PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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Planetary Nebulae as Extragalactic Distance Indicators

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Abstract. The planetary nebula luminosity function (PNLF) plays a key role in the distance ladder, as it is the only general purpose standard candle that is applicable to both Pop I and Pop II systems. We review the physics underlying the method, and compare its distances to distances obtained from Cepheids and surface brightness fluctuations (SBF). We show that PNLF distances agree with the geometric distances to the LMC and NGC 4258, and that, on a galaxy-by-galaxy basis, the relative PNLF, Cepheid, and SBF distances are in excellent agreement with no systematic trends. However, even though the PNLF and SBF methods are both calibrated by Cepheids, the PNLF distance scale is $\sim$ 17% smaller than the SBF scale. We discuss this offset, and examine the possible causes of the discrepancy.

1. Introduction

The Planetary Nebula Luminosity Function (PNLF) occupies an important position on the extragalactic distance ladder. As Figure 1 demonstrates, there is precious little overlap between the Pop I distance ladder, which uses Cepheids, the Tully-Fisher relation, and SN Ia, and the Pop II scale, which includes the surface brightness fluctuation technique, the globular cluster luminosity function, and the elliptical galaxy fundamental plane. Consequently, systematic errors between the two scales are to be expected. One way to avoid this problem is to observe both spiral and elliptical galaxies in a common cluster, and assume that both types of galaxies are at the same distance. However, as observations in the Virgo Cluster demonstrate, this is a dangerous assumption (*e.g.,* Ciardullo et al. 1998; West & Blakesless 2000). A better way to link the two distance ladders is via a galaxy-to-galaxy comparison using techniques that work in both systems. The PNLF is the only method that can do this.

Planetary nebula (PN)-based distances are relatively new. Although the potential of using PN for distance measurements was hinted at in the 1960's (Henize & Westerlund 1963; Hodge 1966), it was not until the late 1970's that pioneering efforts in the field were made (Ford & Jenner 1978; Jacoby & Lesser 1981; Lawrie & Graham 1983). These works used the brightest PN of a galaxy as a standard candle, and were therefore subject to biases associated with sample size and distance. The modern era of PN distance measurements began in 1989, with the analysis of the entire [O III] λ5007 PN luminosity function (Jacoby 1989; Ciardullo et al. 1989).

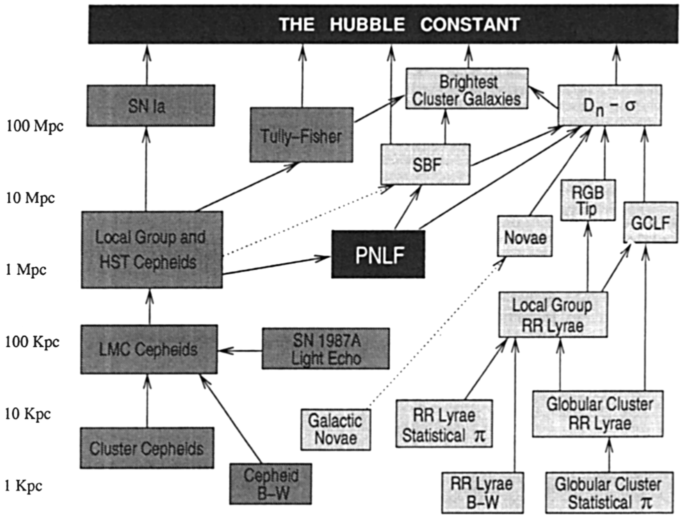

Figure 1. The extragalactic distance ladder. On the left are techniques applicable to Pop I systems; on the right are Pop II distance indicators. The dotted lines represent calibrations that are particularly uncertain. The PNLF is the best way to bridge the two distance scales.

