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A COMPARISON OF THE PLANETARY NEBULA LUMINOSITY FUNCTION AND SURFACE BRIGHTNESS FLUCTUATION DISTANCE SCALES

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ABSTRACT

Two of the best techniques for measuring distances greater than ~3 Mpc are the planetary nebula luminosity function (PNLF) and the surface brightness fluctuation (SBF) method. We compare the results of both methods and analyze the internal and external errors associated with the measurements. We find that the PNLF distances are systematically larger than the SBF distances by 0.07 ± 0.03 mag, but this error can be entirely attributed to uncertainties in the Local Group calibrations which both methods employ. After correcting for this effect, we find the random scatter in the difference between the PNLF and SBF distance determinations, $\Delta = (m-M)_{\rm SBF} - (m-M)_{\rm PNLF} = 0.17$ mag, is in exact agreement with that predicted from the internal uncertainties of the methods. We show that Δ is not measurably correlated with such parameters as galaxy color, metallicity, specific PN density, and specific globular cluster frequency, but does correlate slightly with galactic absolute B magnitude. We discuss the reality of this correlation and show that the trend is not important for extragalactic distance applications.

Subject headings: distance scale — galaxies: distances and redshifts — galaxies: photometry — galaxies: stellar content — planetary nebulae: general

1. INTRODUCTION

Recently, two very different methods have claimed to produce measurements of extragalactic distances out to ~20 Mpc to better than 10%. The first, the planetary nebula luminosity function (PNLF), declares that there is a sharp turnover in the [O III] λ5007 luminosity function of bright planetary nebulae (PNs), and that the absolute luminosity of this break is insensitive to the parent stellar population's age or metallicity (Jacoby 1989; Jacoby, Ciardullo, & Ford 1990; Ciardullo, Jacoby, & Harris 1991). The second method, which measures surface brightness fluctuations (SBF) within a galaxy, asserts that the mean magnitude and specific density of giant stars in an old stellar population is a predictable function of the galaxy's color (Tonry & Schneider 1988; Tonry, Ajhar, & Luppino 1990; Tonry 1991; Ajhar 1992). Yet, despite the differences in approach, both methods produce distances in close agreement with each other (cf. Jacoby et al. 1992) and yield values for the Hubble constant of $H_0 \approx 80$ km s^{-1} Mpc^{-1}. This agreement has led some to begin considering the implications a large Hubble constant has for the luminosity of Type Ia supernovae (Fukugita & Hogan 1991) and the density and age of the universe (Peacock 1991).

The PNLF and SBF techniques measure totally different stellar and galactic properties, yet in many ways, the techniques are similar. Both methods work best on early-type galaxies and produce excellent internal consistency when applied to galaxies within clusters. Moreover, recent advances in our understanding of post-asymptotic giant branch stellar evolution (Dopita, Jacoby, & Vassiliadis 1992; Mendez et al. 1993) and the statistical properties of stellar populations (Worthey 1993; Buzzoni 1993) confirm that the accuracies of both techniques should be high. Nevertheless, because our knowledge of stellar mass loss and galactic star formation is limited, these models still require observational confirmation. Hence at present, both the PNLF and SBF rely on the Local Group galaxies M31 and M32 for their calibration, and the applicability of each method to galaxies of differing Hubble types and stellar populations must be empirically tested.

The most remarkable aspect of both the PNLF and SBF techniques is the small external uncertainties claimed in their results. A typical PNLF distance estimate carries a relative uncertainty of only ~5%; distance determinations from the SBF technique give similarly small errors. In this paper, we test these claims by comparing the PNLF and SBF distances to 15 galaxies measured by both techniques. In § 2 we produce a list of distances for both methods under a common set of assumptions and give the total error associated with each measurement. In § 3, we show that a systematic difference exists between the PNLF and SBF distance scales, but that the offset is entirely consistent with uncertainties in the Local Group calibration. We then show that the remaining random scatter between the two measurements is exactly that expected from the internal uncertainties of the individual PNLF and SBF measurements, and that the scatter is uncorrelated with galaxy color, metallicity, distance, number of PNs, or specific globular cluster frequency.

