The Hubble Constant From observations of the Brightest Red Giant Stars in a Virgo-cluster Galaxy

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The nearest large groups of elliptical galaxies, in the Virgo and Fornax clusters, play central roles in determining the Hubble constant \( H_0 \) and thus the cosmological rate of expansion. Since the relative distances between these two clusters and more remote clusters are well known, robust distance determinations to Virgo and Fornax will establish the Hubble constant for the local universe. In addition, elliptical galaxies reside predominantly in the cores of clusters, so that distance calibrations for ellipticals will minimize the uncertainties due to the possible large extent of clusters along the line of sight. A powerful and direct way of establishing such distances is to use the brightest red-giant stars, which have nearly uniform luminosities\(^1,2\). Here we report the direct observation of the old red giant stars in a dwarf elliptical galaxy in the Virgo cluster. We determine a distance to this galaxy, and thus to the core of the Virgo cluster, of \( \sim 15.7 \pm 1.5 \) Megaparsecs, from which we estimate a Hubble constant of \( H_0 = 77 \pm 8 \) km s\(^{-1}\) Mpc\(^{-1}\). Under the assumption of a low-density Universe with the simplest cosmology, the age of the Universe is no more than 12-13 billion years.
For the old, low-mass stars that dominate the stellar population in elliptical galaxies, the post-main-sequence evolution along the giant branch terminates at the point of core helium ignition which defines the tip of the red giant branch (TRGB). If these stars are imaged in the near-infrared $I$ band, the small dependence of the TRGB bolometric luminosity on stellar composition (metallicity) almost completely cancels the bolometric correction, leaving the absolute magnitude $M_I(\text{TRGB})$ at the same level to within $\pm 0.1$ magnitude for any metallicity in the range $[\text{Fe/H}] \lesssim -0.7^{1,2,3,4}$. The TRGB luminosity can be calibrated from the giant branches in nearby globular clusters$^{1,5}$, whose distances are set in turn by RR Lyrae parallaxes and main-sequence fitting to subdwarfs. The TRGB method thus yields distance measurements for other galaxies that are only two steps removed from fundamental trigonometric parallaxes and independent of any other methods involving Local Group calibrators. By contrast, the Cepheid-based distance calibrations$^{6,7,8,9,10}$ lie three or four steps away from fundamental parallax methods by the time they reach remote galaxies such as the rich proving grounds of Virgo and Fornax.

We have used the superb imaging resolution of the Hubble Space Telescope to achieve the first TRGB distance calibration to a Virgo galaxy. Our target was the nucleated dwarf elliptical VCC 1104 = IC 3388, which has a projected location 43′ (or $\sim 200$ kpc) northeast of the central giant M87, and thus well within the $\sim 1$-Mega parsec projected core radius of the Virgo ellipticals$^{11}$. We obtained deep $I$-band (filter F814W) exposures of this galaxy in June 1997 with the WFPC2 camera on HST. Twelve images adding up to a total exposure time of 32200 sec were re-registered and co-added to generate a final composite image in which the galaxy is beautifully resolved, displaying a sheet of faint stars across the entire WFPC2 field.

Photometry of the stars on the final image was carried out with the DAOPHOT II suite of software$^{12}$. To set the zero point of the $I$-magnitude scale, we used our ground-based WIYN photometry to determine $I$ magnitudes for 6 of the brightest stars in the WFPC2 image field, and then determined the mean offset between the instrumental magnitudes and the true $I$ to within an uncertainty $\sigma(I) = \pm 0.04$. The normal prescription for self-calibration of the WFPC2 F814W filter via aperture photometry$^{13}$ was also used on 14 stars in the WF2,3,4 fields, yielding a zeropoint with $\sigma(I) = \pm 0.03$ uncertainty. These two methods gave zeropoints which differed by only 0.02 mag. An additional systematic zeropoint uncertainty may arise when we transfer the magnitude scale for the relatively bright calibration stars to the faint RGB stars we are interested in, because of the charge transfer efficiency effect on the WFPC2 CCDs$^{14}$. The CTE effect should, however, be relatively small here since our individual (full-orbit) exposures are the longest possible, yielding background levels of 25 DN per exposure. The published CTE equations$^{14}$ suggest that any zeropoint correction is likely to be no larger than $\simeq 0.04$ mag, but it should be
kept in mind when interpreting the total error budget listed in Table 1.

