Planetary nebulae (PN) luminosity function (LF) distances

Roberto H. Méndez
Institute for Astronomy
University of Hawaii, Honolulu
June 2014
Outline

• The history of the PNLF, and how it works
• Initial skepticism and MonteCarlo simulations
• Comparison with SBF and TRGB distances
• New PNLF distances
• Possible solutions to a stellar astrophysics enigma
Basic properties of PNs

- Outflowing low-density gas and dust particles
- Expansion velocity: 10 – 50 km/s
- Maximum size: approximately 1 pc
- Time for dissipation: about 30,000 years
- Electron density: 100 – 100,000 per cubic cm
- Mass: 0.1 – 1 solar mass

- Physical processes: shocks produced by stellar post-AGB mass loss (high-speed wind); gas ionization by high-energy photons; recombination; collisional excitation of metastable levels near ground states, and emission of “forbidden lines”; dust heating by stellar and nebular radiation.
A typical medium-excitation PN spectrum
From fluxes to magnitudes

• The monochromatic flux corresponding to the visual magnitude is:
  \[ F_{5480} = 0.365 \times 10^{-0.4} \, \text{V \ erg \ cm}^{-2} \, \text{s}^{-1} \, \text{cm}^{-1} \]

• If we want a visual flux integrated over the whole visual filter, in
  \[ \text{erg \ cm}^{-2} \, \text{s}^{-1}, \] we must multiply by the equivalent width of the
  Johnson V filter, which is 874 Angstroms, but expressed in cm.

• To define “Jacoby equivalent magnitudes” we start with the nebular
  flux in 5007, which is of course in \[ \text{erg \ cm}^{-2} \, \text{s}^{-1}: \]
  \[ F_{5007} = 0.365 \times 8.74 \times 10^{-6} \times 10^{-0.4 \, m(5007)} \]
  \[ \log F_{5007} = -5.496 - 0.4 \, m(5007), \] from which we get:
  \[ m(5007) = -2.5 \log F(5007) -13.74 \]
From fluxes to magnitudes

- We call I(5007) the nebular flux in erg cm\(^{-2}\) s\(^{-1}\)
- We can define “Jacoby magnitudes” in the following way:
  \[ m(5007) = -2.5 \log I(5007) - 13.74 \]
- The constant -13.74 is arbitrary.
- Now we can build the PN luminosity function (PNLF): how many PNs are found at each apparent m(5007)
Pioneer work

• Ford, Jacoby, Ciardullo started detecting and measuring PNs in nearby galaxies in the late 70’s and early 80’s.
• They noticed that the absolute magnitudes M(5007) of the brightest PNs always had a similar value.
• On this purely empirical basis, they proposed to assume that the bright end of the PNLF is universal, and use it as a standard candle.
The analytical representation of the PNLF (Ciardullo et al. 1989)

Exponential + cutoff term

\[ N(M) \propto e^{0.307M} \left\{ 1 - e^{3(M-M^*)} \right\} \]

\[ M = -2.5 \log F_{5007} - 13.74 \]

M* is calibrated using a galaxy at a known distance. If we use the bulge of M 31, M* = -4.5.

We assume that the shape and absolute brightness of the PNLF bright end is universal.
Fitting the PNLF of M 81

\[ m(5007) = 23.3, 24.3, 25.3 \]