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TABLE 1

OBSERVED PROPERTIES OF GALAXIES

Galaxy	B_T^{0}[a]	$(U-V)_T^{0}$[a]	Mg_2[b]	$(m_{1550}-V)$[c]	S[d]	PNLF and SBF References
NGC 1316	9.31	1.25	0.298	...	...	McMillan et al. 1993; Tonry 1993
NGC 1399	10.22	1.46	0.334	2.05	12.0	McMillan et al. 1993; Tonry 1993
NGC 1404	10.88	1.52	0.317	3.30	0.9	McMillan et al. 1993; Tonry 1991
NGC 3031	7.40	1.52	...	...	...	Jacoby et al. 1989; Tonry 1991
NGC 3115	9.75	1.42	0.309	3.43	2.3	
NGC 3377	10.98	1.14	0.270	...	2.6	Ciardullo et al. 1989a; Tonry 1991
NGC 3379	10.17	1.46	0.308	3.86	1.3	Ciardullo et al. 1989a; Tonry et al. 1990
NGC 3384	10.75	1.30	...	...	1.1	Ciardullo et al. 1989a
NGC 4374	9.91	1.44	0.305	3.55	5.6	Jacoby et al. 1990; Tonry et al. 1990
NGC 4406	9.71	1.36	0.311	3.72	5.4	Jacoby et al. 1990; Tonry et al. 1990
NGC 4472	9.26	1.51	0.306	3.42	5.0	Jacoby et al. 1990; Tonry et al. 1990
NGC 4486	9.47	1.48	0.289	2.04	14.0	Jacoby et al. 1990
NGC 4594	8.39	1.30	...	...	1.7	Ford et al. 1993
NGC 4649	9.70	1.63	0.338	2.24	5.9	Jacoby et al. 1990
NGC 5128	6.72	1.20	...	...	2.6	Hui et al. 1993; Tonry & Schechter 1990

[a] From the RC3 catalog (de Vaucouleurs et al. 1991).
[b] From Davies et al. 1987 and Gorgas et al. 1990.
[c] From Burstein et al. 1988.
[d] From Harris 1991.

2. THE DATA

For our comparison, we use the entire sample of galaxies with well-determined PNLF and SBF distance measurements. This set of 15 galaxies includes three galaxies in the Leo I Group, three galaxies in the Fornax Cluster, five galaxies in the Virgo Cluster, and four noncluster galaxies, but excludes low-luminosity galaxies, such as NGC 205 and NGC 5253, that have sparse, ill-defined PNLFs. A list of the galaxies, along with their properties and observational references, appears in Table 1.

Unfortunately, as published, the PNLF and SBF distances are not directly comparable, due to different assumptions about the Local Group distance scale and Galactic extinction. SBF distances all assume a distance of 770 kpc to the M31/M32 system (Freedman & Madore 1990) and adopt the interstellar extinction values of Burstein & Heiles (1984) and Burstein et al. (1987) on a galaxy-by-galaxy basis. PNLF distances, however, are based on an M31 distance of 710 kpc (Welch et al. 1986) and reference a variety of reddening estimates. Thus, before any comparison can be attempted, the PNLF and SBF distances must be adjusted to reflect a common set of assumptions.

This is done in Table 2, which lists the observed values for $\bar{I}$, $(V-I)$, and m^* for each galaxy (not adjusted for foreground extinction), along with the adopted values of A_B and the extinction-corrected PNLF and SBF distance determinations. In the table, the PNLF distances have been scaled to an M31 distance of 770 kpc and an M31 total extinction of $A_{5007} = 0.85\ A_B = 0.27$ mag. This has the effect of systematically increasing all the previously published PNLF distance moduli by 0.06 mag. In addition, the distances quoted in the table all use the foreground extinction values given by Burstein & Heiles (1984) and Burstein et al. (1987), or $A_B = 0.0$ if that value is negative. To convert these B-band extinction estimates to total extinctions in V, I, and $\lambda 5007$, we have assumed a Savage & Mathis (1979) reddening curve, with $A_B = 4.10E(B-V)$, $A_V = 3.10E(B-V)$, $A_I = 1.50E(B-V)$, and $A_{5007} = 3.50E(B-V)$.

