VI. PLANETARY NEBULAE IN GALACTIC SYSTEMS

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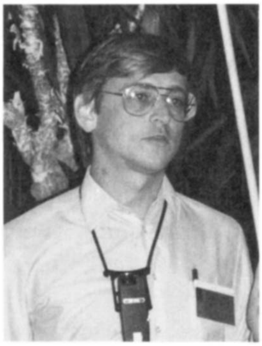
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LUMINOSITY FUNCTIONS OF PLANETARY NEBULAE

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ABSTRACT. Luminosity functions of planetary nebulae contain information about the central star mass distributions, nebular, central star, and progenitor evolution, stellar death rates, and a galaxy's star formation and chemical evolution histories. Appropriate observing strategies can be used in combination with various models to extract some of the parameters of these functions. The principal results from these studies are that the central star mass distribution is narrow ($\sigma \sim 0.02 - 0.04 M_\odot$), the number of PN in a galaxy depends on galaxy color, and the number of PN in the Galaxy is $\sim 10^4$.

The most extensive application of luminosity function studies has been exploiting the bright end cutoff as a distance indicator. Distances for 25 galaxies have been measured using the methodology outlined by Jacoby, Ciardullo, and collaborators. The PNLF method compares extremely well with other techniques, and is accurate to $\sim 5\%$. In fact, there is no evidence for systematic effects of any kind, although a small (5-10%) metallicity correction needs to be applied for metal-poor systems.

1. Introduction

Luminosity function studies of planetary nebulae (PN) have recently received a great deal of attention. The increased awareness derives primarily from using the [O III] planetary nebula luminosity function (PNLF) to derive distances to galaxies. These distances, in turn, have important consequences for the Hubble Constant and the age of the Universe.

The first discussions of the PNLF can be traced back 30 years to Henize and Westerlund (1963) who measured the bright end of the SMC PNLF. Those authors stated quite clearly that they found an upper limit to the PN luminosities, and this limit was very similar to that found by O'Dell (1962) for the Galaxy and predicted by Shklovsky (1956). They stopped short, however, of suggesting that this fiducial may be used as an extragalactic distance indicator, perhaps because Galactic PN luminosities have always been plagued by inaccurate distances. Consequently, most PNLF studies have targeted large collections of PN with a single distance (*e.g.,* those in the Galactic Bulge, the Magellanic Clouds, M31) rather than those in the solar neighborhood. It is a remarkable irony that distances to far-off galaxies can be measured quite accurately ($\sim 5\%$) using PN, but distances to the

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much closer Galactic PN usually cannot be measured to better than a factor of 2.

In addition to the extragalactic distance scale, motivation to study the PNLF derives from interest in 1) estimating the total number of PN in galaxies (including ours), 2) deriving central star mass distributions, 3) testing central star and nebula evolution theory, and 4) testing progenitor evolution and dredge-up theory. In addition, the various parameters describing the star formation history and chemical enrichment are also somehow convolved into the physical processes that determine the PNLF, but these represent a weak dependence and cannot be extracted easily.

In the following discussion, we define the PNLF to be the number of PN as a function of magnitude in a particular emission line. An example is shown in Figure 1. For distant galaxies, [O III] λ5007 is the only reasonable line to explore because it is generally the brightest line in the visible spectrum. Furthermore, the [O III] PNLF exhibits much lower sensitivity to metallicity variations than the Balmer line PNLF (Dopita *et al.* 1992), and so it has greater value as an extragalactic distance indicator. The use of [O III] does, however, introduce a selection effect against low excitation nebulae that may affect estimates of the total PN population. Other lines, such as Hβ, suffer less from this effect and have been used extensively for nearby PN samples (*e.g.*, Pottasch 1990; Stasińska *et al.* 1991).

