TESTING DISTANCE ESTIMATORS WITH THE FUNDAMENTAL MANIFOLD

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Received 2011 August 23; accepted 2012 January 5; published 2012 February 29

ABSTRACT

We demonstrate how the Fundamental Manifold (FM) can be used to cross-calibrate distance estimators even when those “standard candles” are not found in the same galaxy. Such an approach greatly increases the number of distance measurements that can be utilized to check for systematic distance errors and the types of estimators that can be compared. Here we compare distances obtained using Type Ia supernova (SN Ia), Cepheids, surface brightness fluctuations, the luminosity of the tip of the red giant branch, circumnuclear masers, eclipsing binaries, RR Lyrae stars, and the planetary nebulae luminosity functions. We find no significant discrepancies (differences are <2σ) between distance methods, although differences at the ∼10% level cannot yet be ruled out. The potential exists for significant refinement because the data used here are heterogeneous B-band magnitudes that will soon be supplanted by homogeneous, near-infrared magnitudes. We illustrate the use of FM distances to (1) revisit the question of the metallicity sensitivity of various estimators, confirming the dependence of SN Ia distances on host galaxy metallicity, and (2) provide an alternative calibration of H0 that replaces the classical ladder approach in the use of extragalactic distance estimators with one that utilizes data over a wide range of distances simultaneously.

Key words: distance scale – galaxies: distances and redshifts

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Distance determinations to galaxies are key to many areas of study in extragalactic astronomy, but remain problematic. The potential for systematic errors lingers much of the work, particularly at the accuracy level of a percent or less currently desired (see review by Freedman & Madore 2010). These concerns can be addressed through cross-calibration among techniques that have independent challenges. For example, one estimator might have a hidden dependence on metallicity, another might be more susceptible to internal extinction. One state-of-the-art recent study compares distances obtained using Type Ia supernovae (SNe Ia) and Cepheid variable stars in the same galaxies (Riess et al. 2011) to claim a distance calibration precision of a few percent.

Such cases, where one has distance measurements from a variety of methods for a specific galaxy, are rare for two reasons. First, because distance estimators are often related to distinct stellar populations, they are not often found within the same stellar system. The classic example is the dichotomy between the Galactic environments of RR Lyrae and Cepheids (Baade 1944). Second, and currently most relevant, is that several factors conspire to limit estimators to distinct distance regimes. Cepheid observations, like those of RR Lyrae, eclipsing binaries and the tip of the red giant branch (TRGB), require observations that resolve the stellar populations of the system and are therefore limited to relatively nearby galaxies, even when using the high angular resolution provided by the Hubble Space Telescope. On the other hand, SNe Ia, due to their rarity, tend to be found in more distant galaxies simply because of the gain in search volume with increasing distance. These effects make it quite difficult to compare the results among certain classes of distance estimators. The Riess et al. (2011) study cited above, which is among the most extensive and complete, is based on only eight galaxies with both Cepheid and SN Ia measurements.

One solution to this limitation relies on identifying a distance estimator that can be applied to all galaxies, near and far, early- or late-type, giant or dwarf. Even if such an estimator has a large intrinsic distance uncertainty for any individual galaxy, and so is not ultimately superior to the other estimators, the gains reaped by being able to compare the relative precision and accuracy of the preferred estimators over many tens, if not hundreds of galaxies, is critical. Distance determinations from scaling relations, such as Tully–Fisher (TF; Tully & Fisher 1977) or Fundamental Plane (FP; Dressler et al. 1987; Djorgovski & Davis 1987), span the range of distances probed by many methods and so provide a fiducial against which different distance estimators can be compared. Their shortcoming is that they are each applicable to different, narrow classes of galaxies, limited in type and luminosity, and therefore do not resolve the entire problem.

In a series of papers, we have presented a new scaling relation that is applicable to all galaxies, regardless of luminosity or morphological class (Zaritsky et al. 2006a, 2006b, 2008, 2011). This relation, termed the Fundamental Manifold (FM) in reference to its most direct antecedent, the FP, presents an opportunity to uncover hidden systematic differences among the current set of distance estimators. Here we use existing data, distances from the NED 1-D database and photometry and kinematics compiled within the HyperLeda database (Paturel et al. 2003), to test this basic idea. Neither the data, due to their inhomogeneity, nor the sample, due to the intractable selection criteria, are optimal for precise cross-calibration of distance estimators and eventual application to related problems, such as the measurement of H0. Therefore, the results presented here should be viewed as only illustrative of what an optimized treatment using the FM could yield. In Section 2 we discuss our selection of the sample, in Section 3 we present the results of this comparison among distance estimators, illustrate how the FM can be used to trace potential internal systematic
dependences, and reverse the calibration and use the FM to obtain distances and estimate $H_0$. In Section 4 we summarize our results.