Note here that our assumptions about foreground extinction are not merely mentioned for completeness. In fact, they are

TABLE 2

PNLF AND SBF DISTANCE MEASUREMENTS

Galaxy	$\bar{I}_{\mathrm{obs}}$	$(V-I)_{\mathrm{obs}}$	m^*	A_B	$(m-M)_{\mathrm{SBF}}$	σ(SBF)	$(m-M)_{\mathrm{PNLF}}$	σ(PNLF)	Δ	$\sigma(\Delta)$
NGC 224	23.28	1.29	20.17	0.31	24.46	0.12	24.46	0.06	...	...
NGC 1316	29.60	1.14	26.65	0.00	31.02	0.12	31.19	0.07	−0.17	0.17
NGC 1399	29.81	1.22	26.69	0.00	30.99	0.10	31.22	0.08	−0.23	0.16
NGC 1404	29.91	1.22	26.67	0.00	31.09	0.09	31.21	0.10	−0.12	0.17
NGC 3031	26.36	1.27	23.60	0.15	27.50	0.09	28.00	0.06	−0.50	0.15
NGC 3115	28.29	1.19	25.72	0.10	29.65	0.25	30.17	0.13	−0.52	0.30
NGC 3377	28.48	1.14	25.65	0.06	29.94	0.08	30.13	0.12	−0.19	0.18
NGC 3379	28.65	1.22	25.52	0.05	29.87	0.07	30.01	0.09	−0.14	0.16
NGC 3384	28.51	1.18	25.61	0.07	29.88	0.12	30.09	0.09	−0.21	0.18
NGC 4374	29.89	1.25	26.57	0.13	31.09	0.08	31.00	0.10	+0.09	0.16
NGC 4406	29.97	1.22	26.56	0.11	31.24	0.08	31.01	0.08	+0.23	0.16
NGC 4472	29.66	1.24	26.30	0.00	30.78	0.07	30.84	0.11	−0.06	0.17
NGC 4486	29.68	1.24	26.39	0.08	30.87	0.10	30.86	0.09	+0.01	0.17
NGC 4594	28.46	1.24	25.36	0.12	29.66	0.08	29.79	0.07	−0.14	0.15
NGC 4649	29.79	1.28	26.36	0.03	30.81	0.08	30.87	0.11	−0.06	0.17
NGC 5128	26.24	1.22	23.61	0.49	27.81	0.08	27.73	0.06	+0.08	0.15

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crucial to any comparison of the two methods. With a PNLF measurement, an underestimate of extinction results in an *overestimate* of the distance, since

$$(m-M)_{\rm PNLF} = (m^*-M^*) - 0.85A_B\,, \qquad (1)$$

where m^* is the observed PNLF cutoff, and $M^* = -4.54$ is the absolute cutoff derived from M31, corrected for the revised M31 distance modulus (cf. Ciardullo et al. 1989b). For the SBF method, however, an underestimate of the extinction actually results in an *underestimate* of the true distance, due to the presence of a color term. According to Tonry (1991), the mean fluctuation magnitude is given by

$$\overline{M_I} = -4.84 + 3(V-I)_0\,. \qquad (2)$$

Hence, in terms of observed quantities, the SBF distance modulus is

$$(m-M)_{\rm SBF} = \bar{I}_{\rm obs} + 4.84 - 3(V-I)_{\rm obs} + 0.80A_B\,, \qquad (3)$$

and the difference between the SBF and PNLF distance moduli is

$$\Delta = \bar{I}_{\rm obs} + 4.84 - 3(V-I)_{\rm obs} - (m^*-M^*) + 1.66A_B\,. \qquad (4)$$

Thus, there is always some extinction value which will bring the PNLF and SBF measurements into agreement, but even a slight error in A_B will cause the two distance moduli to disagree, even if both techniques work perfectly.

Table 2 lists the value of Δ for each galaxy, along with the estimated random errors in $(m-M)_{\rm PNLF}$, $(m-M)_{\rm SBF}$, and Δ. The PNLF uncertainties include the formal uncertainties in the maximum likelihood fits (which accounts for errors in the PN photometry), the estimated error in the standard star measurements, and the estimated uncertainty in the [O III] λ5007 filter transmission curve. The uncertainties in the SBF distances include the error in the measurement of $\bar{I}_{\rm obs}$ and the error in the measurement of the galactic $(V-I)$ color (typically ~0.02 mag). The quoted error for Δ combines both these uncertainties with that estimated by Burstein & Heiles (1984) for the foreground Galactic extinction [$\sigma_{E(B-V)} = 0.015$]. Uncertainties introduced by errors in the PNLF and SBF Local Group calibrations are not included in the table, since these produce systematic, rather than random, scatter in Δ. Note that several of the tabulated distances have not been previously published, and that the SBF distance to NGC 4406 has been revised downward by 0.14 mag from that implied by the measurements of Tonry et al. (1990), due to a redetermination of the galaxy's $(V-I)$ color.