We used additional ground-based images of VCC 1104 (obtained with the WIYN telescope at Kitt Peak National Observatory) to measure its integrated color profiles and thus its metallicity. We find \((U - B) = 0.20 \pm 0.05\) and \((B - V) = 0.74 \pm 0.02\), which give \([\text{Fe/H}] \simeq -1.3 \pm 0.2\) through the normal relation between metallicity and integrated color for globular clusters\(^{15}\). The galaxy is therefore squarely in the low-metallicity regime within which \(M_I(\text{TRGB})\) is constant.

Close to the center of VCC 1104, individual stars are too crowded for reliable photometry even with HST’s high resolution. We conservatively kept only measurements of stars more than 15'' (equivalent to about 1 kiloparsec in projected distance) from the galaxy center, leaving a total ‘clean’ sample of \(\simeq 1500\) stars brighter than \(I = 27.5\) for which blending and crowding were negligible. Extensive artificial-star simulations show that our limiting magnitude (50% detection completeness) is \(I \simeq 27.5\) in these outer regions.

The raw luminosity function (LF) of the detected stars is shown in the upper panel of Fig. 1. It has three components: (a) the dominant contribution of the RGB stars in the galaxy, (b) a small (<20%) contribution of brighter asymptotic giant stars (AGB) on their second GB ascent, and (c) a contribution from faint, starlike background objects. We model the entire LF through a maximum-likelihood fitting approach\(^{16}\). The RGB luminosity function \(N(I)\) is assumed to have a step-function onset at \(I(\text{TRGB})\) followed by an exponential rise to fainter magnitudes. To this we add an AGB population starting 1.0 mag brighter than the TRGB and rising exponentially to fainter magnitudes (though with much smaller amplitude than the RGB itself). We set the exponential slopes for both RGB and AGB at \(\Delta \log N/\Delta I = 0.96\) from the \((\log N, I)\) form of the LF. Finally, we convolve the ideal model with the photometric error function \(\sigma(I)\) and completeness function \(f(I)\) (both of which are known from the artificial-star simulations). The smoothed background \(b(I)\) is added, and the fully transformed model is finally matched to the observed LF. In general, the LF for this galaxy very strongly resembles the ones published recently for two dwarf ellipticals in the nearby M81 group\(^{17}\), for which the \((I, V - I)\) color-magnitude diagrams exhibit a strong RGB component terminating sharply at the TRGB, with a sprinkling of AGB stars continuing upward brighter than the tip for about 0.8 magnitude.

The free parameters in the LF fit are the assumed \(I(\text{TRGB})\) and the fractional contribution of the AGB, which are adjusted to find the best match (maximum likelihood) to the normalized LF. Our model solution gives \(I(\text{TRGB}) = 26.82 \pm 0.06\). Variations in the size of the AGB population, or differences in the RGB slope exponent, do affect the overall goodness of fit of the model LF, but the deduced magnitude of the TRGB is almost completely insensitive to either parameter because of its intrinsically sharp step-function nature. (Realistic changes in the exponential slope, or the AGB population ratio, resulted
in only $\pm 0.01 - 0.02$ differences in the TRGB value). Similarly, even neglecting the contribution of the background $b(I)$ altogether does not change the deduced TRGB significantly.

As a check on the solution, we applied the Sobel edge-detection filter\textsuperscript{1,2} in its continuous form to the observed luminosity function (lower panel of Fig. 1). This method, though cruder, has the advantage that it is model-independent; it gives the same answer for $I(\text{TRGB})$ to within $\pm 0.1$ magnitude.

The distance to the galaxy is set once we adopt an absolute magnitude for the TRGB, $M_I(\text{TRGB}) = -4.2 \pm 0.1$ (see Fig. 2). Our derived distance modulus for VCC 1104 is then $(m - M)_0 = 30.98 \pm 0.20$ for a foreground Virgo absorption $A_I = 0.04$. Our resulting distance to VCC 1104, and therefore the Virgo cluster core, is

$$d(\text{Virgo}) = (15.7 \pm 1.5) \text{ Mpc}.$$  

This result agrees to within its quoted uncertainty with other recent measurements such as through planetary nebula luminosity functions\textsuperscript{18}, surface brightness fluctuations for E/S0 galaxies\textsuperscript{19}, and the Cepheids in spiral galaxies that are high-probability Virgo members\textsuperscript{6,7,8,9,10}.

The error budget is summarized in Table 1 along with those for the Cepheid and PNLF (planetary nebula) techniques. For single Virgo galaxies selected \textit{at random}, a major advantage of either the TRGB or PNLF methods should be a smaller geometric depth effect, since the Virgo ‘core’ defined by the elliptical galaxies is expected to be smaller than the more widespread Cepheid spirals (but see below).