### TABLE 14
**RECENT VIRGO DISTANCE ESTIMATES**

<table>
<thead>
<tr>
<th>Method</th>
<th>Distance (Mpc)</th>
<th>Distance Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean of six methods for early-type galaxies (de Vaucouleurs 1985)</td>
<td>11.9 ± 0.6</td>
<td>30.37</td>
</tr>
<tr>
<td>Luminosity fluctuations (Tonry, Ajhar, and Luppino 1989)</td>
<td>13.9 ± 1.2</td>
<td>30.72</td>
</tr>
<tr>
<td>L-σ-Σ relation (Pierce 1989)</td>
<td>14.4 ± 1.6</td>
<td>30.79</td>
</tr>
<tr>
<td>IR Tully-Fisher relation (Aaronson et al. 1986)</td>
<td>14.6 ± 0.8</td>
<td>30.82</td>
</tr>
<tr>
<td>H ii region luminosities (Melnick, Terlevich, and Moles 1988)</td>
<td>15.1 ± 1.0</td>
<td>30.89</td>
</tr>
<tr>
<td>Optical Tully-Fisher relation (Pierce and Tully 1988)</td>
<td>15.6 ± 1.5</td>
<td>30.97</td>
</tr>
<tr>
<td>Optical Tully-Fisher relation (Fouqué et al. 1990)</td>
<td>19.1 ± 1.8</td>
<td>31.41</td>
</tr>
<tr>
<td>Novae (Pritchet and van den Bergh 1987)</td>
<td>19.5 ± 3.9</td>
<td>31.45</td>
</tr>
<tr>
<td>IR Tully-Fisher relation (Sandage and Tammann 1984)</td>
<td>19.7 ± 3.1</td>
<td>31.47</td>
</tr>
<tr>
<td>Type I supernovae (Sandage and Tammann 1982)</td>
<td>21.7 ± 3.1</td>
<td>31.68</td>
</tr>
<tr>
<td>Globular cluster luminosity function (Harris 1988)</td>
<td>21.9 ± 2.2</td>
<td>31.70</td>
</tr>
<tr>
<td>Mean of five methods (Tammann 1988)</td>
<td>22.2 ± 2.4</td>
<td>31.73</td>
</tr>
<tr>
<td>This paper</td>
<td>14.7 ± 1.0</td>
<td>30.84</td>
</tr>
</tbody>
</table>
Initial skepticism: why this method could not possibly work

- Sample size effects: the PN population of a more luminous galaxy, being more numerous, is more likely to show a few very bright PNs. The cutoff would have to change.

- Population effects: older populations should have fainter PNLFs, because the mass and luminosity of stars evolving right now into white dwarfs should be lower.

- Metallicity effects: metal-poor galaxies should produce fainter PNLFs.

- Optical thickness effects: if PNs start leaking H-ionizing photons emitted by the central star, PNs will become fainter than expected.
The bright end of the PNLF is the same in all stellar populations (except the most metal poor).

The bulge, inner-disk, and outer-disk of M31 have the same bright-end cutoff (to $\sigma_{M^*} \sim 0.05$ mag).
The Leo I Group

Five galaxies, five Hubble types, same PNLF cutoff.
Fig. 5.—Values of $M^*$ derived for 13 galaxies using the Cepheid distances of Freedman et al. (2001), plotted against galactic metallicity, as determined from the emission lines of H II regions. The error bars have been computed by combining the uncertainties associated with the PNLF fits, the Cepheid distances, and the Galactic foreground extinction. The dotted line shows the Dopita et al. (1992) theoretical dependence of $M^*$ on metallicity. Note the excellent agreement between the model and the observations on the low-metallicity side of the curve. The values of $M^*$ in high-metallicity galaxies are presumably determined by the galaxies’ lower metallicity stars.
If we want to test how well we understand the PNLF

- It is not ideal to rely on the analytical formula, because too many different factors contribute to its final shape.
- An alternative way is to produce simulated PNLFs, using Monte Carlo techniques.
- In this way you can try to model all the most important effects, and check how successful you are in reproducing the real PNLF.
- The idea is not to make perfect fits using many parameters; it is to see how well you can do with as few parameters as possible.
Monte Carlo simulations of PNLFs

Generate a set of central stars with random post-AGB ages and masses.

Using evolutionary tracks, derive the corresponding central star luminosities and surface temperatures.

We chose post-AGB H-burning evolutionary tracks from Schönberner (1989) and Blöcker (1995).

Using recombination theory and empirical information about leaking of H-ionizing photons, calculate the nebular Hbeta luminosities.

Assuming a distribution of ratios 5007/Hbeta, obtain the luminosities in 5007 and compute the PNLF.

A simulation for 1500 central stars
Building the PNLF simulation

Post-AGB age: uniform random distribution from 0 to 30,000 years, counted from the moment when the stellar Teff becomes 25,000 K.