3. DISCUSSION

Figure 1 shows a histogram of the difference between the SBF and PNLF distance moduli. From the figure, it is immediately apparent that there is a systematic difference in the two scales, in the sense that the SBF distances are smaller by $\langle\Delta\rangle \sim -0.1$ mag. This offset is significant: although the scatter in Δ is substantial, the mean value, $\langle\Delta\rangle = -0.13 \pm 0.05$, differs from zero at the 99% confidence level. Clearly, the Local Group calibration for one or both of the methods is incorrect.

To understand this discrepancy, it is necessary to examine the uncertainties that enter into the PNLF and SBF calibrations. Chief among these are the uncertainty in the PNLF fit to the planetaries of M31 (estimated by Ciardullo et al. 1989b to be 0.04 mag), the uncertainty in the determination of $\bar{I}_{\rm obs}$ for M31 and M32 (estimated by Tonry et al. 1990 to be 0.10 mag), and the uncertainty in the foreground B-band extinction to M31 and M32 (estimated by Burstein & Heiles 1984 to be 0.06 mag). The combination of these error terms alone yields a total uncertainty in $\langle\Delta\rangle$ of 0.13 mag. Hence the offset in Figure 1 is entirely consistent with that expected from errors in the PNLF and SBF Local Group calibration. No additional scale error, such as might be caused by population differences between the M31/M32 system and the giant ellipticals of Virgo and Fornax, is needed.

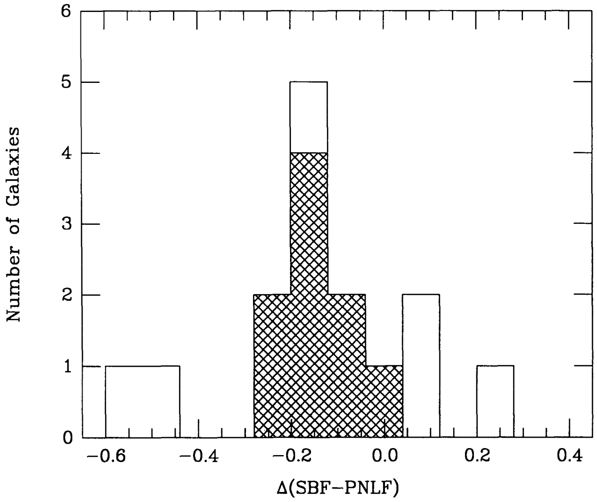

FIG. 1.—A histogram of the difference between the SBF and PNLF distance moduli, binned into 0.08 mag intervals. The filled squares represent galaxies with Burstein & Heiles (1984) foreground extinction estimates $A_B <$ 0.10; the open squares display galaxies with larger Galactic extinctions. The implied scatter in Δ is 0.20 mag about a mean of -0.13 mag. The systematic offset is entirely consistent with uncertainties in the PNLF and SBF Local Group calibrations and Galactic extinction, and the observed scatter about this mean is exactly that predicted from the uncertainties of the individual measurements.

Also illustrated in Figure 1 is the excellent agreement between the relative SBF and PNLF distances. After correcting for the systematic offset, only three galaxies have PNLF distances that differ from their SBF counterparts by more than 10%. Moreover, of the nine galaxies with foreground extinctions $A_B < 0.10$, none scatters further from $\langle\Delta\rangle$ by more than 0.13 mag, or 6% in distance. To some degree, this small dispersion of $\sigma \approx 0.08$ mag must be fortuitous, since from the internal PNLF and SBF errors alone, we would expect a random scatter of ~0.12 mag in Δ. Nevertheless, the remarkable agreement does show that the true internal errors associated with the methods are certainly not much larger than those estimated.