Two extreme possibilities may have significantly biased our result: (1) We may have unluckily picked a target which genuinely lies on the near (or far) side of the Virgo cluster core. The distribution of intergalactic planetary nebula within Virgo\textsuperscript{20} suggests that the intracluster stars may extend as much as 3 Mpc towards us along the line of sight, though it is unclear whether or not the core distribution of E and dE galaxies is similarly extended\textsuperscript{11}. Ultimately, the only safeguard we have against this type of accident is to acquire data for more galaxies of similar type and determine their distribution of distances. (2) This particular dwarf elliptical could have a huge population of bright AGB stars which mimic the normal first-ascent RGB tip, and which would cause us to underestimate its distance. However, no such AGB population is seen in the outskirts of similar dwarf ellipticals (see ref. 17 for an excellent comparison), or even in the halos of larger galaxies\textsuperscript{21,22,23}.

To compute the Hubble constant, we use our measured Virgo distance to step outward to the Coma cluster, whose mean redshift in the CMB frame\textsuperscript{24,25} is $v(\text{Coma}) = (7100 \pm 100) \text{ km s}^{-1}$. The relative distance modulus $\Delta m(\text{Coma–Virgo})$ appears now to be the most poorly known quantity in the logical chain, with measured estimates ranging from $\simeq 3.4$ to
4.1$^{26}$. Recent measurements particularly through the $D_n - \sigma$ method for fundamental-plane ellipticals$^{27,28}$ suggest a mean $\langle \Delta m \rangle \approx 3.85 \pm 0.15$, which we adopt here. Thus, $d(\text{Coma}) = (92.5 \pm 10.3)$ Mpc and the Hubble constant is

$$H_0 = (77 \pm 9) \text{ km s}^{-1} \text{ Mpc}^{-1}.$$ 

The corresponding expansion age for the universe is $(12.6 \pm 1.5)$ Gyr for $\Omega \simeq 0$, or $(8.4 \pm 1.0)$ Gyr for critical density ($\Omega = 1$). The former value, for a very low-density universe, now fits with little room to spare within the lowest currently estimated ages for the oldest Milky Way globular clusters, which are in the range of $11 - 13$ Gyr$^{29,30}$. The high-$\Omega$ expansion time is, of course, still strongly in conflict with these ages.

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References

1. Lee, M. G., Freedman, W. L., & Madore, B. F. The Tip of the Red Giant Branch As a Distance Indicator for Resolved Galaxies. *Astrophys.J.* **417**, 553-559 (1993).

2. Mould, J., & Kristian, J. The Stellar Populations in the Halos of M31 and M33. *Astrophys.J.* **305**, 591-599 (1986).

3. Lee, M. G. The Distance to Nearby Galaxy NGC 3109 Based on the Tip of the Red Giant Branch. *Astrophys.J.* **408**, 409-415 (1993).

4. Sakai, S., Madore, B. F., & Freedman, W. L. Tip of the Red Giant Branch Distances to Galaxies. III. The Dwarf Galaxy Sextans A. *Astrophys.J.* **461**, 713-723 (1996).

5. Da Costa, G. S., & Armandroff, T. E. Standard Globular Cluster Giant Branches in the $(M_I, (V-I)_o)$ Plane. *Astron.J.* **100**, 162-181 (1990).

6. Pierce, M. J., Welch, D. L., McClure, R. D., van den Bergh, S., Racine, R., & Stetson, P. B. The Hubble Constant and Virgo Cluster Distance from Observations of Cepheid Variables. *Nature* **371**, 385-389 (1994).

7. Freedman, W. L. et al. Distance to the Virgo Cluster galaxy M100 from Hubble Space Telescope Observations of Cepheids. *Nature* **371**, 757-762 (1994).

8. Ferrarese, L. et al. The Extragalactic Distance Scale Key Project. IV. The Discovery of Cepheids and a New Distance to M100 Using the HST. *Astrophys.J.* **464**, 568-599 (1996).

9. Saha, A., Sandage, A., Labhardt, L., Tammann, G. A., Macchetto, F. D., & Panagia, N. Cepheid Calibration of the Peak Brightness of SNeIa. V. SN1981B in NGC 4536. *Astrophys.J.* **466**, 55-91 (1996).

10. Saha, A., Sandage, A., Labhardt, L., Tammann, G. A., Macchetto, F. D., & Panagia, N. Cepheid Calibration of the Peak Brightness of SNeIa. VI. SN1960F in NGC 4496A. *Astrophys.J.Suppl.* **107**, 693-737 (1996).