Since then, the PNLF has become one of the most thoroughly tested extragalactic standard candles. Internal tests in M31, M81 (Magrini et al. 2001), and NGC 5128 (Hui et al. 1993) have demonstrated that the PNLF of galaxy bulges (and elliptical galaxy interiors) is statistically identical to that of star-forming disks or galactic halos. Similarly, tests in the NGC 1023 Group (2 galaxies; Ciardullo, Jacoby, & Harris 1991), the Fornax Cluster (3 galaxies; McMillan, Ciardullo, & Jacoby 1993), and the Leo I Group (5 galaxies; Ciardullo, Jacoby & Ford 1989; Feldmeier, Ciardullo, & Jacoby 1997; Ciardullo et al. 2002) have shown that there is no systematic difference between the PNLFs of cluster ellipticals and spirals. In fact, PNLF measurements in the Virgo Cluster (Jacoby, Ciardullo, & Ford 1990) easily resolved the background M86 Group from the main body of the cluster. Since the difference in distance between these two groups is only $\sim$ 15%, these data demonstrate the impressive precision of the method.

2. Basics of the Technique

In principle, PNLF measurements are simple. One images a galaxy through a narrow-band filter (typically 30 to 50 Å wide) tuned to the wavelength of the redshifted [O III] λ5007 emission line. One then takes a similar image through a broader off-band filter and compares the two frames. Point sources which appear on the on-band frame, but are completely invisible on the offband frame, are planetary nebula candidates.

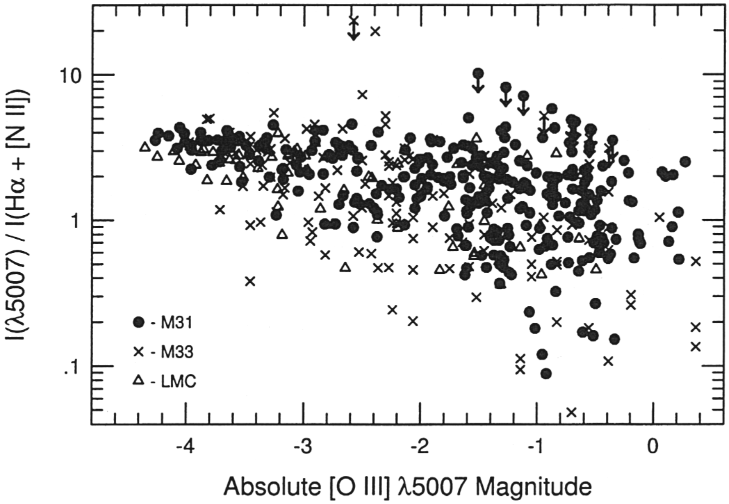

Figure 2. The [O III] λ5007 to Hα ratio for PN in the bulge of M31, the disk of M33, and the Large Magellanic Cloud. Note that for PN in the top $\sim$ 1 mag of the luminosity function, [O III] λ5007 is always at least twice as bright as Hα.

A slight complication occurs when making PN measurements in spiral galaxies. H II regions are also strong [O III] λ5007 emitters, and in these systems, star-forming regions can numerically overwhelm the planetaries. Fortunately, most H II regions are resolvable (at least in galaxies closer than $\sim$ 10 Mpc), and thus can immediately be eliminated from the sample. To remove the remaining contaminants, we can take advantage of the distinctive distribution PN have in emission-line space. As illustrated in Figure 2, PN in the top magnitude of the [O III] λ5007 PNLF all have λ5007 brighter than Hα+[N II]. This is in contrast to most H II regions, which typically have Hα as their brightest line. Since this rule does not appear to depend on stellar population, the line ratio can be used to effectively remove any remaining H II regions from the list of PN candidates.

Once a statistical sample of PN has been identified, the objects can be photometrically measured to yield [O III] λ5007 magnitudes via

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

A PNLF distance can then be derived by fitting the observed luminosity function to an empirical law. For simplicity, Ciardullo et al. (1989) have suggested

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

although other relations are possible (*e.g.*, Mendez et al. 1993).