Of the galaxies plotted in Figure 1, three are clearly outlyers. The most discrepant object is NGC 3115, which has a value of Δ that differs from the mean by 0.40 mag. However, the SBF distance to this galaxy has a large internal error, due to the color difference between the galaxy's bulge and disk. Because an SBF distance measurement depends critically on the $(V-I)$ color of the underlying stellar population, a color gradient within a galaxy can generate a large uncertainty in the computed distance. While it is possible to compensate for such gradients by creating multicomponent models of the galaxy and analyzing the surface brightness fluctuations as a function of color, at present, such an analysis has not been performed on NGC 3115. As a result, the SBF distance measurement for

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this galaxy has a 1 σ uncertainty of $\sim$0.25 mag. A large value for Δ therefore is not unexpected.

A more interesting outlyer is NGC 3031 (M81), an Sb galaxy which has a formal internal error of 0.15 mag. According to Table 2, Δ for this galaxy is -0.50, which implies that the SBF and PNLF measurements differ by 2.5 σ. Hence, this data point represents a possible failure of one or both of the methods. However, it is exceedingly probable that the discrepancy in M81's computed distances arises not from the distance measurements, but from the estimate of foreground extinction. Based on galaxy counts and Galactic H I emission, Burstein & Heiles (1984) estimate the total extinction in *B* toward M81 to be $A_B = 0.15$. However, the foreground extinction in that region of the sky is very patchy (Sandage 1976; Magnani & de Vries 1986) and reddening estimates based on *IRAS* 100 μm emission (Boulanger & Pérault 1988), observed star counts (Magnani & de Vries 1986), and Hα to radio continuum measurements (Kaufman et al. 1987) all give *B*-band extinctions much larger than this. In fact, since both the PNLF and SBF distance estimates refer to measurements of M81's bulge, the most appropriate extinction estimate to use is probably that derived from the Hα/Hβ ratio of the galaxy's nuclear emission (Peimbert & Torres-Peimbert 1981). If we adopt this value of $A_B = 0.41$, then Δ for M81 becomes -0.07 and the two distance measurements are in perfect agreement.

Among the 15 galaxies with both SBF and PNLF measurements, the only true outlyer is NGC 4406, which has a value of Δ 0.36 mag larger than the mean. This offset cannot be explained solely through reddening: even if there were no Galactic extinction, Δ for NGC 4406 would still be $+0.05$, or 0.15 mag above the mean for our sample. In order to reduce Δ further, A_B would have to be negative. Nevertheless, despite the discrepancy, NGC 4406 does not represent a series failure of the methods. If we ignore the very uncertain measurement for NGC 3115, and adopt the Balmer-decrement based extinction estimate of $A_B = 0.41$ to the bulge of M81, then $\langle \Delta \rangle$ for the remaining 13 galaxies is -0.07, and the dispersion about this mean is only 0.13 mag. This latter value is less than the expected dispersion of $\sim$0.17 mag estimated from the internal uncertainties of the measurements! Some galaxies with $\Delta = 0.36$ are thus expected and do not represent a serious concern.

Figure 2 plots the difference between the SBF and PNLF distance moduli, as a function of galaxy color, metallicity, distance, absolute magnitude, number of PNs in the distance determination, bolometric-luminosity specific PN density, and specific globular cluster frequency. As is illustrated, the physical properties of the 15 galaxies vary substantially, and a wide range of early-type populations are represented. Thus our sample has the variety needed to test for systematic errors between the measurement techniques. Just as important, however, is the fact that the bulge of M31, which serves as the calibrator for both methods, also lies well within the parameter space covered by our sample. Its use as an absolute calibrator is therefore well justified.

As Figure 2 demonstrates, if there is a systematic error associated with either the PNLF or SBF methods, it must be much smaller than the amplitude of the random scatter. For example, if either technique were strongly affected by changes in stellar populations, then we might expect Δ to correlate with galaxy color or metallicity, but no measurable trend exists. Similarly, if the PNLF fitting procedure uses an improper empirical function, or if the measurements of surface brightness fluctuations are contaminated by a population of faint globular clusters, then we might see a correlation with the number of PNs used in the distance determination, or with specific globular cluster frequency, but again, the data show no such behavior. Instead, as Table 3 shows, the only systematic effect present in the data is a weak correlation with galaxy absolute *B* magnitude, in the sense that the SBF technique derives slightly larger distances for the brighter galaxies. This trend, which was first noticed by Bottinelli et al. (1991), is only marginally significant, however, and the Spearman rank-order test suggests that there is still a $\sim$4% chance that the correlation could be random.