Mass: from the IMF plus a constant SFR plus an initial-to-final mass relation we obtain exponential mass distributions with a maximum at 0.55-0.57 solar masses, decreasing towards larger masses. We assume that stars less massive than 0.55 solar masses evolve too slowly to produce visible PNs.

For a population without recent star formation we cut the mass distribution at some maximum final mass, because all the initially more massive stars have already evolved into white dwarfs.

Fig. 4. An example of the exponential random central star mass distri-
Initial-final mass relation

Fig. 12.—Initial-final mass relation, constructed by showing all of the stars from each cluster as a single data point, as labeled. The best-fit linear least-squares relation (solid curve) is indicated in the panel, and is found to provide an adequate fit to the data (reduced $\chi^2$ per degree of freedom is $\chi^2 = 1.2$). The dashed curve shows the initial-final mass relation calculated by Hansen et al. (2007) to fit the white dwarf cooling sequence of the globular cluster NGC 6397 (see § 9).
Building the PNLF simulation

Knowing stellar L and T, using recombination theory and empirical information about leaking of H-ionizing photons, calculate the nebular H\(\beta\) luminosities.

\[ L(\text{H}\beta) \text{ is proportional to } L \text{ and } f(T) \text{ if the nebula absorbs all the H-ionizing photons.} \]

If some photons are leaking, the nebula will be fainter. So we need to introduce an absorbing factor. This absorbing factor=1 if absorption is complete, and zero if all photons escape.

We generate the absorbing factor using random numbers, so that some, but not all, of the PNs will be completely optically thick.

Once we have \( L(\text{H}\beta) \), assuming a distribution of ratios \( 5007/\text{H}\beta \), obtain the luminosities in \( 5007 \) and compute the PNLF.

• How to get the ratios 5007/Hbeta: we can use PN model sequences calculated by Schönberner et al. 2007 A&A 473, 467.

• These models assume a spherical nebula and follow its evolution as the central star evolves across the HR diagram. A one-dimensional radiation-hydrodynamics code computes ionization, recombination, heating and cooling, fully time-dependently. Metallicity slightly below solar.

• Since the models are spherical, they cannot predict when a bipolar nebula starts leaking ionizing photons. So we decided to combine their 5007/Hbeta ratios (not too affected by the onset of UV photon leaking) with our randomly generated absorbing factors.
From ApJ 681, 325

Fig. 1.—Solid lines are post-AGB evolutionary tracks for six central star masses in the log \( T_{\text{eff}} - \log L \) plane. Dashed lines (unlabeled) are two interpolated tracks generated as in Méndez & Soffner (1997).

Fig. 2.—\( I(5007)/I(\text{H}\beta) \) line ratio vs. central star effective temperature for two hydrodynamical sequences calculated in SJSS07. \( Z_{\text{G)} \) means the metallicity of our Galactic disk. The nebula following track 4 (solid line) remains always optically thick, while along track 6 (dotted line) the nebula becomes optically thin to H-ionizing photons as the central star evolves. The ratio is always larger in the optically thin phase, but the difference is seldom larger than about 10% in the relevant bright phases.
From ApJ 681, 325

Fig. 3.—Solid lines are PN evolutionary tracks for the six central star masses, taken from SJSS07, in the $l$-$(5007)$ plane; $l(5007)$ is on the scale $l(H\beta) = 100$. The dashed lines (unlabeled) are two interpolated tracks, each corresponding to one of the interpolated stellar evolutionary tracks shown in Fig. 1. The interpolated PN evolutionary track generation is explained in § 4.

Fig. 5.—Histograms of the intensity of $L5007$, on the scale $l(H\beta) = 100$. The dashed line indicates the histogram for 983 objects in our Galaxy. The other two histograms have been normalized to this number. The dotted line is the histogram for 118 LMC objects. The full line is our new distribution, generated as described in the text.
And now we empirically

...try to determine what maximum final mass we need to fit the observed PNLFs in different galaxies. The answer is about 0.63 solar masses for bulges of spirals like M 31 and also for elliptical galaxies (which is a very interesting problem).

