Cepheid and SNIa Distance Scales.

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Abstract. We first discuss why there remains continuing, strong motivation to investigate Hubble’s Constant. Then we review new evidence from an investigation of the Galactic Open Clusters containing Cepheids by Hoyle et al. that the metallicity dependence of the Cepheid P-L relation is stronger than expected. This result is supported by a new analysis of mainly HST Distance Scale Key Project data which shows a correlation between host galaxy metallicity and the rms scatter around the Cepheid P-L relation. If Cepheids do have a significant metallicity dependence then an already existing scale error for Tully-Fisher distances becomes worse and the distances of the Virgo and Fornax clusters extend to more than 20Mpc, decreasing the value of $H_0$. Finally, if the Cepheids have a metallicity dependence then so do Type Ia Supernovae since the metallicity corrected Cepheid distances to eight galaxies with SNIa now suggests that the SNIa peak luminosity is fainter in metal poor galaxies. As well as having important implications for $H_0$, this would also imply that the evidence for a non-zero cosmological constant from the SNIa Hubble Diagram may be subject to corrections for metallicity which are as big as the effects of cosmology.

1. Status of Extragalactic Distance Scale

One major motivation for studying Hubble’s Constant is the complicated nature of the current standard model in cosmology, $\Lambda$-CDM. In this model, to order of magnitude, $\Omega_{\text{baryon}} \approx \Omega_{\text{CDM}} \approx \Omega_\Lambda$ and this seems unnatural. The coincidence between the CDM and Baryon densities worried a few when CDM was first introduced (Peebles 1984, Shanks 1985). The coincidence between $\Omega_\Lambda$ and the others worried many more (eg Dolgov, 1983, Peebles and Ratra, 1988 and Wetterich, 1988). These fine-tuning problems of the standard model are compounded by the fact that the inflation model on which the standard model sits, was partly based on a fine-tuning argument, the flatness-problem; to begin by eliminating one fine tuning problem only to end up with several gives the appearance, at least, of circular reasoning!

Shanks (1985, 1991, 1999) noted that a simpler model immediately became available if $H_0$ actually lay below 50 kms$^{-1}$ Mpc$^{-1}$. An inflationary model with
Figure 1. A comparison between HST Cepheid and TF distances which suggests that TF distances show a significant scale-error with the TF distance to galaxies at the distance of the Virgo cluster being underestimated by $22\pm 5.2\%$. The dashed line shows the best fit with $(m-M)_{TF} = 0.915 \pm 0.036 \times (m-M)_{Ceph} + 2.204$.

$\Omega_{baryon}=1$ is then better placed to escape the baryon nucleosynthesis constraint. Simultaneously, the low value of $H_0$ means that the X-ray gas in the Coma cluster increases towards the Coma virial mass and the lifetime of an Einstein-de Sitter Universe extends to become compatible with the ages of the oldest stars. Given the historical uncertainty there has been in the value of $H_0$, this provides clear motivation for investigating the distance scale route to a better determination of Hubble’s Constant.

2. A New Era for Determining $H_0$

Some 25 galaxies have had Cepheids detected by HST. Seventeen of these were observed by the HST Distance Scale Key Project (Freedman et al, 1994). Seven were observed in galaxies with SNIa by Sandage and collaborators (eg Sandage et al, 1996) and M96 in the Leo I Group was observed by Tanvir et al (1995). In Fig. 1 we use these data to update the comparison of I-band TF distances of Pierce & Tully (1992) with HST Cepheid distances. As can be seen, the result implies that TF distance moduli at Virgo underestimated by $\approx 25\pm 5\%$. This reduces Tully-Fisher estimates of $H_0$ from $\approx 85$ to $\approx 65\text{km s}^{-1}\text{Mpc}^{-1}$ (Giovanelli et al, 1997, Shanks 1997, Shanks, 1999, Sakai et al, 1999). The correlation of Cepheid residuals with line-width suggests TF distances may be Malmquist biased - possibly implying a bigger TF scale error at larger distances. This clear problem for TF distances, which previously has been the ‘gold standard’
Figure 2. The UBV 2-colour plot from Hoyle, Shanks and Tanvir (2001) for the Galactic open cluster, NGC7790, which contains 3 Cepheids. The data is not well fitted by a solar metallicity, zero-age main sequence 2-colour diagram since different values of the reddening, E(B-V) are implied by the B stars and the F stars as shown. One interpretation is that the correct E(B-V) is given by the B stars and that the F stars are showing UV-excess caused by the cluster metallicity being significantly lower than Solar.

of secondary distance indicators, warns that errors in the extragalactic distance scale may still be seriously underestimated!