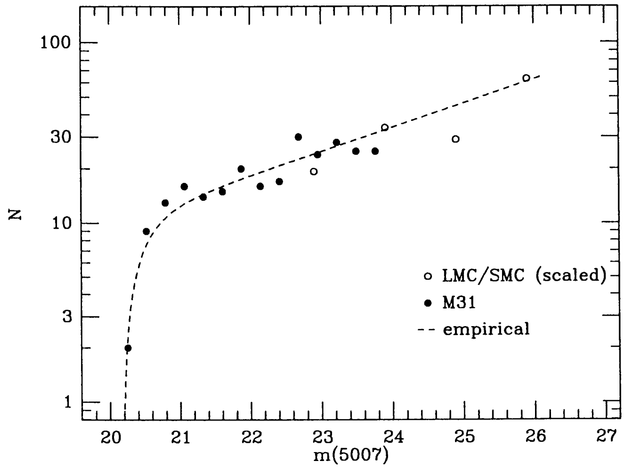

Figure 1. The [O III] PNLF of the bulge of M31 (solid points) extending 3.5 mag below M^*. Open points show the Jacoby (1980) Magellanic Cloud PNLF (minus the invalid identifications noted by Boroson and Liebert [1989]) after scaling to match the sample size of the M31 data. The overall PNLF spans 6 magnitudes. Equation (2) is shown as the smooth curve.

2. Results From PNLF Studies

The first observational determination of the [O III] PNLF was made by Jacoby (1980) for PN in the Magellanic Clouds. His primary interest was to derive the number of PN in Local Group galaxies by comparing complete samples of objects in the brightest few magnitudes of the PNLF with the PNLF of the LMC and SMC. Jacoby derived the V-band luminosity-specific PN density for 10 Local Group galaxies and used their mean PN density to estimate a Galactic PN population of $10,000 \pm 4000$. A more detailed accounting of the problem has been carried out by Peimbert (1990; see also this volume) who derived a total Galactic PN population of 7200 ± 1800. Since these estimates are based on extrapolations of [O III] PNLFs, they may be subject to the aforementioned selection effect.

Pottasch (1984) compared the Hβ PNLF in the Galactic bulge with the Magellanic Cloud PNLF. The functions exhibit a similar range of luminosities, which Pottasch took as a strong indication that the adopted distances to the Magellanic Clouds, the Galactic Bulge, and the solar neighborhood sample were credible. The shapes of the PNLFs were not directly comparable, however, due to drastically different selection criteria, and so it was not possible to argue for the use of PN as a distance indicator. Although the possibility had been suspected much earlier (Hodge 1966), the first serious proposal outlining the PNLF technique for deriving extragalactic distances was presented many years later (Jacoby, Ciardullo, and Ford 1988). Jacoby (1989) and Ciardullo *et al.* (1989a) described the underlying astrophysics and details of the method (see §3).

In principle, the shape of the PNLF can be computed from stellar and nebular evolution theory. Henize and Westerlund (1963) made the initial attempt, by assuming a non-evolving central star and a uniformly expanding nebular shell. Despite the apparent simplicity of this model, it predicts the faint end of the PNLF rather well.

Jacoby (1989) simulated the [O III] PNLF to a much finer precision by using improved nebula models and central star evolutionary tracks to produce a grid of models having central star age and mass as independent variables. For a given set of central star evolutionary tracks (*e.g.,* Wood and Faulkner 1986), these 2 parameters define the luminosity and temperature of the star, while age alone determines the size and density of the surrounding nebula. The grid represents the time history of the emission-line fluxes escaping the nebula as a function of central star mass. By selecting central star masses according to some distribution function, and selecting ages randomly for many hypothetical PN, a PNLF in any emission line can be simulated. Jacoby found that it was necessary to invoke a rather small central star dispersion (0.02 $M_{\odot}$) to match the rapidity of the bright end cutoff in the observed PNLF of 5 different galaxies. Combined with the fast evolutionary time scales for high mass central stars, the 0.02 $M_{\odot}$ high mass Gaussian width serves to truncate the PNLF. It is worth emphasizing that the small dispersion applies only to the very brightest PN as measured in λ5007 and that the dispersion width depends on the adopted core mass-luminosity relationship (that of Schönberner [1979] in this case). Furthermore, the possible convergence of evolutionary tracks due to continuing mass loss after the AGB (Vassiliadis and Wood 1992) would reduce the high mass cutoff rate since stars with high initial masses will approach the low mass tracks later in their lifetimes.