It would be higher (about 1 solar mass) for galaxies with recent star formation. But the PNLF hardly changes (those massive central stars are quite rare, and there may be extra internal extinction in their nebulae).
Changing the maximum final mass

**Fig. 10.** Four simulations of the PNLF, assuming $\mu_{\text{max}} = 0.65$. The four PNLFs are normalized to a sample size of 5000. The PNLF represented by a solid line was produced using the final mass distribution in Fig. 4, which corresponds to a constant SFR. For the other PNLFs we adopted maximum final masses of 0.66 (dotted), 0.63 (dashed) and 0.60 (dash-dotted) solar masses (see text).

**Fig. 9.** Simulated PNLFs for $\mu_{\text{max}} = 1$, sample size = 1000, and three maximum final masses: 1.19 (full line), 0.70 (dotted) and 0.63 solar masses (dashed). In each case the exponential mass distribution has been truncated at the limiting mass.
The case for leaking nebulae

Fig. 4. A PNLF simulation for the LMC, assuming that all PNs are completely optically thick (for all objects $\mu=1$). The diamonds represent the observed $\lambda 5007$ PNLF of the LMC, from data collected in the literature (see text, Sect. 4). The LMC is assumed to be at a distance of 50 Mpc, and we adopt an average logarithmic extinction at $H\beta$, $c=0.19$

Fig. 7. The statistically complete $\lambda 5007$ PNLF in M 31 (samples A + B of Ciardullo et al. 1989), adopting a distance of 770 kpc, compared with a simulated PNLF with $\mu_{\text{max}} = 1$, sample size = 1000, and maximum final mass 0.63 solar masses. The choice of maximum final mass will be
This is a simulation of a collection of 1500 central stars burning H. The evolutionary tracks show a quick drop in luminosity as the H-burning shell is extinguished and the star goes into the white dwarf cooling track. For that reason there is a lack of central stars at log L between 2.5 and 3. This lack of central stars leads us to expect a lack of intermediate-brightness PNs.
We can obtain a variety of PNLF shapes by changing the central star mass distribution.

Adding more low-mass stars you can “fill in” the intermediate 5007 magnitudes.

Another way of doing that could be by introducing He burners.
Figure 6. Evolution in the HR diagram for models with buffer masses between ~ 0.15 and 0.75 times the maximum possible.
Figure 7. **Evolution** in the HR diagram for models with buffer masses between 0.75 and 0.85 times the maximum possible.
Figure 8. Evolution in the HR diagram for models with buffer masses between 0.85 and 1.00 times the maximum possible.
PNLF shapes can become a tool

• Better empirical knowledge of PNLF shapes down to fainter magnitudes would be the only way of testing how reliable is the Monte Carlo method to generate a simulated PNLF.

• In the future we might be able to make improvements in the PNLF simulations, and even learn something about post-AGB evolution, like e.g. the ratio of He-burners to H-burners.

• But there is a big problem…
The unexplained fact

Since we expect elliptical galaxies to have old populations, the initial mass is more or less 1 solar mass, and the maximum final mass is expected to be 0.55 solar masses. Then the PNLF becomes very faint. In fact the galaxy would have trouble producing visible PNs; and indeed the specific PN formation rate is smaller in ellipticals than in spiral galaxies.

However, the observed PNLF bright end stays constant. The maximum final mass is observed to be ~0.63 Msun.
Something funny happened in M 15

The central star of K 648 in M 15 is relatively bright; therefore it can be studied spectroscopically using non-LTE model atmospheres. The analysis (McCarthy et al. 1997, IAU Symp 180, p. 122) gave the following parameters: Teff=43,000 K, log g = 3.9 which imply a central star mass of 0.6 solar masses. The spectroscopic distance is 11 kpc, in agreement with the globular cluster distance.
K648 (M15)

Also...

