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THE PLANETARY NEBULA DISTANCE TO M101

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ABSTRACT

We report the results of an [O III] λ5007 survey for planetary nebulae (PNs) in the giant Sc galaxy M101 (NGC 5457). By comparing on-band/off-band [O III] λ5007 images with images taken in Hα and the *R*-band filter, we identify 65 PN candidates in the interarm and outer regions of the galaxy. From these data and the empirical planetary nebula luminosity function (PNLF), we derive a distance to the galaxy of 7.7 ± 0.5 Mpc, in excellent agreement with the distance of 7.4 ± 0.7 Mpc measured using *Hubble Space Telescope* observations of Cepheids (Kelson and coworkers). This observation demonstrates that the PNLF technique can be successfully applied to late-type galaxies, and provides an important overlap between the Population I and Population II distance scales. It also places a strong limit on the possible variation of the PNLF with population age.

Subject headings: distance scale — galaxies: distances and redshifts — galaxies: individual (M101, NGC 5457) — planetary nebulae: general

1. INTRODUCTION

A fundamental weakness of the current extragalactic distance scale is the small amount of overlap and cross-checks between some of the techniques. In fact, there are actually two distinct distance scales: a Population II scale, defined by the planetary nebula luminosity function (PNLF), surface brightness fluctuations (SBFs), the globular cluster luminosity function (GCLF), and the elliptical galaxy fundamental plane (D_n-σ) relations, and a Population I scale, involving Cepheid variables, supernovae, and the Tully-Fisher relation. Remarkably, there are only five galaxies that are part of both systems: (1) M31, which is the primary calibrator for the PNLF and SBF methods (Ciardullo et al. 1989b; Tonry 1991), (2) the Large Magellanic Cloud, whose PNLF distance may be affected by the galaxy's low metallicity (Jacoby, Walker, & Ciardullo 1990; Ciardullo & Jacoby 1992), (3) NGC 5253, which has a low metal abundance, a sparse PNLF, and an SBF distance that disagrees with that from the Cepheids (Phillips et al. 1992), (4) M81, which has an uncertain and complicated foreground extinction (see the image by Sandage 1976 and the discussion in Ciardullo, Jacoby, & Tonry 1993), and (5) NGC 300, which has a sparse, oddly shaped PNLF and a correspondingly large (±0.4 mag) distance uncertainty (Soffner et al. 1996). Despite all the checks and comparisons, the calibration of the Population II distance scale rests solely on these five galaxies. All other calibrations are indirect (i.e., they use different galaxies within a common cluster) and are thus susceptible to systematic errors due to galaxy segregation.

In order to reduce any systematic errors between the two distance scales, the number of galaxies common to both systems must be increased. Unfortunately, this is not easy to do. The D_n-σ and Tully-Fisher relations obviously cannot be used, since they are by nature restricted to one type of galaxy. Similarly, the edge-on and early-type spirals that are conducive to SBF and GCLF measurements are not ideal for the detection of Cepheids. Finally, though Type Ia supernovae (SNs Ia) occur in galaxies of all Hubble types, their rate in spirals is much greater than that in ellipticals (van den Bergh & McClure 1994; van den Bergh & Tammann 1991). Consequently, most nearby, well-observed SNs Ia have been in late-type systems, and the few well-observed supernovae within nearby, early-type hosts have been spectroscopically peculiar (Branch, Fisher, & Nugent 1993). Since, even at larger redshifts, only a small fraction of SN Ia host galaxies are suitable for D_n-σ measurements (Hamuy et al. 1995), opportunities to overlap SNs Ia directly with Population II distances are extremely limited.