Stasińska *et al.* (1991) used a similar Monte Carlo approach to determine that the ionized mass in the Galactic bulge nebulae is $\sim 0.2M_{\odot}$ and that the dispersion in central star masses is 0.04-0.05 $M_{\odot}$. Although the latter value is higher than that derived by Jacoby (1989), the two results cannot be compared directly because Stasińska *et al.* adopted the Schönberner (1981, 1983) central star evolutionary tracks. In addition, selection effects and line-of-sight depth to the Galactic bulge act to smooth the observed PNLF such that the apparent dispersion in core mass is larger than the intrinsic dispersion. Consequently, the estimate of 0.04-0.05 $M_{\odot}$ should be viewed as an upper limit.

Dopita *et al.* (1992) investigated the effects of metallicity variations on the PNLF. Jacoby's (1989) limited effort to probe the sensitivity of the PNLF to metallicity was concerned only with the effect on the nebula. Because the central star characteristics also change with metallicity, Dopita *et al.* included that effect in assessing the impact of metallicity variations on the total system (see §3.2).

3. Extragalactic Distances Using the PNLF

Early attempts to use PN as distance indicators (Ford and Jenner 1978; Jacoby and Lesser 1981; Lawrie and Graham 1983; Ford *et al.* 1989) were based on the brightest few objects. Any method that relies on the extremes of a population is subject to systematic sampling errors; consequently, those early studies received relatively little attention.

The systematic errors can be minimized by incorporating the shape of the luminosity function into the analysis. Along these lines, Ciardullo *et al.* (1989a) described a robust and objective method for deriving distances using the method of maximum likelihood. The procedure accounts for all known observational uncertainties (such as photometric errors and filter calibration) in a rigorous manner without resorting to the deleterious effects of histogram sampling. Given the [O III] magnitudes for a few dozen PN, the approach is to find the magnitude shift relative to a reference PNLF such that the probability of observing the PN is maximized. Figure 2 illustrates a typical PNLF and probability curve.

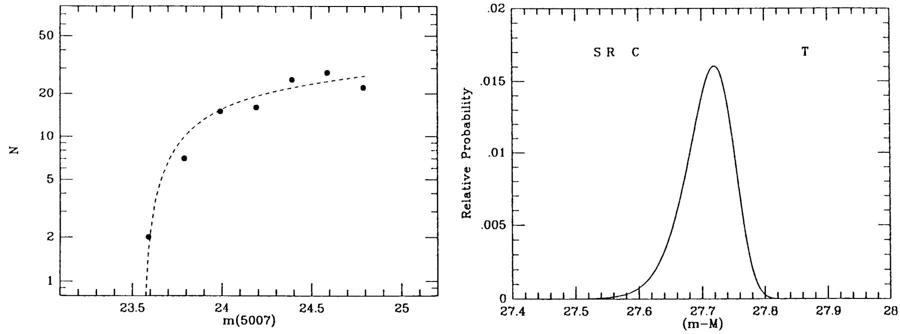

Figure 2. The [O III] PNLF for the bulge of M81, extending ~ 1.2 mag below M^* (left panel) with equation (2) shown as the smooth curve, and the maximum likelihood probability distribution (representing the formal errors only) for the distance modulus (right panel). Symbols S, R, T, C refer to the distance moduli derived using SBF, brightest red stars, Tully-Fisher, and Cepheids. Uncertainties for each method are typically ±0.3 mag, corresponding to the total extent of the figure.

Ciardullo *et al.* adopted the PNLF from the bulge of M31 as a reference because its distance is well-determined (van den Bergh 1991), it has a large PN population (see Figure 1), and it has the color and metallicity typical of the giant ellipticals for which the method is most applicable and provocative. For ease of computation, the M31 PNLF has been approximated by the empirical law (solid curve in Figure 1),

$$N(M) \propto e^{0.307M}(1 - e^{3(M^*-M)}) \tag{1}$$

where M is related to the $\lambda 5007$ flux of a PN by

$$M = -2.5 \log F_{5007} - 13.74 \tag{2}$$

and M^* is the absolute magnitude of the bright end cutoff. From the M31 observations, $M^* = -4.48$. The revised M31 distance (770 kpc) of Freedman and Madore (1990) and the extinction ($A_{5007} = 0.28$) from Burstein and Heiles (1984) would yield an M^* that is 0.06 mag brighter. Distances quoted in this review refer to the original estimate for M^*.