3. NGC7790 Cepheid metallicity dependence?

New JKT 1.0m + CTIO 0.9m + UKIRT UBVK photometry of Cepheid Open Clusters by Hoyle et al. (2001) has uncovered an anomaly in the NGC7790 UBV 2-colour diagram, in that the F stars in the cluster show a strong UV excess with respect to zero-age main sequence stars (see Fig. 2). The result is confirmed by independent photometric data (Fry, 1997, Fry and Carney, 1997) as shown in Fig. 7b of Hoyle et al (2001). If the UV excess is caused by metallicity then NGC7790 would have [Fe/H] \approx -1.5 ! To keep the Galactic Cepheid P-L relation as tight as previously observed implies that Cepheids may have a stronger metallicity dependence, \Delta M \approx -0.66\Delta [Fe/H], than previously expected, in the sense that low metallicity Cepheids are intrinsically fainter. Currently we are obtaining metallicities for the F stars in NGC7790 in order to confirm this result.
Figure 3. Relationship between mean r.m.s. dispersion (V-band) about the Cepheid P-L relation and metallicity of HII regions in the vicinity of the Cepheids. Data from the H_0 Key Project team is shown as squares. Sandage et al data is shown as circles and the Tanvir et al data as a triangle. Finally, the LMC is shown as a cross. Dashed vertical lines show the effect of removing outliers in the P-L relations of two galaxies. The result of a least squares fit to the data is also shown.

4. HST Cepheid metallicity dependence

Meanwhile, Allen & Shanks (2001) have found an \( \approx 3\sigma \) correlation between dispersion around the Cepheid P-L relation and galaxy metallicity for HST Cepheid galaxies (see Fig. 3). This again suggests a strong Cepheid P-L metallicity dependence and tends to support the results described above. The more extended star-formation history of high metallicity galaxies may leave a wide range of metallicities than in low metallicity galaxies like the LMC, resulting in a higher P-L dispersion if Cepheid luminosities at given period depend strongly on metallicity.

Allen & Shanks (2001) also obtain Cepheid distances via truncated maximum likelihood P-L fits to account for magnitude incompleteness caused by the non-negligible scatter in the HST P-L relations. They found that Cepheid galaxy distances at the limit of HST reach are too low. The higher than expected P-L dispersion for distant, metal-rich galaxies accentuates this effect. The conclusion is that current HST Cepheid distance moduli may be underestimated by more than 0.5 mag at the redshift of Virgo and Fornax due to both metallicity and statistical incompleteness bias. The TF distances discussed above are then underestimates by approximately 1 magnitude.
Eight HST Cepheid galaxies also have Type Ia distances. Correcting the Cepheid scale for metallicity and incompleteness bias as above and then using these distances to derive peak luminosities using the SNIa data from Gibson et al. (2000), implies a strong correlation between Type Ia peak luminosity and metallicity. Such a scatter in SNIa luminosities could easily be disguised by magnitude selection effects at moderate redshifts. At higher redshift the correlation is in the right direction to explain away the need for a cosmological constant in the Supernova Hubble Diagram results, since galaxies at high redshift might be expected to have lower metallicity. Thus the conclusion is that if Cepheids have strong metallicity dependence then so have SNIa and therefore SNIa estimates of $q_0$ and $H_0$ may require significant corrections for metallicity.

5. Conclusions - Implications for $H_0$ and SNIa

Our conclusions are as follows:-

- Key Project HST Cepheid distances imply Tully-Fisher distances at Virgo/Fornax are underestimated by $\approx 25\pm5\%$, reducing $H_0$ from $\approx 85$ to $\approx 65\text{km s}^{-1}\text{Mpc}^{-1}$.

- TF distances may be Malmquist biased, suggesting there may be a bigger TF scale error at larger distances.
• If the UV excess of F stars in open cluster NGC7790 is caused by low metallicity then Cepheids have a strong metallicity dependence, $\Delta M \approx -0.66\Delta[Fe/H]$.

• Current HST Cepheid distances may be significantly underestimated at Virgo/Fornax redshifts due to metallicity and magnitude incompleteness bias, implying that values of $H_0 < 50 \text{km s}^{-1} \text{Mpc}^{-1}$ may still not be ruled out.

• If Cepheids have a strong metallicity dependence then so have SNIa. Thus significant metallicity corrections may need to be applied to the Type Ia Hubble Diagram before reliable estimates of $q_0$ or $H_0$ can be made.

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