2. THE DATA

2.1. Distances

We utilize the NED 1-D database, which is a compilation of published distances from a wide-ranging set of methods. Without prejudice for or against any of the entries in the database, we calculate the weighted average (weighting inversely by the quoted uncertainty and neglecting the measurement if no uncertainty is given) for each of the distance estimators, for each galaxy. We require at least two measurements using a particular method to calculate a mean distance measurement for a given galaxy. There are 1153 galaxies for which we retrieve a distance using at least one of the methods we are comparing. In Figure 1, we show how distance estimators are often effectively constrained to distinct distance ranges. More critically, the distribution of objects with SN Ia distance measurements overlaps very little with the other methods, limiting the number of systems that can be used to directly check for potential systematic errors in the cosmologically critical SN Ia distances.

2.2. Photometry and Kinematics

To obtain the structural parameters necessary to place a galaxy on the FM, we search the HyperLeda database (Paturel et al. 2003), which provides morphologies, kinematic measurements, magnitudes, and structural parameters, the latter two based on the work of Prugniel & Heraudeau (1998), for those galaxies for which we obtained distances from NED 1-D. For the HI rotation measurements, we adopt the homogenized values provided in HyperLeda, which include an inclination correction. We calculate weighted averages of both the stellar rotation and velocity dispersion measurements where available, and only accept values only if there are at least two measurements of either quantity, and if either the rotation or dispersion is larger than 10 km s$^{-1}$, to avoid the systems with the largest fractional uncertainties. For the morphologies, we average T-Types using uniform weights and require a minimum of only one measurement. The photometric parameters are taken from the archival $B$-band data, which are the most prevalent.

There are various reasons (star formation, extinction) to use redder-band photometry, and we will discuss results using the available $I$-band data. In the future, we will use the S$^4$G database (Sheth et al. 2010) to obtain photometric parameters at 3.6 $\mu$m, which appear to significantly reduce the scatter in scaling relations (Freedman & Madore 2011; Freedman et al. 2011). The distribution of morphologies, for the subsample of galaxies for which morphologies are cataloged, is shown in Figure 2. Again, we find that certain distance estimators are limited in their coverage, making comparison on an object-by-object basis difficult. There are 343 galaxies with both distance measurements and the necessary data to place them on the FM.

For a subset of the data, we also obtain an optical color, $(B - V)_0$, from the RC3 catalog (de Vaucouleurs et al. 1991) to investigate the role of color, and, by inference, of differences in the stellar mass-to-light ratio, on a galaxy’s deviation from the FM. We use observed magnitudes rather than $k$-corrected rest-frame magnitudes, because, despite the large range in distance of the NED 1-D sample, those galaxies with all of the necessary data lie at $cz < 6000$ km s$^{-1}$. One evident avenue for progress is obtaining these data for a larger fraction of the galaxies with SN Ia distances, and thereby also extending the sample to greater distances.
Our compilation of the available data is presented in Table 1.

3. THE FUNDAMENTAL MANIFOLD AND TESTS OF DISTANCE ESTIMATORS

3.1. Overview of the Fundamental Manifold

The FM has been described in detail elsewhere (Zaritsky et al. 2008, 2011), but, in summary, it is derived from the virial theorem with the additional information that the mass-to-light ratio within \( r_e \), \( \Upsilon_e \), can be either (1) measured independently (e.g., via strong gravitational lensing) or (2) estimated using an empirical function of the internal kinematics, \( V \), and the surface brightness within \( r_e \), \( I_e \). In the latter case, we have found that the structural differences (spatial and kinematic) among galaxies, other than those captured in the variations in \( \Upsilon_e \), \( r_e \), can be expressed independent of wavelength and has only a zero-point term to calibrate (rather than slope in TF or “tilt” in FP)

\[
\log r_e = 2 \log V - \log I_e - \log \Upsilon_e - C,
\]

where \( V \) is expressed as the combination of pressure (\( \sigma \)) and rotational support (\( v_r \)), \( V^2 \equiv \sigma^2 + v_r^2/\alpha \) (\( \alpha \) is expected to lie between 2 and 3; Weiner et al. 2006; Zaritsky et al. 2011), and \( C \) is a constant that is effectively the zero point of the FM distance estimator. With measurements (or estimates) of all terms on the right-hand side of the equation, one solves for \( r_e \), which, in concert with the angular measurement of \( r_e \), provides the distance. Because we generally lack independent estimates of \( \Upsilon_e \), we use the empirical relationship for \( \Upsilon_e (V, I_e) \) derived from existing data (Zaritsky et al. 2011). Use of the empirical relationship reintroduces wavelength dependences and additional complexity (analogous to FP “tilt”), but the FM still retains the advantage over previous scaling relations in that it is applicable to all galaxies.