Table 1 lists all galaxies with an observed PNLF and their derived distances.

3.1. TESTING PROCEDURES

One reason for the quick acceptance of PNLF distances is that its proponents did not present their results until after they had verified that the method works. They performed numerous tests, both internal and external, designed to assess the accuracy of their results; in fact, the PNLF method has been tested more carefully than any other general purpose distance technique.

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The easier tests to perform were the "internal" tests which compared the distances to several galaxies within a single cluster. This was done for the Leo I galaxies NGC 3377, NGC 3379, and NGC 3384 (Ciardullo *et al.* 1989b). Distances to these galaxies demonstrated unprecedented internal accuracy (2.5% rms) for a galaxy distance technique. Furthermore, the method was tested over a small, but non-negligible, range in both Hubble type (E6-SB0) and metallicity (25%). Following these encouraging results, Jacoby *et al.* (1990) pushed the method further and derived distances to 6 galaxies in the Virgo Cluster core. Here, a wider range of metallicities was encompassed (55%), yet the distances all agreed (5% rms) within the range expected for a large galaxy cluster. Another internal test compared the distance of an edge-on Sb galaxy (NGC 891) to that of its neighbor, an SB0 galaxy with relatively recent star formation (NGC 1023) (Ciardullo *et al.* 1991). The purpose of this test was to identify any systematic error introduced by using an Sb galaxy (*e.g.,* M31) as a reference for earlier galaxy types. The resulting distances were identical, and the relatively sparse sample of PN identified above the disk of NGC 891 (33) compared to NGC 1023 (110) did not compromise the results.

TABLE 1. Summary of PNLF Results to Date

Name	Type	Nr. PN	$(m-M)_0$	$\alpha_{2.5}(\times 10^9)$
Local Group				
LMC	SBm	42	18.44 ± 0.18	32
SMC	Im	8	19.09 ± 0.29	48
185	dE3p	4	...	...
205	S0/E5p	12	24.68 ± 0.35	54 ± 18
221	E2	9	24.58 ± 0.60	38 ± 17
224	Sb	104	24.26 ± 0.04	11.0 ± 2.0
NGC 1023 Group				
891	Sb	34	29.97 ± 0.16	...
1023	SB0	97	29.97 ± 0.14	22.3 ± 3.7
Fornax Cluster				
1399	E1	53	31.01 ± 0.08	...
1404	E2	53	31.17 ± 0.07	...
Leo I Group				
3377	E6	22	30.07 ± 0.17	38.3 ± 8.8
3379	E0	45	29.96 ± 0.16	21.4 ± 3.3
3384	SB0	43	30.03 ± 0.16	39.7 ± 6.4
Virgo Cluster				
4374	E1	37	30.98 ± 0.18	17.5 ± 3.1
4382	S0	59	30.79 ± 0.17	...
4406	S0/E3	59	30.98 ± 0.17	13.9 ± 2.0
4472	E1/S0	26	30.71 ± 0.19	6.7 ± 1.4
4486	E0	36	30.81 ± 0.17	8.8 ± 1.5
4649	S0	16	30.76 ± 0.19	6.5 ± 2.0
NGC 5128 Group				
5128	S0p	224	27.73 ± 0.04	26.8 ± 5.7
5253	Amor	16	28.08 ± 0.29	...
Other				
3031	Sb	88	27.72 ± 0.25	16.2 ± 2.0
3109	Sm	7	26.00	145
3115	S0	52	30.11 ± 0.20	25.0 ± 7.4
4594	Sa	204	29.76 ± 0.04	17.6 ± 1.7
Bulge	Sbc	22	14.54 ± 0.20	...

Notes:

1. No metallicity corrections (Ciardullo and Jacoby 1992) have been applied to the distances.

2. All results are from Ciardullo, Jacoby, and collaborators except: the Galactic Bulge (Pottasch 1990), NGC 3109 (Richer and McCall 1992), and NGC 4594 (Hui *et al.* 1993).