Méndez et al. (2005, ApJ 627, 767) studied individual bright PNs in NGC 4697 and found that in order to explain the high $H_\beta$ nebular luminosities, the central star luminosities must be at least 7000 $L_\odot$, which translates into a mass of at least 0.625$M_\odot$ if the standard post-AGB evolutionary tracks are used.
In summary

We do not understand why the PNLF method works.
8. Surface Brightness Fluctuations

Basic Idea

• Elliptical galaxies have smooth and regular surface brightness profiles

• However, more distant galaxies look smoother with pixel-to-pixel variations much smaller

• this has a simple reason: number of stars per pixel in a galaxy increases with distance → assuming Poissonian fluctuations of the number of stars in a galaxy between volume elements we expect smaller variance

Key Papers

• Tonry & Schneider, 1988, AJ 96, 807
• Tonry et al., 1997, ApJ 475, 399
The idea...

2 galaxies at different distance

M32 @ 0.75 Mpc

N7768 @ 100 Mpc

Jacoby et al., 1992, PASP 104, 599

Cantiello, MIAPP WS
The basic SBF relation

- Let us call $F$ the star flux (signal) per pixel, and $f$ the average flux per star. There are $N$ stars per pixel. Then $F = N f$
- The dispersion $\sigma = N^{0.5} f = F / N^{0.5}$
- So we can write $\sigma^2 / F = F/N = f = L / 4\pi d^2$
- In other words, knowing $F$ and $\sigma$ we can calculate a quantity which is inversely proportional to the square of the distance.
- You need to calibrate this method with a galaxy at a known distance.
Comparison to the distances from Surface Brightness Fluctuations

• Initially there seemed to be perfect agreement between PNLF and SBF (Ciardullo et al. 1993 ApJ 419, 479) from a sample of 16 galaxies.
• Then the SBF distances were recalibrated (Tonry et al. 2001 ApJ 546, 681). More galaxies were added, and some problems started to appear.
Comparisons to cepheid distances
PNLF vs SBF distances around the year 2000
Fig. 7.—Histogram of the difference between the PNLF and SBF distance moduli for 28 galaxies measured by both methods. The two worst outliers are the edge-on galaxies NGC 4565 ($\Delta \mu = -0.80$) and NGC 891 ($\Delta \mu = +0.71$). NGC 4258 is also an outlier ($\Delta \mu = -0.70$). The curve represents the expected dispersion of the data. The figure demonstrates that, except for the edge-on galaxies, there is excellent agreement between the internal and external errors of the methods.

The histogram in Figure 7 shows the difference between for additional sources of errors, a dependent term in the scatter.

This latter conclusion is clear if the method were significantly affected by metallicity, then $\Delta \mu$ would correlate with magnitude or color. As Figure 6 shows, similarly, if the form of the PNLF were to change, the $\Delta \mu$ would correlate with absolute magnitude. This correlation does not exist for the residuals are plotted against $(m - M)_{SBF}$ for all galaxies with $(m - M)_{SBF}$ in the figure. There is no chance that a correlation exists with the internal modulus. Such a trend might be expected in these systems, given the foreground emission-line galaxies (e.g., rich clusters) foreground into the sample. The five most distant objects are also the most significant correlation with distance given the impression left from the figure. For these distances, the PNLF and SBF are in agreement.

Unfortunately, the same cannot be said for the absolute distances. As Figure 7 shows, in the sense that SBF distances
At about this time

- We started using PNLF simulations to measure distances.
- Our motivation to detect the PNs was not distances; it was mostly kinematics. But since we expected to detect hundreds of PNs per galaxy, it was an excellent opportunity to test in practice how important are sample size effects, and how well we could reproduce PNLF shapes.
Galaxies studied with FOCAS (Subaru) and/or FORS (ESO VLT)