As with any empirical relationship, the relationship changes slightly depending on the data used to define it, and uncertainties in the fitting function ultimately translate to systematic uncertainties in the distances estimated using the FM. Consequently, comparing FM distances to those obtained using other distance estimators provides a test of both the FM and the independent distance estimators. Comparisons of the FM and multiple independent methods will allow us to distinguish between systematic problems in the FM versus problems with the individual independent estimators. Here we choose to define the fitting function using only the spheroidal galaxies in the original data (Zaritsky et al. 2008), which are expected to have minimal stellar mass-to-light ratio variations. We exclude globular clusters and ultracompact dwarfs, whose nature is still controversial (see Zaritsky et al. 2011) and that extend the FM beyond the \( r_e \) range needed for this work. Although changes in the fitting function for \( \Upsilon_e \) will affect the results, the fitting function is most constrained in exactly the parameter range most relevant here—that of disk and spheroid galaxies with luminosities around \( L_e \). The functional form we use is

\[
\log \Upsilon_e = 2.12 - 0.28 \log V - 0.82 \log I_e + 0.15 \log^2 I_e
\]

\[
+ 0.26 \log^2 V - 0.09 \log V \log I_e - 0.64.
\]

This equation provides an estimate of \( \Upsilon_e \) in the \( I \) band. There are two related, but distinct, questions that will be addressed in the following section: how much does the use of \( B \)-band magnitudes increase the scatter (there would be no increase if all galaxies had the same \( B-I \) color) and how much scatter is introduced in the \( I \)-band \( \Upsilon_e \) by differences in stellar populations?

To test each distance method, we use the distances provided by NED 1-D to calculate the physical value of \( r_e \) and then place the galaxy on the FM. In our original work, from which we take our fitting function for \( \Upsilon_e \), we used simple Hubble flow distances with an adopted Hubble parameter. Any difference between the true Hubble parameter and that adopted previously will affect the calibration of \( \Upsilon_e \) and \( C \), manifesting itself as a zero-point shift (i.e., as a change in \( C \)). We therefore have freedom to adjust the zero point of the FM as needed (see below for our treatment of this) and so our discussion here focuses on relative differences between distance estimators rather than on an absolute calibration.

3.2. Morphology-related Differences

One consideration before proceeding with our comparison of distance estimators and the FM is that of the appropriate choice of \( \alpha \) in the definition of \( V \). In previous work we adopted \( \alpha = 2 \), as also done by others (e.g., Burstein et al. 1997; Kassin et al. 2007). However, reasonable models suggest that values between 2 and 3 are plausible (see Weiner et al. 2006). Because \( v_r/\sigma \) maps onto morphological type, and morphological type maps onto color, which is presumably related to the stellar mass-to-light ratio, there is the potential to misidentify a relationship between the FM residual (the deviation of a galaxy from the FM) and \( \alpha \), with one that is truly due to color (or vice versa).