More important than these internal tests were the tests for external errors between the PNLF method and distances derived by other reliable indicators. Only the RR Lyrae and Cepheid variables are considered "unassailable" techniques. This is unfortunate because the former cannot be used beyond ~1 Mpc, and the latter are not found in early-type systems where the PNLF method is most applicable. Nevertheless, the PNLF method can be used in the nearer spirals where HII region discrimination is possible based on spatial resolution. Three Cepheid galaxies have been observed: M81 (Jacoby *et al.* 1989), the LMC, and the SMC (Jacoby *et al.* 1990). The PNLF and Cepheid distances are 3.5 and 3.3 Mpc, 49 and 51 kpc, and 66 and 56 kpc, respectively. The agreement is exceptionally good for the first 2 cases. The SMC has a metallicity ~0.1 that of M31's bulge which, according to the models of Dopita *et al.* (1992) and the observational test by Ciardullo and Jacoby (1992), requires a correction (see §3.2) of 12% downward to 59 kpc. (The SMC PN sample represents about 30% of the data used in the latter experiment, so this distance correction is not completely independent of the empirical calibration.) Thus, the method reproduces accepted values whether sample sizes are large (88 PN in M81) or small (35/8 in the LMC/SMC), thereby demonstrating the robustness of the maximum likelihood luminosity function fitting technique. In addition, Pottasch (1990) derived the distance to the Galactic bulge using the PNLF approach. His result of 8.1 kpc compares well with that of other indicators that yield 7.7 kpc (Reid 1989).

Another way to search for systematic effects is to compare distances to individual galaxies using different methods. Until recently, this approach provided little new information because most methods suffer from large random errors that mask the external effects. With the advent of the PNLF and surface brightness fluctuation (SBF) techniques, we can make comparisons for the first time that are capable of resolving systematic effects at the 5% level. Jacoby *et al.* (1992) performed a cross-comparison for the 7 primary methods of extragalactic distance determination currently in use: PNLF, SBF, globular cluster luminosity functions (GCLF), novae, Type Ia supernovae, $D_n - \sigma$, and Tully-Fisher. The review by Jacoby *et al.* (1992) describes each of these methods in detail: their advantages, disadvantages, strengths, and weaknesses. The comparisons demonstrate that each method yields distances having accuracies very close to what their proponents predict. The PNLF method, for instance, agrees with the SBF distances on a galaxy-by-galaxy basis to within 8% rms, suggesting that the PNLF contribution to the error is ~ 5%. Figure 3 illustrates the excellent agreement among the best methods.

Based on direct observational tests, it appears that the internal consistency and external accuracy of the PNLF technique is excellent. Bottinelli *et al.* (1991), however, raised a specter of doubt about the PNLF distance to Virgo. In particular, they suggested that (1) there is a correlation between the distance moduli and apparent galaxy magnitudes in Virgo in the sense that brighter galaxies are found to be closer, (2) there is a trend in the comparison between the PNLF distances and the SBF distances presented by Tonry (1991), (3) the brightest few tenths of the PNLF is similar to a power law for which the tradeoff between distance and sample size represents a degenerate solution, and (4) there is a correlation between PN identification rates and parent galaxy luminosity.

Mendez *et al.* (1992) review these issues. They demonstrate quantitatively that items (1) and (3) are insignificant or erroneous and item (2) is most likely the result of a small (5%) systematic error in the SBF distances rather than in the PNLF method. Item (4) is quite real, as was first discussed by Peimbert (1990), and further supported by Ciardullo *et al.* (1991) and Richer and McCall (1992). However, rather than being an artifact of improperly applying the PNLF technique, the drop-off in the bright PN population as galaxy luminosity rises can be understood as a consequence of stellar evolution (see §3.3).

3.2. EFFECTS OF METALLICITY

Every distance indicator (other than geometric methods) is affected by metallicity, but most indicators are too imprecise to discern the effects (*e.g.*, $D_n - \sigma$). Because the PNLF technique is among the most precise, it is possible to distinguish effects as small as 5%. Dopita *et al.* (1992) predicted that the distances derived using the PNLF method would be affected by less than ~ 10% for metallicities within a factor of ~ 3 of solar, and this trend has been confirmed observationally (Ciardullo and Jacoby 1992).