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>PNs found</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4697</td>
<td>E5</td>
<td>591</td>
<td>11 Mpc</td>
</tr>
<tr>
<td>NGC 1344</td>
<td>E5</td>
<td>197</td>
<td>19 Mpc</td>
</tr>
<tr>
<td>NGC 821</td>
<td>E5</td>
<td>167</td>
<td>19 Mpc</td>
</tr>
<tr>
<td>NGC 4649</td>
<td>E2</td>
<td>326</td>
<td>15 Mpc</td>
</tr>
<tr>
<td>NGC 5866</td>
<td>S0</td>
<td>242</td>
<td>15 Mpc</td>
</tr>
<tr>
<td>M 82</td>
<td>Edge-on S</td>
<td>109</td>
<td>4 Mpc</td>
</tr>
<tr>
<td>NGC 891</td>
<td>Edge-on S</td>
<td>125</td>
<td>10 Mpc</td>
</tr>
<tr>
<td>NGC 5907</td>
<td>Edge-on S</td>
<td>in prep.</td>
<td>in prep.</td>
</tr>
<tr>
<td>NGC 4244</td>
<td>Edge-on S</td>
<td>69</td>
<td>5 Mpc</td>
</tr>
<tr>
<td>IC 10</td>
<td>dwarf Irr</td>
<td>35</td>
<td>0.7 Mpc</td>
</tr>
</tbody>
</table>
An example:
the PNLF of NGC 4697

The solid lines are Monte Carlo simulations of the PNLF for different total PN populations.

Knowing the apparent mags(5007), we can build a histogram describing how many PNs there are within each bin of 0.2 mag.

Adopting a distance modulus and correcting for foreground extinction, we get the absolute mags, so that we can compare the observed PNLF (squares) with the simulations.

We find the best fit, giving total PN population and distance modulus.
The case of NGC 4697

• In their 2002 paper, ApJ 577, 31 (PNs as standard candles XII), Ciardullo et al. took the data from Mendez et al. (2001) and recalculated the PNLF distance.
• They obtained a distance modulus 29.9
• Mz et al. had obtained 31.1
• At that time the SBF distance modulus (Tonry et al. 2001) was 31.3
• Could this indicate a possible solution?
PNLF shapes
SBF distances were recalibrated

- Jensen et al. (2003 ApJ 583, 712) applied a correction of -0.16 mag to all the I-SBF distances of Tonry et al. (2001 ApJ 546, 681)
- This was done to adjust to the Cepheid zero point of Freedman et al. (2001 ApJ 553, 47)
- This apparently solved part of the problem. Could a slight adjustment of PNLF distances eliminate the remaining discrepancy?
Ciardullo vs. Monte Carlo

NGC 1344, m - M = 31.18
Extinction = 0.066 mag

NGC 1344, m - M = 31.38
Extinction = 0.066 mag
Ciardullo vs. MonteCarlo

M 60, $m - M = 30.75$
Extinction = 0.09 mag

$M (5007)$

$-5$ $-4$ $-3$ $-2$

log number

$-5$ $-4$ $-3$ $-2$

log number
PNLF Distance of NGC 891

Our best distance modulus: **29.70 ± 0.20**

Ciardullo et al. (1991) with 33 PNs: **29.97 ± 0.07** - **29.86 ± 0.11**

Surface Brightness Fluctuation (SBF) distance (Tonry et al. 2001): **29.61 ± 0.14**
## New comparison

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>PNLF Ciard</th>
<th>My PNLF</th>
<th>Jensen SBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4697</td>
<td>29.89</td>
<td>30.10</td>
<td>30.19</td>
</tr>
<tr>
<td>NGC 1344</td>
<td>31.18</td>
<td>31.38</td>
<td>31.32</td>
</tr>
<tr>
<td>NGC 821</td>
<td>31.25</td>
<td>31.45</td>
<td>31.75</td>
</tr>
<tr>
<td>M 60</td>
<td>30.75</td>
<td>30.65</td>
<td>30.97</td>
</tr>
</tbody>
</table>
Then SBF distances increased again

<table>
<thead>
<tr>
<th>Galaxy Name</th>
<th>My PNLF</th>
<th>Jensen 2003</th>
<th>Blakeslee 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4697</td>
<td>30.10</td>
<td>30.19</td>
<td>30.49</td>
</tr>
<tr>
<td>NGC 1344</td>
<td>31.38</td>
<td>31.32</td>
<td>31.60</td>
</tr>
<tr>
<td>M 60</td>
<td>30.65</td>
<td>30.97</td>
<td>31.08</td>
</tr>
</tbody>
</table>

(HST ACS survey)
PNLF vs SBF distances

Figure 16. Difference between PNLF and SBF distance modulus plotted as a function of SBF distance modulus, for 23 galaxies. Non-elliptical galaxies are plotted as diamonds, while for ellipticals we show just the error bars. The two galaxies near $m - M = 28$ are NGC 5128 and M 81. The only two galaxies with a positive $\Delta m$ are NGC 4258 and NGC 3115. The agglomeration of galaxies between $m - M = 31$ and 32 is dominated by the Virgo and Fornax clusters. Our recent PNLF additions, ellipticals NGC 1344 in Fornax and NGC 821, are indicated as squares.
Conclusions

• The PNLF shape effect can explain part of the difference between PNLF and SBF distances, up to about 0.2 mag.