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Table 1

The Sample

| Name     | \( B_r \) \((B - V)_0 \) | \( \mu_e \) | \( 2r_e \) (arcsec) | \( v_r, \text{HI} \) (km s\(^{-1}\)) | \( v_r, \text{e} \) (km s\(^{-1}\)) | \( \sigma \) (km s\(^{-1}\)) | \( D_C \) (Mpc) | \( D_{\text{TRGB}} \) (Mpc) | \( D_H \) (Mpc) | \( D_{\text{APF}} \) (Mpc) | \( D_{\text{PN}} \) (Mpc) | \( D_{\text{MR}} \) (Mpc) | \( D_M \) (Mpc) | \( D_H \) (Mpc) | \( c^2 \) (km s\(^{-1}\)) |
|----------|----------------|----------|-----------------|----------------|----------------|--------------|-------------|----------------|-------------|----------------|----------------|----------------|-------------|-------------|--------------|
| NGC 7814 | 11.38         | 0.83     | 22.23           | 118.1          | 230.7          | 0.0          | 172.9       | ...          | ...          | ...          | ...          | ...          | 12.70       | ...          | 1047         |
| NGC 0055 | 8.68          | 0.54     | 22.18           | 400.1          | 58.9           | 0.0          | 0.0         | 1.92         | 2.10         | 0.64         | 0.63         | 0.63         | 0.63         | ...          | 142          |
| NGC 0147 | 10.65         | 0.78     | 24.02           | 376.8          | 0.0            | 26.4         | 0.0         | ...          | ...          | ...          | ...          | ...          | ...          | ...          | 176          |
| NGC 0150 | 11.90         | 0.50     | 21.40           | 63.4           | 164.9          | 0.0          | 0.0         | 0.0          | ...          | ...          | ...          | ...          | ...          | ...          | 1566         |
| NGC 0185 | 10.38         | 0.73     | 22.11           | 177.1          | 0.0            | 23.3         | 0.0         | ...          | ...          | ...          | ...          | ...          | ...          | ...          | ...          |
| NGC 0205 | 9.00          | 0.82     | 21.82           | 292.5          | 0.0            | 33.5         | 0.0         | ...          | ...          | ...          | ...          | ...          | ...          | ...          | ...          |
| NGC 0221 | 1.91          | 0.88     | 18.75           | 65.2           | 0.0            | 80.9         | 0.0         | 0.69         | 0.77         | 0.82         | 0.82         | 0.82         | 0.82         | ...          | ...          |
| NGC 0224 | 4.88          | 0.68     | 19.89           | 802.0          | 0.0            | 183.2        | 0.80        | 0.75         | 0.72         | 0.77         | 0.77         | 0.77         | 0.77         | ...          | ...          |
| NGC 0247 | 9.42          | 0.54     | 23.37           | 492.2          | 249.8          | 0.0          | 3.76        | 3.60         | ...          | ...          | ...          | ...          | ...          | ...          | 142          |
| NGC 0221 | 9.19          | 0.88     | 18.75           | 65.2           | 0.0            | 80.9         | 0.0         | 0.69         | 0.77         | 0.82         | 0.82         | 0.82         | 0.82         | ...          | ...          |
| NGC 0300 | 8.51          | 0.58     | 22.87           | 594.5          | 85.1           | 0.0          | 1.99        | 1.96         | ...          | ...          | ...          | ...          | ...          | ...          | 150          |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Without the proper choice of \( \alpha \) and some means of avoiding differences in stellar mass-to-light ratios beyond those included in the empirical calibration of \( Y_e \), there will be systematic differences when comparing distances to early- and late-type galaxies. We will mitigate this difficulty by (1) proceeding to optimize our choice of \( \alpha \), (2) removing any residual correlation between FM residuals and color, and (3) providing comparisons among galaxies of similar morphological type.

There is indeed a strong correlation between \((B - V)_0\) and \(v_r/\sigma\) (a Spearman rank correlation test for our sample puts the probability of it arising at random at \(4 \times 10^{-5}\)). As such, for the purpose of constraining \( \sigma \) we work with a subsample for which \( v_r/\sigma \) is independent of color (Figure 3); \((B - V)_0 > 0.85\) and \(v_r/\sigma > 0.2\) (the probability of the correlation arising randomly for this sample is 0.79). This particular part of the analysis, the derivation of \( \alpha \), is restricted to early-type galaxies because \( \sigma \) is generally not available for disk galaxies. As a result, the galaxies in Figure 3 are naturally restricted to fairly red colors. If a hidden correlation remains, we expect some of that to influence the best-fit value of \( \alpha \), again because \( v_r/\sigma \) is expected to correlate with color, and eventually lead potentially to differences between FM residuals and morphological type.

For this subsample, we calculate the root mean square (rms) residual about the FM (allowing the zero point to float) and identify the value of \( \alpha \) that minimizes the rms (\( \alpha = 2.68 \); see Figure 4). Reassuringly, this value lies within the theoretically plausible range and we adopt this value of \( \alpha \) for the remainder of this study. However, this calculation is unfortunately quite sensitive to the selected subsample. For example, if we select galaxies that have \((B - V)_0 > 0.8\) (instead of 0.85), then the minimum rms residual occurs at \( \alpha = 1.81 \) (although a correlation between color and \( v_r/\sigma \) still exists at >1\( \sigma \) confidence for this sample and so this sample is not preferred).