11. Ferguson, H. C., & Sandage, A. The Spatial Distributions and Intrinsic Shapes of Dwarf Elliptical Galaxies in the Virgo and Fornax Clusters. *Astrophys.J.Letters* **346**, L53-L56 (1989).

12. Stetson, P. B., Davis, L. E., & Crabtree, D. R. Future Development of the DAOPHOT Crowded-Field Photometry Package, in *CCDs in Astronomy*, ASP Conf. Ser. **8**, edited by G. H. Jacoby (ASP, San Francisco), 289-304 (1990).

13. Holtzman, J. A. et al. The Photometric Performance and Calibration of WFPC2. *Publ.Astron.Soc.Pacific* **107**, 1065-1093 (1995).

14. Whitmore, B., & Heyer, I. New Results on Charge Transfer Efficiency and Constraints on Flat-Field Accuracy. Space Telescope Science Institute, Instrument Science Report 97-08 (1997).
15. Couture, J., Harris, W. E., & Allwright, J. W. B. BVI Photometry of Globular Clusters in M87. *Astrophys.J.Suppl.* **73**, 671-683 (1990).
16. Secker, J., & Harris, W. E. A Maximum-Likelihood Analysis of Globular Cluster Luminosity Distributions in the Virgo Cluster. *Astron.J.* **105**, 1358-1368 (1993).
17. Caldwell, N., Armandroff, T. E., Da Costa, G. S., & Seitzer, P. Dwarf Elliptical Galaxies in the M81 Group: The Structure and Stellar Populations of BK5N and F8D1. *Astron.J.* **115**, 535-558 (1998).
18. Jacoby, G. H., Ciardullo, R., & Ford, H. C. Planetary Nebulae as Standard Candles. V. The Distance to the Virgo Cluster. *Astrophys.J.* **356**, 332-349 (1990).
19. Tonry, J. L., Blakeslee, J. P., Ajhar, E. A., & Dressler, A. The SBF Survey of Galaxy Distances. I. Sample Selection, Photometric Calibration, and the Hubble Constant. *Astrophys.J.* **475**, 399-413 (1997).
20. Feldmeier, J. J., Ciardullo, R., & Jacoby, G. H. Intracluster Planetary Nebulae in the Virgo Cluster I. Initial Results. *Astrophys.J.* in press (1998).
21. Soria, R. et al. Detection of the Tip of the Red Giant Branch in NGC 5128. *Astrophys.J.* **465**, 79-90 (1996).
22. Elson, R. A. W. Red giants in the halo of the S0 galaxy NGC 3115: a distance and a bimodal metallicity distribution. *Mon.Not.R.Astron.Soc.* **286**, 771-776 (1997).
23. Sakai, S., Madore, B. F., Freedman, W. L., Lauer, T. R., Ajhar, E. A., & Baum, W. A. Detection of the Tip of the Red Giant Branch in NGC 3379 (M105) in the Leo I Group Using the Hubble Space Telescope. *Astrophys.J.* **478**, 49-57 (1997).
24. Colless, M., & Dunn, A. M. Structure and Dynamics of the Coma Cluster. *Astrophys.J.* **458**, 435-454 (1996).
25. Mould, J. et al. Limits on the Hubble Constant from the HST Distance of M100. *Astrophys.J.* **449**, 413-421 (1995).
26. van den Bergh, S. The Hubble Parameter. *Publ.Astron.Soc.Pacific* **104**, 861-883 (1992).
27. Faber, S. M. et al. Spectroscopy and Photometry of Elliptical Galaxies: VI. Sample Selection and Data Summary. *Astrophys.J.Suppl.* **69**, 763-808 (1989).
28. Hjorth, J., & Tanvir, N. R. Calibration of the Fundamental Plane Zero Point in the Leo I Group and an Estimate of the Hubble Constant. *Astrophys.J.* **482**, 68-74 (1997).
29. Harris, W. E. et al. NGC 2419, M92, and the Age Gradient in the Galactic Halo. *Astron.J.* **114**, 1030-1042 (1997).
30. Gratton, R. G., Fusi Pecci, F., Carretta, E., Clementini, G., Corsi, C. E., & Lattanzi, M. Ages of Globular Clusters from Hipparcos Parallaxes of Local Subdwarfs. *Astrophys.J.* **491**, 749-771 (1997).
31. Cassisi, S., & Salaris, M. The tip of the Red Giant Branch as a Distance Indicator: theoretical calibration and the value of \( H_0 \). *Mem.soc.Astron.Ital.*, in press (1998).
Table 1. Virgo Distance Error Budget

