a paper appeared by Reid et al. (2010) which summarizes the combined evidence from SDSS, WMAP, and SNe Ia as $H_0 = 65.5 \pm 2.5$. 
The mapping of the cosmic expansion has two aspects:

I. The Character of the Expansion Field
   From local velocities to the cosmic expansion – only relative distances needed

II. The Calibration of the Expansion Rate ($H_0$)
   Unbiased linear distances are essential

Hubble’s (1953) last Hubble diagram

The almost dispersionless diagram implies a non-expanding Universe: “no recession factor”
Important Progress: Humason, Mayall, & Sandage (1956) (providing 620 redshifts)

The Hubble diagram of brightest cluster galaxies. The theoretical part was written by Sandage; first attempt to measure the deceleration of the expansion. The curved line corresponds to a closed Universe with \( q_0 = 2.5 \), which speaks against the steady-state model \( (q_0 = -1) \) then in vogue (see also Hoyle & Sandage 1956).
The Foundation of Observational Cosmology


Intermezzo: Speculations about large non-cosmological redshifts (Arp 1967 and many followers). Sandage as leader against the speculations.

Sandage (1972; Paper II of a series of 8 papers, considering also Seyfert galaxies, radio galaxies and quasars)

![Graph showing the brightest galaxies in 84 clusters](image)

A most exigent observing program: identification; positioning; blind photometry; photographic spectroscopy at the limit of the technical possibilities (> 100 nights on 200-inch). The straight line corresponds to a flat Universe with $q_0 = 0.5$. 
Allan Sandage in 1970 when speculations about large non-cosmological redshifts had become virulent. Under enormous pressure he had developed painful arthritis in his hands, which is reflected in this picture.
Kristian, Sandage, & Westphal (1978)

End of the program of the $m - \log z$ relation of brightest cluster galaxies because the curvature caused by de- or ac-celeration is strongly overshadowed by luminosity evolution of brightest cluster E galaxies (Frogel et al. 1978)

In the same year Sandage published a collection of 719 redshifts – probably the largest collection of photographic, hand-reduced redshifts by a single author.
The linearity of the expansion field \( (300 < \frac{v}{220/\text{CMB}} < 30,000 \, \text{km/s}) \) from 480 relative distances (Cepheid, TRGB, SNe Ia, and relative 21cm line distances of Masters et al. 2006).

The Hubble diagram can be smoothly extended to \( z > 1 \) by overlapping SNe Ia samples (e.g. Hicken et al. 2009; Kessler et al. 2009; Conley et al. 2011).
Residuals from Linear Expansion

The linearity beyond 30,000 kms\(^{-1}\) is well documented by SNe Ia (e.g. Hicken et al. 2009; Kessler et al. 2009, Conley et al. 2011).

The high degree of linearity can be used to test previous distance determinations for systematic distance-dependent errors.
Tests of Previous Distance Determinations for Spurious Changes of $H_0$ with Distance

1) Distances from surface brightness fluctuations (SBF; Tonry et al. 2001)

2) Distances from the luminosity function of planetary nebulae (PNLF; Ciardullo et al. 2002, Feldmaier et al. 2007, Herrmann et al. 2008)
The Dipole Motion Relative to the CMB

The velocity residuals are plotted against the angle $\alpha$ from the apex $A_{\text{corr}}$ (corrected for the local velocity vector of 220 kms$^{-1}$ toward the Virgo cluster).

![Graph showing dipole motion relative to CMB](image)

Conclusion:
Galaxies in the contracting Local Supercluster ($v_{220} < 3500$ kms$^{-1}$) have no significant systematic motion toward the CMB apex.
The Local Supercluster moves coherently relative to the galaxies in a shell with $3500 < v_{220} < 7000$ kms$^{-1}$ with a velocity of $448\pm73$ kms$^{-1}$ toward $A_{\text{corr}}$. (The expected value is $495$ kms$^{-1}$).
Streamings within 7000 kms$^{-1}$ (schematic)