The robustness of the \( \alpha \) determination needs to be improved both by obtaining a larger sample of galaxies and by performing this analysis with photometry in a filter band that is less sensitive to morphological type (and, by relation, to color). The effect of varying \( \alpha \) is principally to alter the relative offset between early- and late-type galaxies relative to the FM (see Section 4), but does not affect the conclusions presented in Section 5.

Any remaining systematic behavior of the FM residuals will point to new phenomenon, including systematic errors in distance estimators. We begin by examining the dependence of FM residual to color (Figure 5). The data show a trend of residual with color. It is not surprising that the early-types have near zero mean residual because the FM relationship we use was defined using spheroidal galaxies (from a different sample based on a range of sources, see Zaritsky et al. 2006a, but early-types nonetheless). Neither the sense nor the magnitude of the trend is necessarily straightforward to explain. There is an expectation of a trend with color because the stellar mass-to-light ratio will change with color. However, other factors change as well. For example, the gas mass fraction of a galaxy correlates with color and mass is unaccounted for in the empirical derivation of \( Y_e \) because we used only spheroidal systems.

We use the mean relationship, shown as the line, to correct all of our data (and so subsequently restrict ourselves to systems with available color measurements). If a particular estimator (including the FM) has a systematic error that depends on galaxy type (color), it will contaminate this plot. As with many of the issues raised, we expect this problem to be mitigated using redder photometry, but proceed nonetheless with the data currently available. Recall that our expression for \( Y_e \) provides an estimate of the total \( I \)-band mass-to-light ratio within \( r_e \), even though we are using \( B \)-band magnitudes. This means that there are two potential sources of scatter introduced by stellar population differences. First, there is the possibility of large variations in \( B - I \) within the sample that then introduce scatter because we implicitly assume a constant \( B - I \) color (solar) when converting \( B \)-band luminosity into the corresponding mass in solar masses. Second, scatter can arise from stellar population

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**Figure 3.** Relationship between color and \( v_r/\sigma \) for galaxies in our sample that have published measurements for stellar velocity dispersion, \( \sigma \), and rotation, \( v_r \). We select the subsample with \( B - V > 0.85 \) and \( v_r/\sigma > 0.2 \), separated with dashed lines, for subsequent analysis because it is large and has no measurable relationship between color and \( v_r/\sigma \) (see the text for an expanded discussion of this selection).

**Figure 4.** Residual about the FM as a function of adopted \( \alpha \). The minimum value at 2.68 is chosen for the remainder of the study.
differences and the associated variations in the stellar mass-to-light ratio.

We show, in Figure 6, the distribution of $B - I$ colors for our galaxy sample, and note that a large fraction of the galaxies are fairly well constrained to colors that vary by about 0.3 mag (a constant difference from solar color is not a cause for concern because we eventually renormalize the entire relation using the surface brightness fluctuation (SBF) distances). More importantly, this range of colors produces small scatter (0.046 dex) in $I$ for all galaxies, but not assuming that the stellar populations are all the same. We conclude that the use of $B$-band magnitudes is not a major source of scatter in the FM, if one does correct for differences in stellar mass-to-light ratios using colors.

to reduce the scatter by two simply by observing at $K$. Further gains are possible if extinction is important (Freedman et al. 2011). If other causes, not related to the photometric passband, contribute comparably to the scatter, or if we can partially account for stellar population differences, then we expect less than a factor of two improvement by going into the infrared. For example, the scatter in our $B$-band FM is the same as in our $I$-band FM ($\sim$0.1 dex) because we have accounted for the stellar population differences at $B$.

The key to interpreting our results is to determine whether multiple estimators show the same systematic behavior in FM residuals, in which case the problem is most likely to lie with the FM or the various corrections we have implemented, or if the FM residuals are peculiar for specific estimators, in which case the fault lies with that particular estimator. On the other hand, if none of the estimators exhibit systematic problems relative to the FM, then we will conclude that the estimators and the FM are accurate distance estimators to at least within the quoted uncertainties.

3.3. Comparing Distance Estimators and the FM

Our aim is to test a variety of popular distance estimators to determine which, if any, may lead to distance estimates with systematic errors. Using the FM as a reference, we now compare estimators that we could not previously test against each other. To do this, we plot the galaxies on the FM using the mean trend of FM residual with $B - V$ color for all galaxies, but not assuming that the stellar populations are all the same. We conclude that the use of $B$-band magnitudes is not a major source of scatter in the FM, if one does correct for differences in stellar mass-to-light ratios using colors.
Figure 7. FM using measured distances. We compare the FMs using different distance estimators and divide the sample into pressure supported (upper panels) and rotationally supported (lower panels). Furthermore, we color and shape code according to galaxy morphology (blue squares for late-type, red circles for early-type). The y-axis is log $r_*$ in kpc, and the x-axis is $2 \log V - \log L_\odot \log \Upsilon_e - C$, where $V$ is in km s$^{-1}$, $L_\odot$ is in $L_\odot$, $\Upsilon_e$ is in solar units, and $C$ is obtained by calibrating to the sample of SBF distances for the pressure-supported galaxies. The line is the 1:1 expectation, not a fit to the data. Individual uncertainties are not plotted, but the scatter is used to estimate the uncertainty in the mean offsets from the 1:1 line.