| Source                                                                 | $\sigma(m - M)$ (magnitudes) |
|-----------------------------------------------------------------------|-------------------------------|
| **TRGB:**                                                             |                               |
| WFPC2 photometric zeropoint uncertainty                              | ±0.03                         |
| TRGB uncertainty from LF model fit                                   | ±0.06                         |
| Uncertainty in Virgo foreground extinction                            | ±0.02                         |
| Internal scatter in $M_I$(TRGB) calibration                          | ±0.10                         |
| Uncertainty in globular cluster distance scale                       | ±0.10                         |
| Geometric depth of Virgo core (±1 Mpc)                               | ±0.13                         |
| **Total uncertainty for TRGB technique (1 galaxy)**                   | ±0.20                         |
| **Cepheids:**                                                        |                               |
| $P-L$ Relation fit of LMC to Virgo spiral                            | ±0.17                         |
| Uncertainty in Cepheid metallicity                                   | ±0.05                         |
| Uncertainty in adopted LMC distance                                  | ±0.10                         |
| Uncertainty in Virgo extinction relative to LMC                      | ±0.02                         |
| Geometric depth of Virgo spirals (±3 Mpc)                            | ±0.35                         |
| **Total uncertainty for Cepheid technique (1 galaxy)**                | ±0.41                         |
| **Planetary Nebulae:**                                               |                               |
| Fitting uncertainty to observed PNLF                                 | ±0.10                         |
| Photometric zeropoint and filter calibration uncertainties            | ±0.06                         |
| Uncertainty in fiducial M31 distance                                 | ±0.02                         |
| Uncertainty in fiducial M31 distance                                 | ±0.10                         |
| Definition in fiducial model PNLF                                    | ±0.05                         |
| Geometric depth of Virgo core (±1 Mpc)                               | ±0.13                         |
| **Total uncertainty for PNLF technique (1 galaxy)**                  | ±0.21                         |

A quantitative overview of the principal internal and external uncertainties in determining the Virgo distance modulus. Figures shown are for one Virgo galaxy picked at random, either from the Virgo E and dE population (for the TRGB and PNLF techniques), or from the spirals (for the Cepheid technique). Data for the PNLF technique are taken from ref. 18, and from ref. 8 for the Cepheids.
Fig. 1. — Upper panel: The observed luminosity function $N(I)$ (number of stars per 0.1-magnitude bin) for the red giants in VCC 1104. The solid line superimposed on the raw data shows the scaled maximum-likelihood fit of the model LF to the data, scaled to match the total population of stars and including the effects of background contamination, photometric error, and detection completeness. The steep rise starting near $I \simeq 26.7$ shows the tip of the red giant branch; ideally, it would show up as a step-function jump exactly at the RGB tip, but it is broadened out by the photometric measurement uncertainty, which is $\sigma(I) = \pm 0.15$ mag at the TRGB level and increases steadily to fainter levels. The steep falloff past $I \sim 27.4$ is due to the declining completeness of detection of fainter stars, which is nearly 100% at the TRGB but drops to 50% at $I \simeq 27.5$ and effectively to zero at $I = 28$. The small bump in the LF at the bright end ($I \simeq 26.3$) is likely to be due to the presence of bright AGB stars. The local background function $b$ – the raw, unsmoothed form of which is shown as the hatched histogram – is defined empirically from the LF on the outermost half of the WF4 camera field, which is furthest from the center of VCC 1104 and in which the stellar density is lowest. However, even at the outer edges of the field, the RGB population from the galaxy contributes noticeably to $b$ and thus the “true” background level is significantly lower than is shown here. Lower panel: Results of the Sobel edge-detection algorithm, as applied to the smoothed and normalized LF. The function $E(I)$ shows a sharp peak wherever it passes through a rapid change in the LF. The AGB population shows up as a small “edge” at $I \sim 26.3$, but it is the peak at $I \sim 26.7$ which we identify as the RGB tip.

Fig. 2. — Fiducial giant branches for standard Milky Way globular clusters (absolute magnitude $M_I$ against color $(V-I)_0$). The clusters measured by Da Costa and Armandroff (ref. 5) have been recalibrated through the Hipparcos subdwarf parallax distance scale (ref. 30). The sequence of cluster RGB’s shown covers the metallicity range $[\text{Fe/H}] = -2.2$ for M15 (leftmost line) up to $[\text{Fe/H}] = -0.7$ for 47 Tucanae (rightmost line); over this range, the red giant branch tip is virtually constant at $M_I(\text{TRGB}) = -4.2 \pm 0.1$. Encouragingly, recent theoretical RGB models (ref. 31) agree well with the empirical calibration.