Note: The velocity vectors do not lie in a plane
II. The Calibration of the Expansion Field (H₀)

(Baade 1948/1952: 250; Hubble maintained H₀ = 526 still in 1953)

1954:  H₀ ~ 200 corrected magnitudes, Cepheids, brightest stars, novae
1956:  H₀ = 180 Humason, Mayall & Sandage
1958:  H₀ = 75 the P-L relation of Cepheids is actually a P-L-color relation, distinction brightest stars vs. HII regions
1962:  H₀ = 98 ± 15 mean of four authors, (75 ± 25 correction to Hubble),
1968:  H₀ = 75 brightest globular clusters (GC)
1970: “The Search for Two Numbers” (H₀, q₀)
1971:  H₀ < 75 Luminosity Classes (LC) of spiral galaxies
1975:  H₀ = 57 “Steps toward the Hubble Constant,” 6 papers (+3 later)
1976:  H₀ = 50 21 cm line width distance of Virgo cluster
(1977 – 1985 de Vaucouleurs’ value of H₀ = 100 ± 10)
1982:  H₀ = 50 first attempt to calibrate Hubble diagram of SNe
1988:  H₀ = 56 ± 13 (local) 21 cm line width distances of field
        H₀ = 68 ± 18 (distant) galaxies allowing for selection bias
1994:  H₀ = 52 first result of the HST program led by Sandage for the luminosity calibration of SNe Ia
1996:  H₀ = 60 luminosity function of GC (GCLF)
2002:  H₀ = 61 new metal-dependent P-L relations of Cepheids
2006:  H₀ = 62.3 summary of the HST SNe Ia project
2008:  H₀ = 62.3 RR Lyr-calibrated tip of the red-giant branch (TRGB)
Complications with the P-C and P-L Relation of Cepheids: Metallicity Dependence.

The P-C and P-L relations of the metal-poor LMC Cepheids and of the very metal-poor SMC Cepheids are plotted *relative* to the same relations of the metal-rich Galactic Cepheids.
New Trouble with Metal-rich Cepheids


The Cepheids in NGC 1309 are – even without correction for internal absorption – excessively blue in $(V-I)$. In the relevant period interval $\langle \Delta(V-I) \rangle = -0.16$ compared to the Galaxy and $-0.14$ compared to LMC.

Also the scatter in $(V-I)$ is unusually large ($\sigma = 0.15$ mag) compared to ($\sigma \leq 0.08$ mag) in the Galaxy and LMC.

The case of NGC 3021 is less pronounced.

(A He effect?)
New Trouble with Metal-rich Cepheids (cont’d)

The P-L relation of the metal-rich Cepheids in NGC 1309 in comparison with the “normal” P-L relation of the metal-rich Cepheids in the Galaxy, NGC 3351, and NGC 4321.

The NGC 1309 Cepheids are shown here on the assumption that the galaxy lies at its SN Ia distance. This, however, has no effect on the flatness of the P-L relation of NGC 1309.
Sandage’s Last Value of $H_0$

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>$v$(median)</th>
<th>$H_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRGB (RR Lyr)</td>
<td>176</td>
<td>400 kms$^{-1}$</td>
<td>62.9±1.6</td>
</tr>
<tr>
<td>Cepheids</td>
<td>29</td>
<td>800 kms$^{-1}$</td>
<td>63.4±1.8</td>
</tr>
<tr>
<td>SNe Ia</td>
<td>218</td>
<td>5000 kms$^{-1}$</td>
<td>62.3±1.3</td>
</tr>
<tr>
<td>adopted</td>
<td></td>
<td></td>
<td>62.3±1.3 (±5.0)</td>
</tr>
</tbody>
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Some months before Sandage’s death Reid et al. (MNRAS 404, 60) published a paper combining the evidence from

- LRG’s from SDSS (7)
- WMAP (5)
- SN Union Sample

\[65.6±2.5\]
Allan Sandage wrote in a letter on Nov. 7, 2010: 
“Do not grieve for me. I go to a far, far better place than I am now on the edge of the zone of life.”