(A color version of this figure is available in the online journal.)

hand, if the normalization or slope errors appear endemic, then the problem will lie with the FM.

For each distance estimator with more than 10 galaxies with all the necessary data, we present the results, showing the pressure-supported systems, which have velocity dispersions and sometimes also have stellar rotation values, $v_r$ (upper panels in the figure), and the purely rotationally supported galaxies, which have no quoted stellar velocity dispersion and for which we adopt the H$\alpha$ width as a measure of $v_r$ (lower panels). In general, if there is a stellar velocity dispersion measurement, the galaxy is a pressure-supported system ($v_r/\sigma < 1$). Within each panel we also color-code based on morphology, dividing the early- and late-type galaxies at a T-Type of 1. We have set the zero point of the FM, $C$, using the results from the pressure-supported, SBF sample, which is our largest subsample of galaxies and also predominantly consists of early-type galaxies, which will be less susceptible to extinction and stellar population variations.

A cursory examination of the panels shows that there are no disastrous problems with any of the distance estimators as applied to any of the galaxy subsamples, even though some perform better than others (either in terms of zero point or scatter). There are a few individual galaxy outliers, although it is often the same galaxy that is an outlier in multiple panels because distances are available from multiple estimators, suggesting that fault lies not with the distance estimate but rather with one of the other parameters that enters the FM. NGC 4704, which has an unusually large residual in the SN Ia panel, is removed from subsequent analysis of the SN Ia distance estimator. In Figure 8 we show the results for galaxies that have distances measured using eclipsing binaries, RR Lyrae, and masers.

In Figure 9 we compare the mean residual and the uncertainty in the mean between the various distance methods, for pressure-supported and rotationally supported galaxies (the values are given in Table 2). The agreement is strikingly good, with the possible exception of results obtained using the "other" methods, although there the uncertainty is large because of the small number of galaxies in that category. None of the differences are statistically significant, but the magnitude of differences is in the range that is potentially important for distance estimators ($\sim$ few %). For example, the difference in zero points obtained using the TRGB and SN Ia methods and pressure-supported galaxies is 0.062, which corresponds to an inferred distance difference of 15%. Unfortunately, for the purpose of identifying if there are any real discrepancies at the target level of a few percent, the
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Figure 9. Mean offsets from FM using distances derived from different estimators. Red circles denote the results for pressure-supported galaxies, while blue squares those for rotation-supported galaxies. “Other” includes results from eclipsing binaries, RR Lyrae and masers for both rotation- and pressure-supported galaxies. Error bars represent the dispersion in the mean value. The distances are referenced by definition to the SBF calibration for pressure-supported galaxies.

(A color version of this figure is available in the online journal.)

Table 2

Mean Offsets from FM

| Distance Estimator | Pressure Supported | Rotationally Supported |
|--------------------|--------------------|------------------------|
| Cepheids           | $-0.002 \pm 0.134$ | $-0.025 \pm 0.023$     |
| SBF                | $0.000 \pm 0.009$  | $-0.004 \pm 0.039$     |
| SN Ia              | $-0.062 \pm 0.027$ | $-0.020 \pm 0.027$     |
| TRGB               | $0.043 \pm 0.068$  | $0.003 \pm 0.048$      |
| PNe                | $0.014 \pm 0.034$  | $-0.049 \pm 0.085$     |

Figure 10. Residuals from the FM as a function of galaxy absolute magnitude for different distance estimators. As in other figures, late-type galaxies plotted as blue squares and early-type galaxies as red circles. Systematic deviations, if present, suggest a possible abundance dependence in the respective distance estimator due to the correlation between galaxy luminosity and mean chemical abundance.

(A color version of this figure is available in the online journal.)