It seems remarkable that the net effect on the [O III] PNLF due to changes in progenitor metallicity is so small, but it can be understood easily as a fortuitous, near-perfect balance between 2 metallicity sensitive processes. While the nebula is affected in a direct manner (higher abundances produce higher [O III] fluxes thanks to the greater availability of oxygen atoms), the central star's UV luminosity is affected in the reverse. The latter behavior is a consequence of the mass loss history of the progenitor: higher metallicity implies greater losses over the lifetime of the star, resulting in a lower central star mass. The two effects offset each other to first order so that the PNLF bright end cutoff remains nearly constant (to within 0.1 mag) until the metallicity of the PN ensemble deviates significantly from solar abundances. Under extreme conditions, one or the other of these non-linear effects overwhelms the balance and a metallicity correction becomes necessary.

Another way to estimate the effects of metallicity is to measure the distance to a single galaxy using different PN populations. Hui (1992) has done this for the nearby galaxy NGC 5128 by dividing a large sample of PN into 4 groups with average galactocentric radii of 2, 5, 7, and 13 arcmin. The abundance gradient in the galaxy serves to create metallicity subsamples, ranging from about twice solar to about half solar. Hui finds the distances to these groups to be 3.65, 3.55, 3.55, and 3.42 Mpc. Furthermore, she finds that the PN production rate increases with radius by 50%, in good agreement with the following section. For a galaxy as close as NGC 5128, the PN production rate variations cannot be an artifact of sampling the PNLF inadequately as Bottinelli *et al.* (1991) have suggested. Also, note that the 5% decrease in the derived distance with radius (*i.e.*, decreasing metallicity) is in excellent agreement with the experiment of Ciardullo and Jacoby (1992).

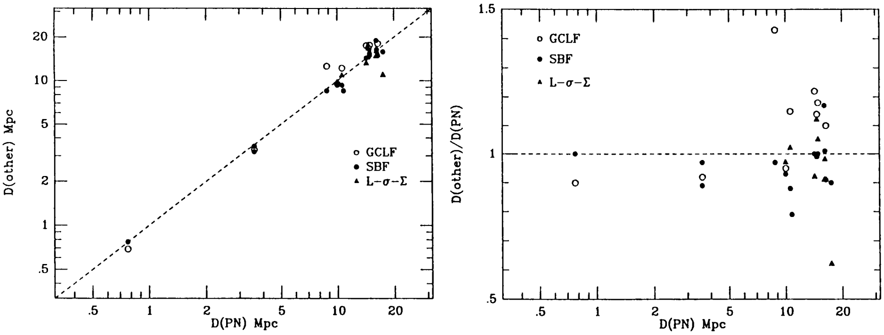

Figure 3. A comparison between the PNLF distances to individual galaxies and those derived using SBF (Tonry 1991), GCLF (Harris 1992, priv. comm.), and the fundamental plane relation (L-σ-Σ) for ellipticals (Pierce 1989). PNLF distances have been increased by 3% to account for the recently revised M31 distance (see text). The (zero-point offsets, rms dispersions) are (-4%,9%), (+11%,17%), and (-6%,14%) for the comparison of the 3 methods respectively. These values become (-3%,8%), (+7%,13%), and (-1%,8%) if the most discrepant galaxy is removed from each sample of 14, 9, and 9 galaxies, respectively. Obviously, the PNLF distances are in very good agreement with distances derived using other methods.

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3.3. THE PN PRODUCTION RATE: A VALUABLE BY-PRODUCT

The procedure for deriving distances requires that the PNLF of a target galaxy be matched to that of the reference galaxy; *i.e.,* the sample sizes must be normalized. In fact, there are 2 variables that enter the solution: distance and number of PN. We define the luminosity-specific PN rate, $\alpha_{2.5}$, as the number of PN in the first 2.5 mag of the PNLF relative to the bolometric luminosity of the sampled region in the host galaxy. In practice, $\alpha_{2.5}$ may have to be estimated from a survey which does not extend 2.5 mags and a correction factor, obtained by extrapolating the integral PNLF, is applied. Figure 4 illustrates M81's 2-dimensional solution for distance modulus and $\alpha_{2.5}$.