• But there is still a systematic difference with SBF, even more if the new SBFs are adopted, since they appear to be more reliable.
At the same time, TRGB distances are becoming more relevant!

PNLF and SBF are not so bad, but they have unresolved issues.

On the other hand, PNLF and SBF agree about how much more distant Fornax is than Virgo.

We need a tie-breaker to decide which method gives better absolute distances. TRGB could be it, if somebody can get TRGB distances to many Virgo and Fornax galaxies. Right now it looks like we have only M 87 (done with HST ACS, Bird et al. 2010, A&A 524, A71).
TRGB vs SBF, PNLF vs SBF

Looking at these diagrams, I get the impression that PNLF and TRGB tend to agree with each other much better than either of them with SBF.

We need more TRGB distances in Virgo and Fornax.
Therefore

- We will have to wait a bit more to verify if TRGB distances support the SBF absolute distances. If that should happen, I would start to think seriously about using the SBF and TRGB distances to study the physics of PNLF formation: there are hints of a variety of PNLF shapes and anomalous PN luminosities.
Using the SBF distance

NGC 821, $m - M = 31.75$
Extinction $= 0.385$ mag
Unsolved problems

- PNLF distances are good, but we do not understand why.
- We need to learn more about the PNLF shape (detect fainter PNs). We need deep spectra of the PNs we have discovered (reddenning, 5007/Hbeta ratio, abundances).
- PNs are good kinematic tracers. For that reason we can expect a continuous effort to discover them in more galaxies. We need good photometry, of course.
- Then, the same PNs may help to understand the conditions for PN formation in various metallicity environments, perhaps helping also to better understand the PNLF invariance and shape.
Weak points of the PNLF method

• Extinction will remain a minor problem; the PNLF method cannot move toward the IR.
• Lack of a good theory for post-AGB mass loss. We cannot explain the superwind phase. What is the incidence of binarity in PN formation?
• Uncertainty in transition times away from the AGB. Could post-AGB evolutionary speeds be a bit wrong? Prediction of UV photon leaking will always be uncertain, because of the complicated geometry and dynamics of PN ejections.
• Monte Carlo simulations cannot deal adequately with late He-shell flashes.
Figure 6. Evolution in the HR diagram for models with buffer masses between ~ 0.15 and 0.75 times the maximum possible.
Figure 7. Evolution in the HR diagram for models with buffer masses between 0.75 and 0.85 times the maximum possible.
Figure 8. Evolution in the HR diagram for models with buffer masses between 0.85 and 1.00 times the maximum possible.
Anomalous PNLF shapes?

We would need to test empirically if anomalous PNLF shapes exist, and how infrequent they are.

Trouble in the Bulge?
Kovacevic et al. 2010, arXiv:1010.1655

Trouble in the halo of M 87?
Longobardi et al. 2013, arXiv: 1309.0006
Possible solutions to the maximum final mass enigma

• Binary mergers (ex-blue stragglers) could produce more massive central stars from low initial masses. But then the colors of ellipticals might show a contribution from those mergers (Ciardullo 2006).

• Soker (2006 ApJ 640, 966) has proposed mass transfer onto a white dwarf from a companion star leaving the AGB. The white dwarf sustains continuous nuclear burning and ionizes the nebula.

• Or perhaps the PNs in ellipticals are all completely optically thick, allowing for brighter PNs even if the central stars are less luminous. This would be quite unexpected (low-mass stars are supposed to evolve more slowly, giving any lost mass time to dissipate).
Direct detection of blue stragglers?

