Recalibration of Luminosity–HI Linewidth Relations and $H_0$

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ABSTRACT. A recalibration of the luminosity–linewidth technique is discussed which introduces
(i) new cluster calibration data, (ii) new corrections for reddening as a function of inclination, and
(iii) a new zero-point calibration using 13 galaxies with distances determined via the cepheid period–
luminosity method. It is found that $H_0 = 82 \pm 16$ km s$^{-1}$ Mpc$^{-1}$ (95% confidence).

1. Introduction

Good relative distances to galaxies can be found from the correlations between their
global luminosities and rotation velocities (Tully & Fisher 1977). It is true that today
there are several methods with smaller apparent scatter, such as exploitation of the plan-
etary nebula luminosity function (Jacoby, Ciardullo, & Ford 1990), surface brightness
fluctuations (Tonry, Ajhar & Luppino 1990), and type Ia supernova peak brightesses
(Reiss, Press, & Kirshner 1996). However the luminosity–rotation rate technique is one
that can be applied to a large fraction of disk galaxies, hence thousands of cases all over
the sky and out to substantial redshifts. It remains the most important distance tool
for studies of deviations from the universal expansion. It can give an estimate of the
Hubble Constant with good $\sqrt{N}$ statistics if given a zero-point calibration. To make the
calibration, we look at galaxies that obey the correlations and which have independently
known distances.

There has been recent progress in the determination of distances to potential calibra-
tors which makes it a good time to redefine the properties of the luminosity–linewidth
correlations. The Hubble Space Telescope (HST) has been used to discover cepheid
variable stars in 8 suitable galaxies and to determine distances based on the period–
luminosity relations for those stars. Today there are 13 appropriate galaxies with dis-
tances determined with this method.

In addition to the new zero-point calibration there are two other significant improve-
ments to the methodology. First, more high quality data and more complete samples are
available. Second, multicolor information extending to the infrared now provides better
information about obscuration to luminosities as a function of inclination.
2. Three Calibration Clusters

Malmquist bias caused by a magnitude limit (Malmquist 1920) can be neutralized if one has a suitable calibration sample. There are three requirements: one, the sample should be *complete* to an absolute magnitude limit fainter than the targets to be subsequently studied; two, the intrinsic properties of the calibrators should be *statistically similar* to the targets; three, the *quality* of the observations should be similar. With sufficient effort the completeness requirement can be met, and with sufficient care the quality of the observed material should be comparable between data sets. It is impossible to be certain that the intrinsic properties of the calibrators are truly representative but there can be some confidence in this proposition if several alternative calibration samples, representative of different environments, have consistent correlation slope and scatter characteristics.

The current calibration uses 89 galaxies in three rather different clusters. The obvious advantage of clusters is the possibility to achieve completeness within a volume to an absolute magnitude limit. The disadvantage is that cluster galaxies may be systematically different from those in the field. Two of the ‘clusters’ used in this study are poor specimens as clusters and were chosen because the environments are arguably the same as the ‘field’. The Ursa Major Cluster contains 62 galaxies with $M_{B,i}^b < -16.5^{m}$, no ellipticals, only 10 S0-S0/a types, and the rest are spirals and irregulars with normal HI content. The cluster has no central core, the radial velocity dispersion is only $\sim 150$ km/s so a crossing time is $\sim 0.5 H_0^{-1}$, and it can be inferred that the region is in an early stage of collapse (Tully et al. 1996). Excluding galaxies with $i < 45^\circ$, $T < S_a$, and interacting/peculiar, leaves a sample of 37 objects. The Pisces ‘cluster’ has been used frequently for distance scale studies (Aaronson et al. 1986; Han & Mould 1992) but it, too, is composed mainly of HI-rich galaxies scattered about several insubstantial knots of early systems and may more properly be viewed as a prominent section of an intracluster filament (Sakai, Giovanelli, & Wegner 1994). Excluding galaxies with $i < 60^\circ$, $T < S_a$, interacting, or with insufficient $S/N$ in the HI signal leaves a sample of 25 objects with $M_{B}^{b,i} < -19^{m}$. The third sample comes from the Coma Cluster, certainly a very rich and dense environment quite unlike the field. A calibration based only on this cluster would be subject to justifiable criticism. However, it is found that the properties of the correlations are compatible between this extreme environment and the others which is an argument that the methodology works over a wide range of environmental conditions. The same exclusions as with Pisces leaves a sample of 27 objects with $M_{B}^{b,i} < -19.3^{m}$. In sum, 89 galaxies are used in the present analysis that satisfy magnitude completeness criteria. About 20 galaxies are missing from a truly complete sample to the present limits because the HI detections currently have insufficient $S/N$.