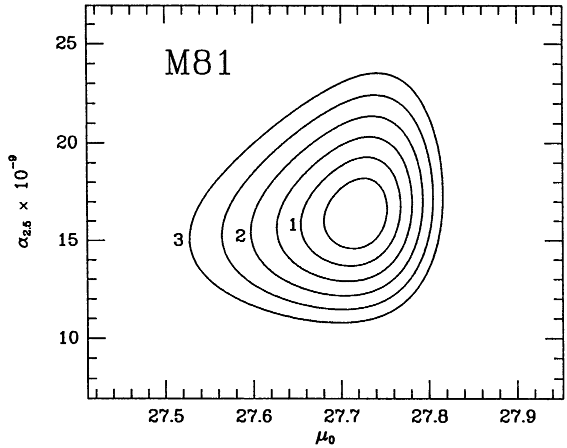

Figure 4. The complete maximum likelihood solution for M81, illustrating the 0.5, 1, 1.5, 2, 2.5, and 3 σ confidence levels in the 2 variables, distance modulus and luminosity specific PN density, $\alpha_{2.5}$. The right panel of Figure 2 is recovered if the vertical span of Figure 4 is collapsed to 1 dimension.

Peimbert (1990) showed that $\alpha_{2.5}$ varies by nearly an order of magnitude, and that the variations correlate extremely well with host galaxy color and absolute magnitude. This result would seem to be disparate with the prediction of Renzini and Buzzoni (1986) that a population's stellar death rate should be nearly independent of its age or IMF. However, the stellar death rate and the PN birth rate are not necessarily identical. Peimbert (1992) proposed that the [O III] bright PN form from young stars and the proportions of the mix of young and old stars correlates with galaxy luminosity and color.

Ciardullo *et al.* (1991) suggested another possibility: the progenitor-core mass relationship is "noisy" so that a given turnoff mass is capable of producing a distribution of core masses, possibly as a consequence of rotation (Weidemann 1990). Weidemann and Koester (1983) showed that this possibility occurs in the Galaxy. Statistically then, an older, redder system produces fewer high mass central stars than a younger one. The [O III] PNLF is truncated, not by the non-existence of high mass central stars, but by their fast evolutionary rates and by their enhanced nebular abundances.

Following Peimbert (1990), Ciardullo *et al.* (1991) and Richer and McCall (1992) confirmed that $\alpha_{2.5}$ correlates with host galaxy color, and showed that it may correlate with UV (1550Å) excess (*e.g.,* Burstein *et al.* 1988) in the sense that the greater the UV excess, the fewer bright PN in the galaxy. A possible explanation is that the source of UV excess originates, at least in part, from those stars that lose so much mass prior to climbing the AGB that they bypass the PN stage to become hot horizontal branch stars (Greggio and

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Renzini 1990). Since AGB mass loss depends on metallicity, these stars may be the high metallicity tail of a galaxy's population. It may therefore be possible for a galaxy's mean metallicity to be so high that the PN represent only a tiny fraction of the dying stars.

Figure 5 illustrates the relationship between $\alpha_{2.5}$ and galaxy color (U-V), metallicity, and UV color. The number of PN in our Galaxy can be estimated from these relations given the color ($U - V = 0.45$) and luminosity ($M_{bol} = -21.2$) (de Vaucouleurs and Pence 1978; de Vaucouleurs 1977). Peimbert's (1990) determination of 7200 is 3-4 times smaller than other recent estimates (Phillips 1989), but the latter generally depend on Galactic PN distance measurements. This matter is still being debated, since $\alpha_{2.5}$ may be subject to excitation level selection effects and Galactic PN distances are uncertain.