Table 3

Magnitude-dependent Offsets from FM

| Distance Estimator | All Data Offsets | Faint Tail Trimmed |
|--------------------|------------------|--------------------|
| Cepheids           | $-0.010 \pm 0.011$ | $0.023 \pm 0.022$  |
| SBF                | $0.033 \pm 0.008$ | $0.037 \pm 0.008$  |
| SN Ia              | $0.013 \pm 0.032$ | $0.093 \pm 0.045$  |
| TRGB               | $0.007 \pm 0.015$ | $-0.043 \pm 0.042$ |
| PNe                | $-0.002 \pm 0.029$ | $0.053 \pm 0.035$  |

error bars are still somewhat too large due to the large amount of scatter in the FM (arising from the heterogeneous \(B\)-band data) and small sample size (as many galaxies lack the full set of measurements needed to calculate the FM).

The uncertainties in our comparison of distance estimators are currently dominated by the number of galaxies in each class and the intrinsic scatter in the FM. The small sample sizes can be addressed relatively easily. Many galaxies with extant distance measurements, particularly those with SN Ia distances, lack the additional measurements (typically \(V\)) necessary to place them on the FM. These can be obtained with ground-based observing. The FM scatter can be improved by going to redder passbands.

3.4. Testing the Metallicity Dependence of Distance Estimators

The FM is not only of use in uncovering systematic differences among distance estimators, but is also potentially useful in uncovering systematic errors in any particular distance estimators within a set of galaxies. One long-running concern is the role chemical abundance might play in affecting distance estimators (see Gallagher et al. 2008; Freedman & Madore 2011, for discussions of the effects on Cepheids and SNe Ia, respectively). Given the correlation between host galaxy gas-phase metallicity and luminosity (Zaritsky et al. 1994), we use our sample to examine whether there are potential dependences on metallicity by measuring correlations between FM residuals and luminosity (a correlation could also implicate another parameter that correlates with luminosity, e.g., mean stellar age). In Figure 10, we show the FM residuals as a function of galaxy absolute magnitude for our five primary estimators. Visually, two of the panels appear to show a trend of increasing FM residual with decreasing luminosity (SBF and SN Ia). However, this similarity among panels overstates the concordance because some of the galaxies, particularly at the bright end, appear in multiple panels. In Table 3, we present measurements of the relationship between the FM residuals and absolute magnitude for each distance estimator. We list both the fit obtained using all of the galaxies and after trimming the poorly populated faint end of the galaxy distribution (either at \(M_B = -17\) or \(-18\)). The only two significant correlations are provided by the SBF and SN Ia data (their rank correlation probabilities of arising at random are both \(<0.3\%\), if we confine the SNe sample to galaxies with \(M_B < -18\)).

If we attribute the slopes to a metallicity dependence in the estimator, we can quantify the effect and compare to previous observations.
determinations. Our best fit for the SN Ia in galaxies with $M_B < -18$ implies a distance offset of $-0.41 \pm 0.11$ dex/[O/H] (for the 4.5 mag/[O/H] relation of Zaritsky et al. 1994), which agrees with the sense found by Howell et al. (2009) and Kelly et al. (2010) in that one would underestimate the distance to SNe in more metal-rich galaxies, because SNe are intrinsically more luminous after light correction. It is difficult to quantitatively compare our results to those of Kelly et al. (2010) for various reasons, including their use of stellar masses versus our use of luminosities and our calibration to gas-phase abundances. However, they find distance modulus variations that correspond to about 0.15 over the one order of magnitude in mass. If we assume that the order of magnitude in mass corresponds to the same magnitude range in luminosity, then we would predict a distance effect of 0.23 dex over the corresponding range, which in turn results in a change of $1.15 \pm 0.30$ in distance modulus. This is a much larger value than that found by Kelly et al. (2010), but the discrepancy is not significantly dramatic given our large uncertainties. Likewise, our value expressed in dex/[O/H] is larger than that found by Howell et al. (2009) ($-0.10 \pm 0.07$), but again the discrepancy is $<3\sigma$. For Cepheids, we find no significant correlation, but our measurement ($0.23 \pm 0.22$ dex mag$^{-1}$ or $-0.92 \pm 0.88$ dex/[O/H] if the correlation arises from metallicity) can be compared to previous determinations. Given the large uncertainties, this result agrees with previous values, which generally range between $-0.1$ and $-0.4$ dex/[O/H] (Romaniello et al. 2008).

3.5. The FM as Distance Estimator

In Figure 11, we show the FM for galaxies that have their distances estimated using multiple techniques (we use the average for the adopted distance). The relation is satisfied by galaxies that range widely over luminosity, morphology, and kinematics. It is tempting to invert the arguments above and use the FM not as a fiducial against which to test various distance estimators, but as a distance estimator itself. As stressed in the Introduction, these particular data are suboptimal for such an experiment, but we proceed nonetheless.