From Mendez et al. 1993, A&A 275, 534:

The “overluminous” objects found by JCF do not necessarily represent the low-probability tail of the distribution we have modeled. The problem has been discussed by JCF, Ciardullo et al. (1991) and Jacoby & Ciardullo (1992). To the alternatives already suggested by them (chance superposition of two PNs in one image; H II regions; supernova remnants) we would add another one, namely the possible existence of a population of ex-blue-stragglers, formed by coalescent binaries; this would account for a few central stars more massive than the maximum final mass, which refers to evolution of single stars (see, for

The distance modulus of Ursa Minor is about 19.3, and blue stragglers have been found at visual mags 22-23.
Possible solutions (cont.)

• Or perhaps the initial to final mass relation is a band, thicker than we think, allowing for high final masses from low initial masses. Weidemann (2000) reported from white dwarfs in clusters that differential mass loss cannot be larger than 0.1 solar masses. But we do not need much more than that...

• This idea is somewhat unpopular, but has not been empirically rejected yet. Metallicity could play a role in widening the initial-to-final mass relation (Meng et al. 2008 A&A 487, 625).
List of collaborators

**PNLF simulations:** Rolf Kudritzki, Till Soffner, Ana Teodorescu, D. Schönberner, R. Jacob, M. Steffen, R. Ciardullo, G. Jacoby.

Stop here.
PNLF, distance and extinction
NGC 300

Next slide shows the [O III] 5007 PNLF (squares; 98 PNs) compared with PNLF simulations produced by Mendez and Soffner 1997, A&A 321, 898. The fit was obtained assuming a distance modulus 26.8 and no reddening. PN population sizes were 240, 350 and 500. Studies of cepheids in NGC 300 (Gieren et al. 2005 ApJ 628, 695) suggest E(B-V)=0.09, which implies an extinction of 0.35 mag for 5007. Then the distance modulus becomes 26.45. Excellent agreement with cepheid distance if we assume same average reddening for both PNs and cepheids.

The shape of the PNLF is very well reproduced by the simulations.
$m - M = 26.8$
The “overluminous” objects found by JCF do not necessarily represent the low-probability tail of the distribution we have modeled. The problem has been discussed by JCF, Ciardullo et al. (1991) and Jacoby & Ciardullo (1992). To the alternatives already suggested by them (chance superposition of two PNs in one image; H II regions; supernova remnants) we would add another one, namely the possible existence of a population of ex-blue-stragglers, formed by coalescent binaries; this would account for a few central stars more massive than the maximum final mass, which refers to evolution of single stars (see, for

As mentioned before, a fit of an observed PNLF provides a simultaneous determination of two parameters: distance modulus and sample size. In their discussion of a “simple stellar population” (an assembly of coeval, initially chemically homogeneous, single stars), Renzini & Buzzoni (1986) use a quantity $B(t)$ which they call the “specific evolutionary flux”, or evolutionary flux per unit luminosity of the parent population. We shall express this quantity in units of $10^{-12}$ stars per year per solar luminosity. $B(t)$ is nearly independent of the adopted initial mass function, and is nearly constant for a wide range of ages. Calculations by Renzini & Buzzoni (1986) give, for ages between 1 and 15 Gyr, a $B(t)$ between 15 and 22, in the aforementioned units. The number of stars $n_j$ in any post-main-sequence phase $j$ of evolution is given by

$$n_j = B(t) \frac{L_T}{t_j}$$

where $L_T$ is the total luminosity of the sampled population, and $t_j$ is the duration of phase $j$ in years.

In the particular case of PNs, if we know the sample size and $L_T$, and if we adopt a typical PN duration of 30,000 years as in Sect. 4, we can estimate the “specific PN formation rate” (per unit luminosity) and compare it with Renzini and Buzzoni’s $B(t)$. Peimbert (1990), using data published by Ciardullo, Jacoby, et al., showed that the specific PN formation rate, which he called $\xi$, is frequently smaller than $B(t)$ and is correlated with the intrinsic color $(B - V)_0$ and with the absolute bolometric magnitude of the corresponding galaxy, in the sense that redder and brighter galaxies have lower values of $\xi$. 