3. Revised Reddening Corrections

Photometry in four bands from $B$ to $K'$, available for the UMa and Pisces samples, make it possible to refine the corrections that must be made for obscuration as a function of inclination. The most sensitive tests use deviations from mean color-magnitude correlations involving $K'$. More inclined galaxies tend to be redder because of obscuration.
Deviations from mean luminosity–linewidth correlations can be used for independent but somewhat less sensitive tests. More inclined galaxies tend to be fainter.

Reddening may be different for different classes of galaxies. Giovaneli et al. (1995) have presented a strong case for a luminosity dependence among spiral systems. There is enough information now available to specify the gross characteristics of this dependency. The results from the 4-band color-magnitude analysis confirms the Giovaneli et al. claim. The four panels of Figure 1 illustrate both the amplitude of the reddening dependency on inclination and the dependency on luminosity. The plots show deviations from mean color–magnitude relations as a function of observed axial ratio, which maps to inclination. Here, $R - K'$ colors are used. Separate luminosity intervals are considered in the separate panels. There is a clear color dependency with axial ratio for the high luminosity systems. The dependency diminishes to negligible for the faintest systems. Curves that describe the relations are of the form $A_R = \gamma_R \log(a/b)$. The dependence of the amplitude parameter $\gamma_R$ on luminosity is displayed in Figure 2.

Giovanelli et al. (1995) found a similar dependence on luminosity though of somewhat larger amplitude. The dashed line in Fig. 2 represents a compromise between their results and ours (translating from $I$ band where the Giovanelli et al. work was done) and the corrections that are used are based on this compromise solution. The enhanced corrections toward the bright end of the luminosity–linewidth relations causes a steepening of those relations, particularly at the shorter wavelength bands. As a consequence, there is a considerably weaker color dependence of the slopes than experienced previously. The new reddening corrections are discussed by Tully et al. (1998).

4. Zero-Point Calibration

The neutralization of Malmquist bias is achieved with regressions that accept errors in the distance independent variable (ie, the linewidths) in a sample that is complete to a limit in the distance dependent variable (ie, magnitudes). At a given magnitude, galaxies on either side of the mean linewidth are equally accessible. It is found that the slopes of the regressions on linewidth are compatible between the three cluster samples. Hence, it seems justified to slide the separate cluster correlations in magnitude to find the relative distance differences that result in a common correlation. A further constraint is provided by the requirement that the relative distances agree between the measurements at different passbands: the agreement between the $B, R, I$ filters is $0.03^m$ rms. After the superposition of the three clusters by minimization of the rms scatter in linewidths we define the slopes of the correlations and measure the relative distances of the three clusters. Pisces is determined to be $2.55^m$ farther away than UMa and Coma is determined to be $3.33^m$ farther away than UMa.