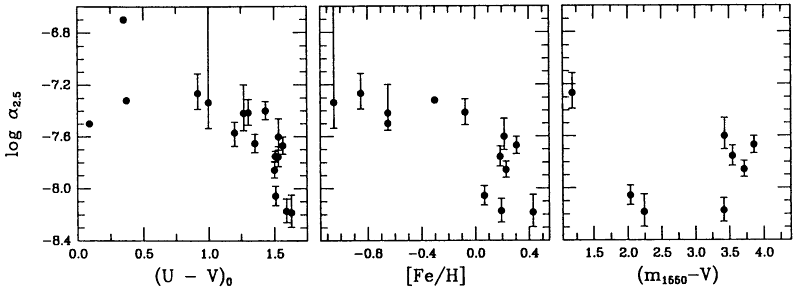

Figure 5. The relationship between $\alpha_{2.5}$ and galaxy color, metallicity, and UV color. A trend is evident for the two leftmost panels. There is only a weak trend, if any, with UV color. The bluest galaxy shown in the right hand panel is NGC 205, a galaxy known to have a rich population of young blue stars, and is therefore very different than the giant ellipticals. If excluded, a more respectable correlation appears.

3.4. THE BRIGHT TAIL OF THE PNLF

A bright extension to the PNLF has been seen in a small number of galaxies. One possible cause for this bright tail arises when galaxies more distant than $\sim$ 10 Mpc are surveyed. The spatial scale becomes so compressed that 2 individual PN can coincide within the seeing disk. The measured brightness of the "double" can exceed M^*, extending the PNLF up to 0.75 mag. It is very unlikely that 2 PN having an M^* luminosity will coincide, and so the magnitude of this effect is typically small ($\lesssim$ 0.3 mag; Jacoby *et al.* 1990). Since the superposition process is well understood, it can be modeled easily and the effects removed during the maximum likelihood fitting process. Generally, there are so few objects in this category ($\sim$ 1%) that this is unnecessary. Additional sources of "PN" having $M_{5007} < M^*$ can be HII regions (Ciardullo *et al.* 1991) and supernova remnants. Since both of these objects are rare or absent in early-type galaxies, they do not impact the method.

Although the mass distribution of PN central stars tends strongly toward low masses (Stasińska *et al.* 1991; Tylenda *et al.* 1991), a few high mass stragglers appear in the the Magellanic Clouds (Kaler and Jacoby 1991) and possibly in the Galactic disk (*e.g.,* Kaler and Jacoby 1989; Mendez *et al.* 1988). Due to rapid evolutionary rates, these are unlikely to be found while bright, and should not participate in the bright end of the PNLF (Kaler and Jacoby 1990, 1991). Furthermore, most of the massive central stars are identified with Type I PN which have enhanced abundances. A simple numerical experiment shows that the nitrogen enhancement competes for collisional energy and therefore serves to diminish the [O III] λ5007 line by 0.4 mag. Thus, PN having high mass central stars are pushed down the PNLF causing a de-selection (Figure 3 of Kaler and Jacoby 1991) when bright [O III] PN are being collected. The possibility cannot be dismissed, however, that some of the objects on the bright tail of the PNLF derive from PN having high mass central stars.

4. Further Issues

The PNLF distance method, while among the best techniques, could be better. The principal areas for improvement are (1) refining the adopted PNLF shape, (2) deriving distances to additional Cepheid galaxies for calibrators, and (3) examining the metallicity sensitivity over a wider range and for more galaxies, and (4) clarifying the theoretical rationale for the bright end cutoff. The technique is currently limited to distances $\lesssim$ 25 Mpc, but this can be pushed to $\sim$ 40 Mpc with large telescopes on excellent sites.

What creates the correlation between $\alpha_{2.5}$ and galaxy luminosity and color? The answer to this question blends stellar evolution, galaxy formation, and PN theories.

An important by-product from PNLF studies is that several hundred PN may be identified in a galaxy. Kinematics of these objects provide a unique sampling of the galaxian gravity field to test for mass-to-light variations and dark matter. The unprecedented study by Hui (1992; also this volume) based on 433 PN in NGC 5128 illustrates the enormous value that extragalactic PN offer.

The measurement of abundances for individual stars in distant galaxies is another by-product with considerable potential. With large telescopes and fiber spectrographs, we are no longer limited to the Magellanic Clouds. M31 and its neighbors are easily within reach, and it will soon be possible to determine the chemical compositions for stars in M81, NGC 5128, and other galaxies at distances up to 4 Mpc.

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