Perhaps the best method of linking the two distance scales is through the planetary nebula luminosity function. Until now, the PNLF technique has been used primarily in elliptical and S0 galaxies, where the problems presented by internal extinction and interloping H II regions are minimal. However, since planetary nebulae (PNs) are not associated with any one stellar population, PN measurements in spirals are possible, at least in theory. To test this premise, we have conducted a survey for planetary nebulae in the large spiral galaxy M101 (NGC 5457). The importance of M101 to the distance scale is almost beyond mention. It has been used to calibrate such diverse distance indicators as the absolute magnitudes of the brightest stars (cf. Humphreys & Aaronson 1987), the linear diameters of H II regions (Sandage & Tammann 1974), the linear diameters of ringlike H II regions (Lawrie & Kwitter 1982), the diameters of bright galaxies (Sandage 1993), and even (though the galaxy is nearly face-on) the Tully-Fisher relation (Tully & Fisher 1977). It has also been host to three supernovae in the past century, including the well-studied SN 1970G (cf. Fesen 1993), and has been surveyed for Cepheids, both from the ground (Alves & Cook 1995) and from space (Kelson et al. 1996).

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M101 is an excellent test bed for PNLF measurements in spirals. The galaxy's high intrinsic luminosity implies the existence of a large number of planetary nebulae and consequently a well-defined PN luminosity function. In addition, the spiral arms of M101 are loosely wound, providing a sizable interarm area where PN identifications can be made with relatively little contamination from H II regions. The task of discriminating PNs from H II regions is further aided by the galaxy's relative proximity; at a distance of ~7.5 Mpc, all but the most compact objects (with diameters $\lesssim$20 pc) will be resolved. Many of the M101 H II regions have also been cataloged (Hodge et al. 1990), providing even more information on the location of these interloping sources. Finally, at the distance of M101, PNs can be identified with ease, since the difficulty of detecting these sources increases nearly as the fourth power of distance.

2. OBSERVATIONS AND ANALYSIS

Our observations were obtained on 1995 April 5–8 and 11, using the prime focus of the Kitt Peak 4 m telescope and the T2KB 2048 × 2048 Tektronix CCD, which has a pixel scale of 0."47 pixel^{-1} and a field of view of 16′ × 16′. We identified PN candidates using the on-band/off-band technique described in previous papers (e.g., Jacoby et al. 1989; Ciardullo, Jacoby, & Ford 1989a). Briefly, we obtained two 1 hr exposures of M101 through a 30 Å wide [O III] λ5007 filter centered at the systemic velocity of the galaxy. Corresponding images were then taken through a 275 Å wide off-band filter (central wavelength ~5300 Å), a 75 Å wide Hα filter, and a broadband R filter. The seeing throughout the observations was always better than 1."2.

We identified PN candidates by "blinking" the sum of the two on-band [O III] images against a corresponding off-band sum. In order to discriminate planetary nebulae from other emission-line sources, we used the following criteria: (1) PN candidates had to have a point-spread function (PSF) consistent with that of a point source, (2) PN candidates had to be present on the [O III] λ5007 image but invisible on the off-band image, and (3) PN candidates had to be invisible in R and invisible (or extremely weak) in Hα. The latter condition was the most valuable, as it efficiently excluded most H II regions (which are typically low-excitation objects compared to PNs). After applying these criteria, 65 objects remained in our sample. Because of the difficulty in unambiguously identifying PNs within the bright, emission-line regions of the spiral arms, most of our PN candidates are located at large galactocentric radii and in the galaxy's interarm regions. Figure 1 (Plate L2) displays an image of M101, with the positions of the PNs superposed.

The PN candidates were measured photometrically using the IRAF version of DAOPHOT (Stetson 1987) and flux-calibrated using Stone (1977) standard stars and the procedures outlined by Jacoby, Quigley, & Africano (1987). The resulting monochromatic fluxes were then converted to m_{5007} magnitudes using

$$m_{5007} = -2.5 \log F_{5007} - 13.74. \qquad (1)$$

The luminosity function of the planetary nebulae is plotted in Figure 2. The sharp bright-end cutoff at $m_{5007} \sim 24.9$ is similar to that seen in every galaxy surveyed to date.

Because our PN survey was conducted primarily in the low surface brightness regions of M101, our ability to detect PNs was not a strong function of galactic position. Thus, we used the results of Jacoby et al. (1989) and Hui et al. (1993), to estimate our limiting magnitude for completeness as the place where the PNLF (which should be exponentially increasing) begins to turn down. To confirm this number, we randomly added artificial stars to our summed on-band image, and reblinked the frames to recover as many of the simulated objects as possible. As expected, the fraction of our recoveries was independent of PN magnitude down to $m_{5007} \sim 25.9$, as long as we excluded the spiral arms and innermost regions of the galaxy from consideration.