In the regime with $M_B^i < -16.5^m$, there are now 8 galaxies with HST cepheid measurements to add to 5 galaxies with ground-based distance determinations from cepheid observations. These 13 galaxies lead to luminosity–linewidth correlations that are consistent with the combined cluster slopes with even less scatter. There is no contradiction to the proposition that the calibrators are similar to the cluster galaxies in properties and provide a reasonable zero-point determination to the magnitude scale. The $R$ band luminosity–linewidth relation for the combined three clusters and calibrator
Fig. 1. Deviations from the mean $R - K'$ color–magnitude relation as a function of axial ratio. A face-on galaxy has $b/a = 1$ and an edge-on galaxy has $b/a \sim 0.2$. The 4 panels illustrate 4 separate bins in $K'$ luminosity, from high luminosity at the upper left to low luminosity at the lower right. Best fit curves are of the form $A_R = \gamma R \log(a/b)$. Most of the evident effect of reddening is in the $R$ band rather than at $K'$. 
Fig. 2. Luminosity dependence of the obscuration amplitude parameter in the $R$ band. *Boxes:* values of $\gamma_R$ corresponding to the curves in Fig. 1a–d. *Triangles:* values of $\gamma_R$ determined from deviations from the mean luminosity–linewidth relation at $R$. *Solid line:* best fit to the plotted data. *Dotted line:* adopted correction; compromise between best fit shown here and Giovanelli et al. results.

data sets is displayed in Figure 3. Relations with similar scatter exist at $I$ and $K'$ and, with greater scatter, at $B$. The calibrators have not been observed at $K'$ so, as yet, only relative distances can be obtained at that band.

5. A Determination of $H_0$

From the combination of the $B, R, I$ fits, the Ursa Major Cluster is found to have a distance modulus of 31.33 corresponding to a distance of 18.5 Mpc. From the relative distances of the clusters, Pisces is at 60 Mpc and Coma is at 86 Mpc. Han & Mould
Fig. 3. $R$-band luminosity–linewidth relation. The linewidth parameter $W_{R}$ is a transformation from the observed HI 20% linewidth to a value statistically equal to twice the maximum rotation velocity. Symbols denote the various samples: open circles–UMa, filled circles–Pisces, stars–Coma, filled boxes–calibrators with cepheid distances.

(1992) report the mean redshifts of these clusters in the microwave background frame to be 4771 km s$^{-1}$ and 7186 km s$^{-1}$, respectively. The Pisces and Coma regions are sufficiently distant that their velocities may be a close approximation to the Hubble expansion. The distances to these clusters indicate $H_0 = 80$ and 84 km s$^{-1}$ Mpc$^{-1}$, respectively.

Statistical errors are estimated to be 8% from the typical rms scatter of 0.40$m$ and the numbers of objects in the samples. There is about a 7% uncertainty due to possible peculiar velocities of the two distant clusters. The present zero-point assumes a modulus of 18.50 for the Large Magellanic Cloud, uncertain to 10%. Systematic errors are estimated to be $< 10\%$ from the observation that the scatter in the luminosity–linewidth
relations is $\sim 0.4''$ in case after case with consistency in slopes between different environments. Hence, systematics, apart from occasional blunders in photometry, are probably not a large fraction of the scatter; ie, $< 1/2 \times 0.4'' \sim 0.2$.

These results are $\sim 13\%$ higher than other recent recalibrations of luminosity–linewidth correlations (Mould et al. 1996; Giovanelli et al. 1997). Lower values of $H_0$ are coming from the distances found by the HST measurements of cepheids which tend to give host luminosities that are brighter at a given linewidth than found for the objects studied from the ground. Maybe the difference is just caused by small numbers. There is about a 15% increase of the distance scale measured in this study from the new zero-point calibration.

On the other hand, there is a partially offsetting effect that comes about through the new absorption corrections. More luminous, highly inclined galaxies are made brighter. The galaxies in Pisces and Coma tend to be brighter than in UMa and the samples are restricted to more inclined systems in these clusters. Hence, overall they receive larger corrections and the cumulative effect is to give them smaller distances by roughly 8%.

Compared with earlier measurements, the new cepheid calibration has caused an increase in distances, but the revised reddening corrections has lead to smaller distances at larger redshifts. The overall mix produces a lower $H_0$ than before but only by $\sim 7\%$. It is sobering to see these systematics of order 10% and to appreciate that even these matters we know about are not well resolved. A current estimate of the Hubble parameter is $H_0 = 82 \pm 16$ km s$^{-1}$ Mpc$^{-1}$ (95% confidence) from the luminosity–linewidth method. This error does not include uncertainty in the zero-point attributable to the distance of the LMC. There is work yet to be done.

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