The underlying cause of the correlation of Δ with absolute magnitude is not clear. The sense of the correlation suggests the problem may be in the adopted form for the planetary nebula luminosity function. If the true PNLF has a high-luminosity tail, then the exclusion of such a tail in the assumed law would cause the distances to galaxies with large numbers of PNs to be underestimated. However, if this were the case, Δ should correlate not with total galaxy luminosity, but with total luminosity *included in the PN survey regions.* No significant correlation exists for this latter quantity.

An alternative explanation for this effect could be that the relation between $\overline{M_I}$ and $(V-I)$ is steeper than 3.0. Support for this possibility is presented by Tonry (1993) who uses new observations of Fornax galaxies to derive a slope 4.0 within the cluster. Such a change removes all semblance of a correlation for the subsample of objects with $A_B < 0.1$, but does little to remove the effect of NGC 4406 and NGC 5128 on the slope.

Whatever the cause of the correlation, its effect on extragalactic distance measurements is slight. If a regression is performed on the data in the absolute magnitude panel of Figure 2, the best-fitting line gives an error of 0.10 ± 0.05 mag in

TABLE 3

CORRELATIONS OF PARAMETERS WITH Δ

Parameter	Number of Objects	Slope	Error in Slope	Spearman Correlation Coefficient	Probability of Randomness
$(U-V)$	15	$+0.03$	0.25	$+0.22$	0.43
Mg_2	11	-0.43	2.73	-0.01	0.98
$(m_{1550}-V)$	9	$+0.05$	0.16	$+0.10$	0.80
$(m-M)$	15	$+0.02$	0.07	$+0.16$	0.57
M_B	15	-0.10	0.05	-0.54	0.04
S	13	$+0.01$	0.02	$+0.39$	0.18
log N(PN)	15	$+0.06$	0.11	$+0.06$	0.84
$\alpha_{2.5}$	15	-0.15	0.17	-0.29	0.29
$M_{\rm bol}$ sampled in PN surveys	15	-0.06	0.06	-0.26	0.35

