Cepheid Luminosity Versus Galaxy Rotation Speed: $L \propto v^{0.7}$

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Abstract

The distance modulus of a galaxy determined from Cepheids differs from its distance modulus determined from Tully-Fisher by an amount that is proportional to the galaxy’s line width, $W_R$: $\Delta \mu \propto (-1.73 \pm 0.46) \log W_R$. While a miscalibration of the slope of Tully-Fisher could in principle produce this effect, we argue that such a miscalibration is very unlikely. The other possible explanation is that the inferred Cepheid luminosity is correlated with the rotation speed $v$ (and hence $W_R$) of its parent galaxy: $L \propto v^{0.7}$. (This proportionality is superposed on the well-established relation between period and luminosity.) Such a dependence would be expected if Cepheid luminosity is correlated with metallicity, since galaxies with deeper potential wells tend to retain more of their metals. It would induce a discrepancy of 0.83 mag between $H_0$ determinations that are calibrated using M31 ($\log W_R = 2.71$) and the $H_0$ determination from SNIa, which is calibrated in galaxies with mean line width $\langle \log W_R \rangle = 2.23$. A discrepancy of 0.83 mag corresponds to the difference between 80 km s$^{-1}$ Mpc$^{-1}$ and 55 km s$^{-1}$ Mpc$^{-1}$, very similar to the actual discrepancy reported in the current literature.

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1. Introduction

Cepheids are the most luminous primary distance indicators. As such, they provide the only method to make direct measurements of the distance to galaxies outside the Local Group. Even so, prior to this decade Cepheid measurements were limited to galaxies within a few Mpc. With the advent of the Hubble Space Telescope (HST) Key Project (Freedman 1997 and references therein), however, Cepheid distance determinations are being obtained for galaxies as far as the Virgo and Fornax clusters. The plan of the Key Project is to calibrate and so cross-check many secondary distance indicators.

A major potential problem for this program is that the inferred Cepheid luminosities (and so the inferred distances) may be a function of metallicity. If so, one could in principle correct the Cepheid distances by determining the correlation of inferred distance with metallicity and then measuring the metallicity of the individual galaxies in which the Cepheids lie. In practice, it is difficult to obtain reliable metallicities for distant galaxies. Freedman & Madore (1990) argued that there is no significant correlation between metallicity and inferred distance based on their analysis of Cepheids found in three fields of varying metallicity in M31. However, Gould (1994) re-analyzed the same data using a more rigorous statistical procedure and found a significant dependence over the metallicity range $-0.5 < \text{[Fe/H]} < 0.2$. Depending on assumptions about systematics, he measured a slope of either

$$\frac{\Delta \mu}{\Delta \text{[Fe/H]}} = 0.88 \pm 0.16, \quad \text{or} \quad \frac{\Delta \mu}{\Delta \text{[Fe/H]}} = 0.56 \pm 0.20,$$

(1.1)

where $\Delta \mu/\Delta \text{[Fe/H]}$ is the correction to the apparent distance modulus per dex of metallicity. The theoretical work of Stothers (1988) and Stift (1995) predict effects of the same order.

Gould (1994) argued that if this relation continued to lower metallicities, it could well explain the discrepancy between different determinations of the Hubble Constant ($H_0$). For example, the calibration of type Ia supernova is based on Cepheid measurements of metal-poor galaxies (whose distances would be relatively overestimated) while the methods of surface brightness fluctuations and planetary nebulae are calibrated in M31 (whose distance would be relatively underestimated). However, the one test that was then available, comparison of the Cepheid and RR Lyrae distances to IC1613, did not appear to confirm the trend.