Using the FM now for all of the galaxies in the sample, we estimate a distance to each, and show the relationship between recessional velocity and distance in Figure 12. We define the FM zero point by setting the mean FM residual among estimators to zero, but define that mean in several different ways. First, we use the SBF calibration. Second, we calculate the weighted mean of the residuals in Table 2, excluding our calibration SBF sample. Third, we use the zero point from the SN Ia for pressure-supported galaxies. The results differ by at most 4 km s$^{-1}$ Mpc$^{-1}$ in the inferred $H_0$. We therefore cite a systematic uncertainty of 4 km s$^{-1}$ Mpc$^{-1}$ in our $H_0$ measurement below. We choose to plot the results using the intermediate value of the FM zero point derived from the three methods (the mean of the residuals of the estimators). The inset shows the result of fitting the relationship for galaxies with $v > 1500$ km s$^{-1}$, $3\sigma$ outliers excluded, binned by 10, and forcing the fit through the origin. We exclude the low $v$ region to minimize the effect of local flows. The resulting slope implies $H_0 = 78 \pm 2$ (random) $\pm 4$ (systematic) km s$^{-1}$ Mpc$^{-1}$. The estimate of the systematic uncertainty does not include a variety of potential problems that are ignored here (modeling of bulk flows, internal extinction corrections, adjustment for potential biases in the galaxy sample, etc.). Therefore, while we treat this result cautiously, we present it to show (1) the level of precision possible with plausible sample sizes and (2) to illustrate how one could determine $H_0$ in a way that utilizes as many (or as few) different distance estimators as desired.

One of those sources of uncertainty, internal extinction, can be mitigated by going to the infrared, as shown most recently.
by Freedman & Madore (2011) for Spitzer wavelengths where the scatter about the TF relation is reduced from 0.43 in the extinction-corrected B-band data to 0.31 in the non-extinction-corrected 3.6 μm data. We expect analogous gains in the FM for galaxies in which internal extinction is important. Depending on the fraction of galaxies in a sample for which extinction contributes significantly to the observed FM scatter, proportional gains in the determination of $H_0$ will follow.

4. CONCLUSIONS

We demonstrate that the FM (Zaritsky et al. 2008) provides a fiducial against which any set of distance estimators can be compared. Many, if not most, galaxies will only ever have distances measured with one method, making it impossible to use them to test distance estimators directly. The FM fiducial, a benchmark for all distance estimators, constrains whether systematic errors exist among estimators and whether they are creeping into even a single estimator as a function of external parameters, such as metallicity. Large sample size is critical for examining selection effects where, for example, one might want to split the sample in various ways (e.g., with environment, luminosity, morphological type, and star formation rate).

Among the distance estimators we examine (SNe Ia, Cepheids, SBFs, the luminosity of the TRGB, circumnuclear masers, eclipsing binaries, RR Lyrae stars, and the planetary nebulae luminosity functions), we find no statistically significant differences ($>2\sigma$), but caution that differences that are unacceptably large for state-of-the-art distance uncertainties ($\sim$ few %) are still allowed by our data. The lack of precision with which we could discriminate among methods is rooted in sample size, which in certain cases is still too small, and in the less-than-optimal data available (B band and heterogeneous). Both of these problems will be resolved with a feasible dedication of resources.

We illustrate the use of the FM distances to (1) test the metallicity sensitivity of different estimators, confirming the SN Ia distance dependence on host galaxy metallicity, and (2) provide an alternative calibration of $H_0$ that replaces the classical ladder approach in the use of extragalactic distance estimators with one that utilizes data over a wide range of distances simultaneously.

We thank Barry Madore and Ian Steer for compiling and generously providing the NASA 1-D distance database without which this project could not have been completed. D.Z. acknowledges financial support for this work from a NASA LTSA award NNG05GE82G and NSF grant AST-0307482. A.I.Z. acknowledges financial support from NASA LTSA award NAG5-11108 and from NSF grant AST-0206084. D.Z. and A.I.Z. thank the Institute of Astronomy at Cambridge University and the Center for Cosmology and Particle Physics at New York University for their hospitality during the completion of this study. We acknowledge the usage of the HyperLeda database (http://leda.univ-lyon1.fr) and thank all those involved for producing this highly useful resource. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We also extend our thanks to those involved in creating and maintaining this excellent resource.

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