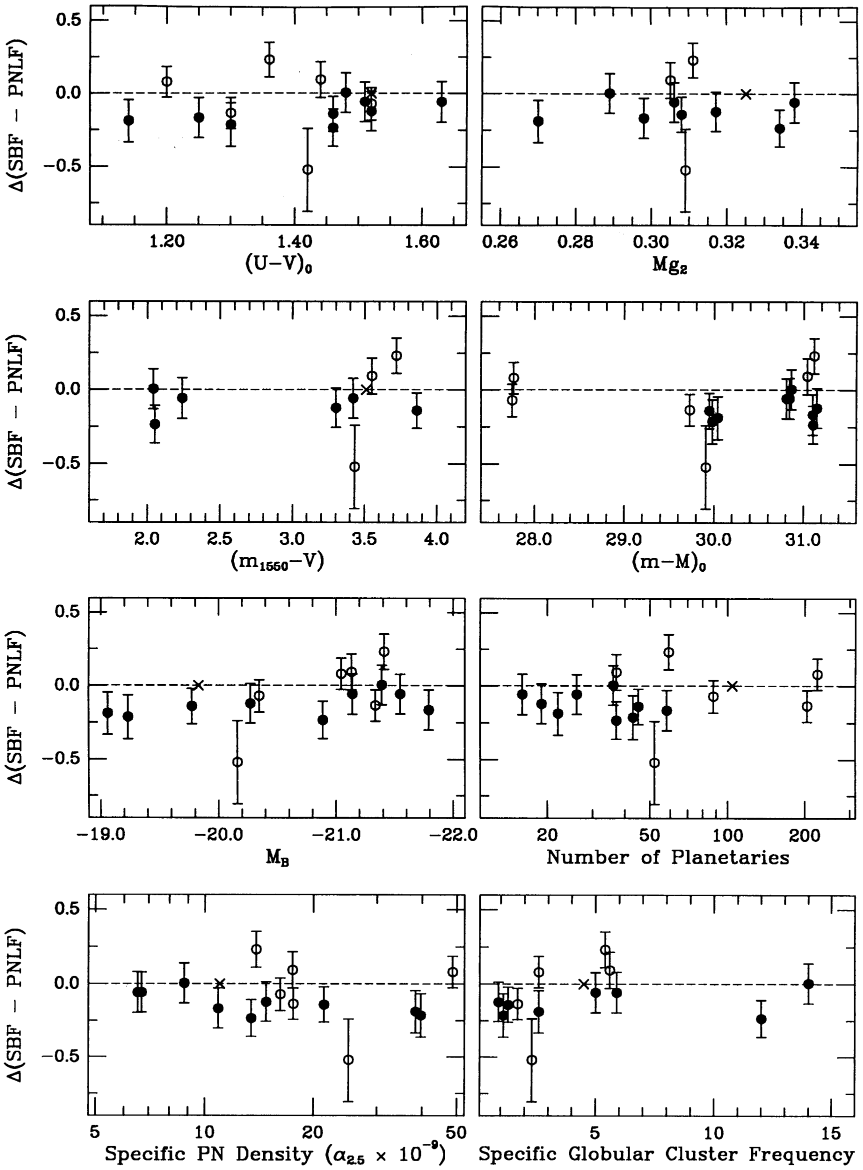

FIG. 2.—The difference between the SBF and PNLF distance moduli, as a function of galaxy color, metallicity, distance, absolute magnitude, number of PNs in the distance determination, bolometric-luminosity specific PN density, and specific globular cluster frequency. The filled circles show galaxies with $A_B < 0.10$; open circles represent galaxies with larger foreground extinctions. The cross marks the bulge properties of the calibration galaxy M31. Burstein & Heiles (1984) extinctions have been used for all galaxies except M81, where we have adopted $A_B = 0.41$ from measurements of the Balmer decrement. The error bars are derived from uncertainties in the PNLF fits and the SBF measurements, but do not include uncertainties in foreground extinction. With the possible exception of absolute B magnitude, the data show that Δ is uncorrelated with any galactic property.

distance modulus for every 1 mag of galaxy luminosity. Interestingly, the 0.13 mag scatter about this line is less than that expected from the internal errors of the techniques (though only at the 1.5 σ level). This smaller than expected scatter suggests that at least some of the trend seen in the figure occurs by chance.

4. SUMMARY

In conclusion, we find that the agreement between the PNLF and SBF distances, both absolute and relative, is extremely good. We do observe a systematic offset of ~0.1 mag between the two distance scales, but this represents less than a 1 σ deviation in the Local Group calibration uncertainties. Further PNLF and SBF observations of M31 and M32 might reduce this offset, but the reconciliation of the two distance scales might also lie in the estimated extinction to the calibrators, since an error of as little as 0.017 mag in $E(B-V)$ would bring the two scales into perfect agreement. Whether extinction is responsible for this 5% scale error, or whether the error lies in the PNLF or SBF calibration cannot be determined at the present time.

We have searched for significant correlations between the differences in distances and a wide variety of astrophysical parameters and galaxy characteristics. No trend appears at a level greater than the ~5% internal scatter of distances. A possible correlation with galaxy absolute magnitude is present at the ~2 σ level, but the amplitude of the effect is less than 5%, and may be caused by small uncertainties in foreground extinction. It is, in fact, a testimony to the precision of the two methods that such a systematic effect can be seen at all. Overall, the 0.17 mag random scatter between the two distance measurements is in perfect agreement with the combined internal errors of the two methods. No other extragalactic distance techniques are capable of such accuracy.

The agreement between the estimated internal errors of the PNLF and SBF methods and the observed dispersion of the measurements places strong limits on the kinds of systematic errors which may be present in the techniques. For example, patchy dust within early-type galaxies cannot be used as a source of systematic error. If such a condition existed, it would cause the SBF distances to be underestimated (by creating excess power in the surface brightness fluctuations) and the PNLF distances to be overestimated (by adding additional extinction). This would certainly create an inconsistency between the internal and external errors. Similarly, any systematic error that effects only one of the distance indicators, such a power-law tail to the PNLF, must also be small. Variations in galaxy metallicity or population age *might* produce correlated errors in the PNLF and SBF distances, but even this is unlikely. Although both techniques are sensitive to the properties of post-asymptotic branch stars, the PNLF measurements depend on the cooling mechanisms of gaseous nebulae, while the SBF results involve the physics of stellar atmospheres. It would require a considerable conspiracy for those two physical mechanisms to produce correlated errors over the wide range of stellar populations displayed in Figure 2.