Subsequently, Beaulieu et al. (1997) found a somewhat smaller dependence ($\Delta \mu/\Delta \text{[Fe/H]} = 0.44_{-0.2}^{+0.1}$) by comparing Cepheids in the Large and Small Magellanic Clouds. They also suggested that much of the conflict between different determinations of $H_0$ could be resolved by taking this effect into account.
Here we show that the ratio of the distance of a galaxy as determined from Cepheids to its distance as determined from Tully-Fisher is a strong function of the galaxy’s rotation speed \( v \) (as inferred from its line width \( W_R^i \)):

\[
\frac{D_{\text{Ceph}}}{D_{\text{TF}}} \propto v^{-0.35}.
\]  

(1.2)

We argue that this dependence is not likely to be due to a miscalibration of the slope of the Tully-Fisher relation. We therefore conclude that Cepheid distances as presently calibrated deviate systematically from the true distances by an amount that depends on the rotation speed of the galaxy. Such a correlation is plausible because galaxies with deeper potential wells retain more of their metals and, according to equation (1.1), Cepheids of higher metallicity are brighter. We therefore interpret equation (1.2) as implying

\[
L_{\text{Ceph}} \propto v^{0.7}.
\]  

(1.3)

This proportionality is valid at fixed period and is superposed on the well-established relation between period and luminosity.

If confirmed by continued investigations, the correlation expressed in equation (1.3) could prove extremely useful. It would mean that rotation speed, which is usually quite easy to measure, could be used as a proxy for metallicity in determining the correction to Cepheid distances.

2. Data

Shanks (1997) finds the zero-point of Tully-Fisher is \(0.46 \pm 0.14\) mag brighter when calibrated from 11 galaxies with \(HST\) Cepheid distances than it is based on the traditional ground-based calibration. Here we repeat Shanks’ analysis but with two changes. First, Shanks effectively fits the data to a model with two parameters: the zero-points of the \(HST\)-calibrated and ground-calibrated Tully-Fisher relations. To these we add a third parameter, the line width of the galaxy corrected for inclination, \(W_R^i\). Second, for our ground-based sample we restrict attention to the four galaxies with good \(BVRI\) Cepheid distances, whereas Shanks considers six galaxies. We do so in order to make this sample (like the \(HST\) sample) as homogeneous as possible and in particular to minimize errors that might be introduced by poorly determined extinction.

Figure 1 shows the distance-modulus difference \((\Delta \mu = 5 \log \frac{D_{\text{Ceph}}}{D_{\text{TF}}})\) versus \(\log W_R^i\) for 15 galaxies. The open circles are taken from Table 1 of Shanks (1997). The error bars are determined by adding the Cepheid and Tully-Fisher
errors in quadrature. The solid triangles represent the distance modulus difference of ground-based BVRI Cepheid distances with Tully-Fisher distances. In order of increasing line width, the Cepheid distances for NGC300, M33, M81, and M31, are taken from Freedman et al. (1992), Freedman, Wilson, & Madore (1991), Madore, Freedman, & Lee (1993), and Madore & Freedman (1991). The Tully-Fisher distances to these four galaxies are derived using the calibration, line widths, B magnitudes, and internal and external extinction from Pierce & Tully (1992). The Tully-Fisher errors are taken to be 0.30 mag and these are again added in quadrature to the Cepheid errors as reported by the observers.

We fit the data to the form

$$\Delta \mu = \alpha + \beta (\log W_R^i - 2.5) + \delta_{HST},$$

(2.1)

where $\delta_{HST}$ is defined to be zero for the four local calibrator galaxies. We find that

$$\alpha = 0.10 \pm 0.17, \quad \beta = -1.73 \pm 0.46, \quad \delta_{HST} = 0.35 \pm 0.20,$$

(2.2)

and $\chi^2 = 6.37$ for 12 degrees of freedom. Note that the slope $\beta$ is detected at the 4 $\sigma$ level so that from a statistical point of view it is certainly justified to introduce this third parameter.

The offset $\delta_{HST}$ is detected only at the 2 $\sigma$ level, so the existence of an offset may or may not be a real effect. If this parameter is removed from equation (2.1), we find a best fit of

$$\alpha = 0.34 \pm 0.09, \quad \beta = -1.73 \pm 0.46,$$

(2.3)

and $\chi^2 = 9.48$ for 13 degrees of freedom. That is, the slope is unaffected by assumptions about the existence of an offset. To the eye it may appear that the point at far upper left (IC4182) plays an unreasonably large role in the fit. However, even if this is removed, the best fit parameters change by well under 1 $\sigma$. In particular the slope is $\beta = -1.68 \pm 0.59$. 
3. Discussion

Barring an extreme statistical fluctuation, the slope $\beta = -1.73$ found in the previous section must be due to systematic errors in either Tully-Fisher distances, Cepheid distances or both. If, for example, the slope of the Tully-Fisher relation had been improperly calibrated, and it was actually 1.73 higher ($-5.75$ rather than $-7.48$ in $B$), then the entire effect seen in Figure 1 would be explained.