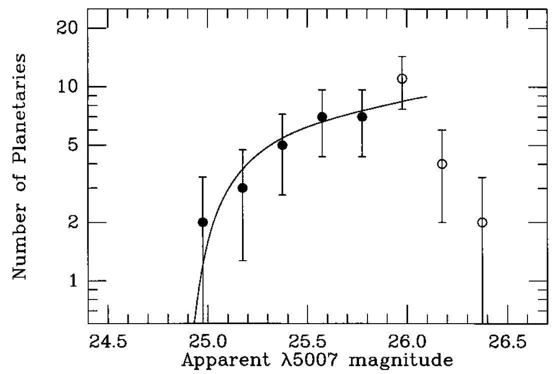

FIG. 2.—Planetary nebula luminosity function for the statistically complete sample of M101 PNs binned into 0.2 mag intervals. The solid line represents the empirical PNLF of eq. (2), convolved with the mean photometric error vs. magnitude relation, and translated to the most likely distance modulus for the galaxy. Open circles indicate objects fainter than the computed completeness limit of $m_{5007} = 25.9$.

To form a statistical sample of PNs, we began by noting the median sky background associated with each PN measurement. After excluding those few objects superposed on bright regions of the galaxy, we picked the worst (most uncertain) background remaining in the sample, and computed the signal-to-noise ratio each PN would have if it were projected on that background. Only those objects that would have been detected with a signal-to-noise ratio greater than 10 (cf. Ciardullo et al. 1987; Hui et al. 1993) on that difficult background were included in our analysis. This procedure removed an additional $\sim\frac{1}{3}$ of the objects from consideration, leaving a total of 27 PNs, with $m_{5007} < 25.9$ in our "complete" PN sample. On-band, off-band, and Hα images of the four brightest PNs in the sample are displayed in Figure 3 (Plate L3).

The PNLF distance to M101 and its formal uncertainty were calculated by convolving the empirical function (Ciardullo et al. 1989b)

$$N(M) \propto e^{0.307M}[1 - e^{3(M^* - M)}], \qquad (2)$$

with a photometric error versus magnitude relation derived from the output of DAOPHOT, and fitting the resultant curve to the statistically complete sample of PNs, via the method of maximum likelihood (Ciardullo et al. 1989b). In order to compare our distance to the current Cepheid distance scale, we adopted $M^* = -4.54$, based on an M31 distance of 770 kpc (Freedman & Madore 1990), a foreground M31 reddening of $A_B = 0.32$ (Burstein & Heiles 1984), and a Savage & Mathis (1979) reddening curve. The derived best-fit distance modulus to M101 (assuming no Galactic extinction; Burstein & Heiles 1984) is $(m - M)_0 = 29.42$; the formal error on this solution is -0.10, $+0.06$. With the M31 distance used in previous PNLF