Considering that the PNLF and SBF methods are strikingly different in detail, we believe that the unprecedented galaxy-for-galaxy agreement represents exceedingly strong support for the distances derived with either of these methods.

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REFERENCES

Ajhar, E. A. 1992, Ph.D. thesis, Massachusetts Institute of Technology
Bottinelli, L., Gouguenheim, L., Paturel, G., & Teerikorpi, P. 1991, A&A, 252, 550
Boulanger, F., & Pérault, M. 1988, ApJ, 330, 964
Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, T. R. 1988, ApJ, 328, 440
Burstein, D., & Heiles, C. 1984, ApJS, 54, 33
Burstein, D., Davies, R. L., Dressler, A., Faber, S. M., Stone, R. P. S., Lynden-Bell, D., Terlevich, R. J., & Wegner, G. 1987, ApJS, 64, 601
Buzzoni, A. 1993, A&A, 275, 433
Ciardullo, R., Jacoby, G. H., & Ford, H. C. 1989a, ApJ, 344, 715
Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989b, ApJ, 339, 53
Ciardullo, R., Jacoby, G. H., & Harris, W. E. 1991, ApJ, 383, 487
Davies, R. L., Burstein, D., Dressler, A., Faber, S. M., Lynden-Bell, D., Terlevich, R. J., & Wegner, G. 1987, ApJS, 64, 581
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalog of Bright Galaxies (New York: Springer)
Dopita, M. A., Jacoby, G. H., & Vassiliadis, E. 1992, ApJ, 389, 27
Ford, H. C., Hui, X., Ciardullo, R., Jacoby, G. H., & Freeman, K. C. 1993, in preparation
Freedman, W. L., & Madore, B. F. 1990, ApJ, 365, 186
Fukugita, M., & Hogan, C. J. 1991, ApJ, 368, L11
Gorgas, J., Efstathiou, G., & Salamanca, A. A. 1990, MNRAS, 245, 217
Harris, W. E. 1991, ARA&A, 29, 543
Hui, X., Ford, H. C., Ciardullo, R., & Jacoby, G. H. 1993, ApJ, 414, 463
Jacoby, G. H. 1989, ApJ, 339, 39
Jacoby, G. H., Branch, D., Ciardullo, R., Davies, R. L., Harris, W. E., Pierce, M. J., Pritchet, C. J., Tonry, J. L., & Welch, D. L. 1992, PASP, 104, 599
Jacoby, G. H., Ciardullo, R., Ford, H. C., & Booth, J. 1989, ApJ, 344, 704
Jacoby, G. H., Ciardullo, R., & Ford, H. C. 1990, ApJ, 356, 332
Kaufman, M., Bash, F. N., Kennicutt, R. C., & Hodge, P. W. 1987, ApJ, 319, 61
Magnani, L., & de Vries, C. P. 1986, A&A, 168, 271
McMillan, R., Ciardullo, R., & Jacoby, G. H. 1993, ApJ, in press
Mendez, R. H., Kudritzki, R. P., Ciardullo, R., & Jacoby, G. H. 1993, A&A, 275, 534
Peacock, J. 1991, Nature, 352, 378
Peimbert, M., & Torres-Peimbert, S. 1981, ApJ, 245, 845
Sandage, A. 1976, AJ, 81, 954
Savage, B. D., & Mathis, J. S. 1979, ARA&A, 17, 73
Tonry, J. L. 1991, ApJ, 373, L1
———. 1993, in preparation
Tonry, J. L., Ajhar, E. A., & Luppino, G. A. 1990, AJ, 100, 1416
Tonry, J. L., & Schechter, P. L. 1990, AJ, 100, 1794
Tonry, J., & Schneider, D. P. 1988, AJ, 96, 807
van den Bergh, S. 1976, ApJ, 208, 673
Welch, D. L., McAlary, C. W., McLaren, R. A., & Madore, B. F. 1986, ApJ, 305, 583
Worthey, G. 1993, ApJ, 409, 530