Is such a large error in the slope of Tully-Fisher possible? This slope is determined from a group of galaxies in the Ursa Major cluster by plotting their apparent magnitudes against their line widths. A quick glance at Figure 3 from Pierce & Tully (1992) shows that the fit is extremely good. The Ursa Major galaxies are assumed all to be at the same distance, but even if they were not, this would only increase the scatter on the diagram and would not change the slope. The one remaining possible problem with Tully-Fisher would be if its slope in Ursa Major differed substantially from that of the galaxies plotted in Figure 1. This solution appears highly implausible to us.

The alternative explanation is that Cepheid luminosities (and therefore inferred Cepheid distances) depend on the rotation speed of the galaxy in which they happen to lie. As discussed in § 1, a dependence with this sign is expected if the inferred Cepheid luminosity (taking account of the apparent extinction as inferred from observed colors) rises with increasing metallicity. Although metallicities are not available for most of the sample, we estimate very roughly that over the range of line widths probed ($\Delta \log W_R^i \sim 0.8$) the metallicity varies by 1.5 dex. We make this estimate by assuming that for the lowest line widths, $[\text{Fe}/\text{H}] \sim -1.3$ (Beaulieu et al. 1997 and references therein), and for the highest line widths, $[\text{Fe}/\text{H}] \sim 0.2$ (Freedman & Madore 1990 and references therein). This leads to an estimate $\Delta \mu / \Delta [\text{Fe}/\text{H}] \sim 1.15 \pm 0.31$, in qualitative agreement with the range of values found by Gould (1994) and reproduced in equation (1.1). We conclude that there is a strong case that the slope seen in Figure 1 is due primarily to a correlation between Cepheid distances and galaxy line widths which is rooted in the dependence of inferred Cepheid luminosity on metallicity.

As discussed by Gould (1994) and Beaulieu et al. (1997), if Cepheid distances depend on metallicity, then some of the divergent estimates of the Hubble constant can be reconciled. For example, surface brightness fluctuations (Tonry et al. 1997) and planetary nebula (Jacoby 1996) which are fundamentally calibrated in M31 ($\log W_R^i = 2.71$) yield $H_0 \sim 80 \text{ km s}^{-1} \text{ Mpc}^{-1}$, while supernova type Ia (Sandage et al. 1996) which are calibrated in 7 galaxies with mean $\langle \log W_R^i \rangle = 2.23$ yields $H_0 \sim 55 \text{ km s}^{-1} \text{ Mpc}^{-1}$. That is, they differ by 0.81 mag. The discrepancy that we would expect based on equation (2.2) is $1.73 \times (2.71 - 2.23) = 0.83$ mag.
Finally, we note that while the evidence that we find for an offset between the local and \textit{HST} calibrations of Tully-Fisher is not as strong as that reported by Shanks (1997), we do think that this question warrants further investigation. We can think of two effects that might give rise to such an offset. First, it is possible that the \textit{HST} Cepheids come preferentially from more outlying (and so metal-poorer) regions of galaxies than do the ground-based Cepheids. This would cause them to be systematically fainter for galaxies of the same line width. Second, environment may affect either the Tully-Fisher or the Cepheid determinations. The \textit{HST} Cepheids come preferentially from clusters and of the two galaxies that appear to lie closer to the ground-based triangles in Figure 1, one is a field galaxy and the other is from the relatively quiescent Leo Group.

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FIGURE CAPTIONS

1) Difference ($\Delta \mu$) between distance moduli as determined from Cepheids and Tully-Fisher as a function of galaxy line width. Open circles are for HST Key Project galaxies and solid triangles are for local Tully-Fisher calibrators with BVRI data. Solid lines are a 3-parameter fit: one zero-point for the HST Cepheids, one for the ground-based Cepheids, and a single slope for both. The dashed line is a 2-parameter fit with one zero-point for all galaxies.
$\Delta \mu$ (Cepheids - Tully-Fisher) vs $\log W_R$