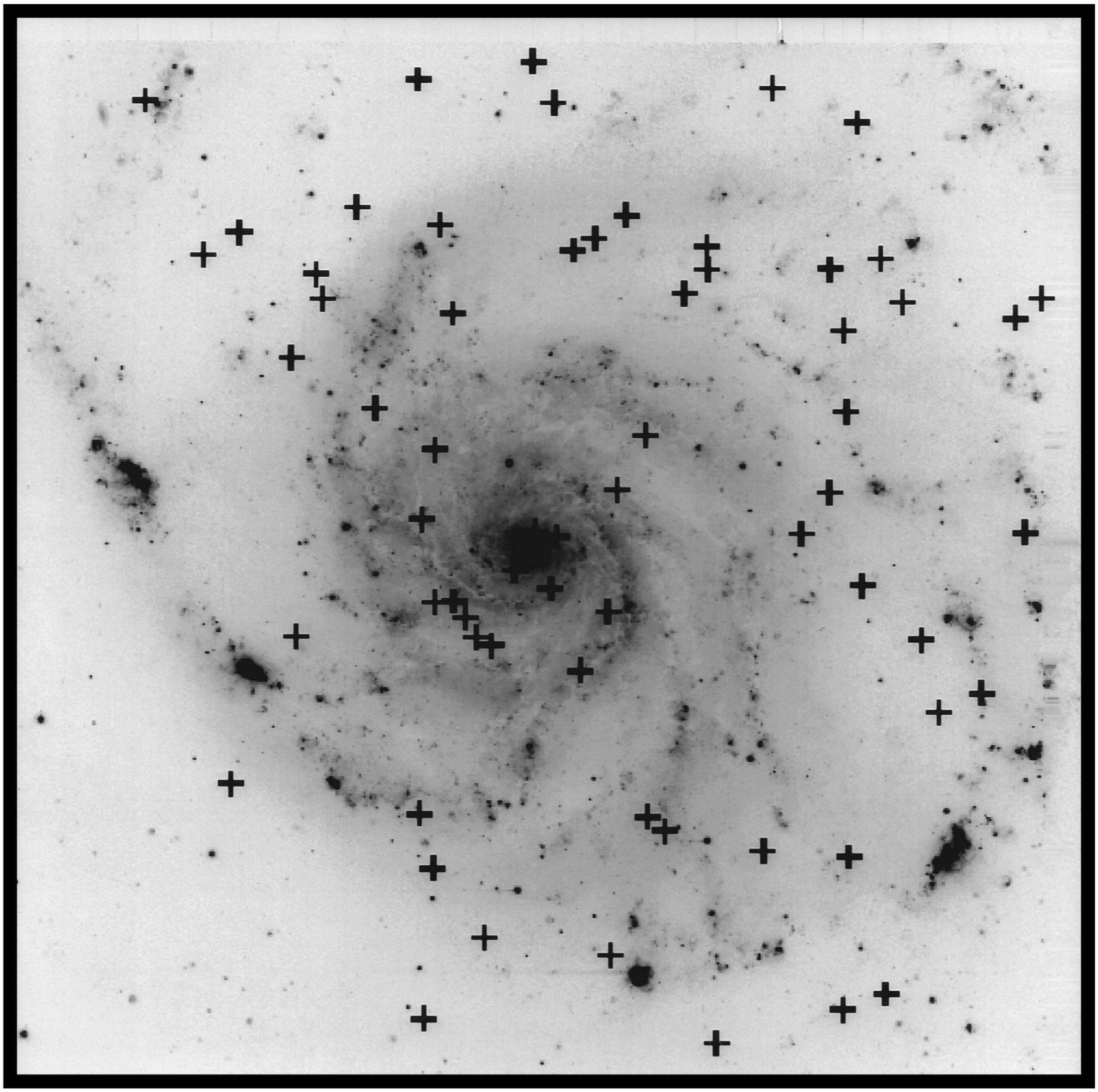

FIG. 1.—Our [O III] λ5007 image of M101, with the positions of our PN candidates superposed. North is up, and east is to the left; the image is 16′ on a side. Although a few PNs are located in bright regions of the galaxy, our identification technique selects against such objects.

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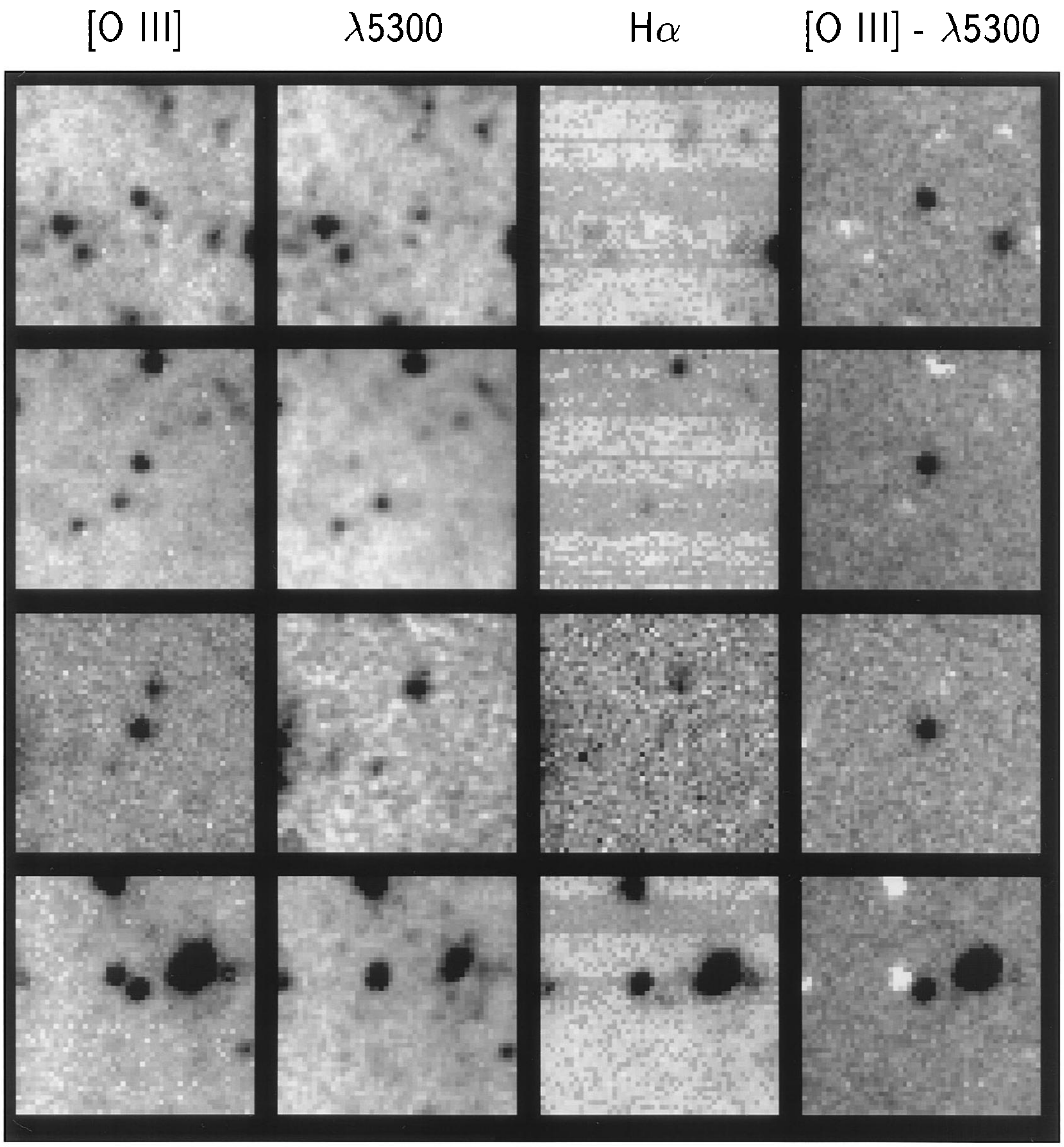

FIG. 3.—Mosaic of the four brightest planetary nebula candidates in our statistical sample of M101 PNs. On the left are images in [O III] λ5007, second from the left are the off-band λ5300 frames, and second from the right are the Hα data. The column on the right displays on-band minus off-band [O III] "difference" images. Each image section is 23″.5 on a side. All the PN candidates have starlike image profiles, and are located in the centers of the image segments.

FELDMEIER, CIARDULLO, & JACOBY (see 461, L26) distance determinations (e.g., Jacoby, Ciardullo, & Ford 1990), this value decreases by 0.06 mag.

The uncertainties quoted above are only those internal to the fitting procedure. To compute the total error budget, these uncertainties must be combined with those associated with the photometric zero point (0.02 mag), the filter response curve (0.04 mag), and the Galactic foreground extinction (0.05 mag, from Burstein & Heiles 1984). In addition, two systematic errors, which affect all PNLF measurements the same way, arise from the uncertain definition of the empirical PNLF (0.05 mag), and, of course, the distance to the calibration galaxy, M31 (0.10 mag). Combining all of these errors, we find the distance modulus of M101 to be 29.42 ± 0.15, which corresponds to a distance of 7.7 ± 0.5 Mpc.

Note that we have not corrected our distance modulus for extinction internal to M101. This is a reasonable assumption, given that PNLF distances are defined by objects at the bright end of the luminosity function. Since PNs are not Population I objects, their scale height should be much greater than that of the dust (Allen 1973). A thin layer of extinction should therefore only distort the faint-end power law of equation (2) by dimming objects on the far side of the galaxy; the computed PNLF distance, which comes from the brightest objects in front of the dust, should remain unaffected. The same argument applies to models with a patchy dust distribution; while some PNs will surely suffer extinction, the brightest PNs detected in an [O III] survey should be dust free. If all (or at least a large majority) of the PN candidates are being extincted, then, of course, our derived PNLF distance will be an overestimate. However, Alves & Cook (1995) found no evidence for internal extinction in their multicolor observations of the M101 Cepheids, and the reddening derived from V and I observations of Cepheids by the *Hubble Space Telescope* is only $E(B - V) = 0.03$ (Kelson et al. 1996). Therefore it seems unlikely that our bright PNs are any more affected.

3. DISCUSSION

Our PNLF distance modulus of $(m - M)_0 = 29.42 \pm 0.15$ is in excellent agreement with that derived from the observations of Cepheids. When scaled to our LMC distance modulus of 18.5, the ground-based measurements of Alves & Cook (1995) give a distance to M101 of $(m - M)_0 = 29.18 \pm 0.13$, 12% smaller than our value. More important, our PNLF distance is statistically indistinguishable from the *Hubble Space Telescope* Cepheid distance of $(m - M)_0 = 29.34 \pm 0.16$. Considering that the M101 PN progenitors are extremely different from those investigated in previous PNLF surveys, this is a remarkable result. The PNLF method was originally calibrated in the old, metal-rich population of the M31 bulge (Ciardullo et al. 1989b), and has usually been applied in E/S0 galaxies and spiral bulges (cf. Jacoby et al. 1992 and references therein). The lone exceptions to this rule, the Magellanic Clouds (Jacoby, Walker, & Ciardullo 1990), NGC 5253 (Phillips et al. 1992), and NGC 300 (Soffner et al. 1996), are all small, metal-poor systems. Thus, the large, metal-rich spiral M101 represents a fundamentally different galactic environment for PNLF measurements. The agreement between our distance and that derived from the Cepheids is an important confirmation of the technique and further verifies the insensitivity of the PNLF to stellar population.

Our result also places a constraint on theories for the invariance of the planetary nebula luminosity function with population age. Models by Jacoby (1989), Méndez et al. (1993), and Han, Podsiadlowski, & Eggleton (1994) all suggest that a population of PNs derived from young, massive stars will have a value of M^* brighter than that seen in an old stellar population. Specifically, Méndez et al. (1993) predict a difference of ~0.5 mag between the PNLF cutoff in a population with a constant star formation rate and that in an old elliptical galaxy. This effect is not seen in our data. Indeed, if there is any effect at all, it goes in the wrong direction; our distance to M101 is slightly larger than that derived from the Cepheids, implying a slightly fainter value for M^*. Alternatively, if we assume that the extinction to the M101 PN is the same as that to its Cepheids [$E(B - V) = 0.03$; Kelson et al. 1996], then our distance is within 1% of the *Hubble Space Telescope* Cepheid result. This agreement confirms the PNLF analysis for the Large Magellanic Cloud, where no age effect was seen (Jacoby, Walker, & Ciardullo 1990).

In the LMC, the effect of age on the PNLF cutoff may be masked by the galaxy's low metal abundance. However, M101 is a metal-rich system. Therefore, some other physical mechanism must be invoked if the discrepancy is to be explained. One possibility may lie in our selection criteria for planetary nebulae. In order to avoid contamination by H II regions, our PN survey preferentially identified objects away from star-forming regions. Consequently, we may be discriminating against the highest mass PNs. Alternatively, our estimate for the magnitude of the PNLF cutoff may be biased by extinction caused by dust. From the arguments presented above, this scenario seems unlikely, but if extinction is responsible, its effect must be balanced exactly by that of age. In either case, our observations provide no evidence for a brightening of the PNLF cutoff in young populations.

There are now six galaxies with both PNLF and Cepheid distance measurements. In every case, the two distances are statistically indistinguishable. With the success of the M101 survey, it is clear that further PNLF-Cepheid comparisons are possible. These observations should provide the link needed to finally produce a unified extragalactic distance scale.

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