Since the PNLF is a secondary standard candle, it relies on galaxies of "known" distance to set the zero point. The original absolute magnitude of the PNLF cutoff, M^*=$-$4.48, was based on an M31 infrared Cepheid distance of 710 kpc (Welch et al. 1986) and a foreground reddening of $E(B-V)$=0.11

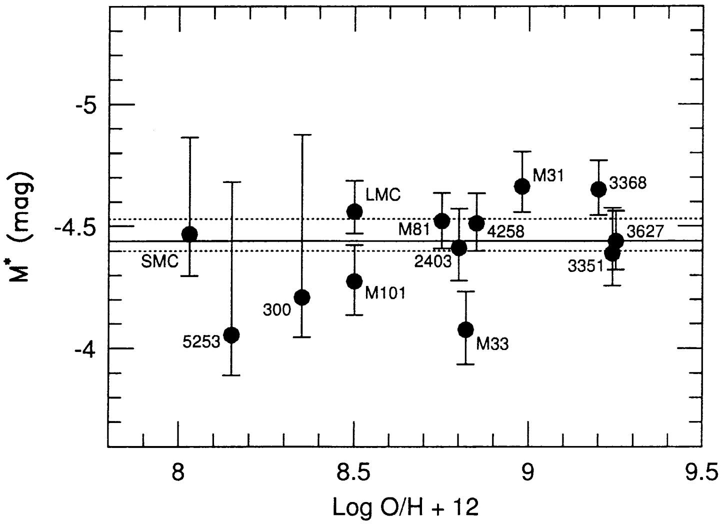

Figure 3. The absolute magnitude of the PNLF cutoff derived from the Cepheid distances to 13 galaxies. The solid line is the weighted mean of the measurements, $M^* = -4.44$; the dotted lines show the 1σ error. The abscissa plots the metallicity of the galaxies' H II regions.

(McClure & Racine 1969). With revised values for M31's distance (750 kpc; Freedman et al. 2001) and reddening ($E(B-V)$=0.062; Schlegel, Finkbeiner, & Davis 1998), M^*=−4.53 and the entire PNLF distance scale increases by ~ 3%. However, rather than basing the PNLF zero point on a single galaxy, it is perhaps better to define M^* using Cepheid distances to many different systems. There are now 13 galaxies with both Cepheid and PNLF photometry. If we adopt the final *HST Key Project* Cepheid distances (uncorrected for metallicity) given by Freedman et al. (2001) and use the DIRBE/IRAS estimates for foreground extinction (Schlegel, Finkbeiner, & Davis 1998), then the mean absolute magnitude of the PNLF cutoff decreases to M^*=−4.44. This is shown in Figure 3. Note that the errors associated with small galaxies are greater than those for large galaxies; this is simply due to the limited number of bright PN present in low-luminosity systems. Also note that the large residual found for M33 is not in conflict with the results of Magrini et al. (2000), who found good agreement between the two distance estimators. Figure 3 adopts the Schlegel, Finkbeiner, & Davis (1998) extinction value, while Magrini et al. used a value derived from the galaxy's Cepheids (Freedman, Wilson, & Madore 1991). This is the only difference between the two measurements, and it points out how assumptions about extinction can affect distance scale studies.

How well does the zero point work? Two galaxies have distances based on simple geometry. The first is the Large Magellanic Cloud: thanks to the light-echo of SN 1987A, the distance to the LMC is fixed at 50.1 ± 3.4 Mpc (*e.g.*, Gould & Uza 1998; Panagia 1999). The planetaries of the galaxy yield a distance of 47.8 ± 4.0 Mpc, in excellent agreement with the geometrical value (Jacoby, Walker, & Ciardullo 1990).

The second system with a known distance is NGC 4258. Orbiting the central black hole of this galaxy is a disk containing maser-emitting gas; the observed Keplerian motion of the gas implies a distance of 7.2 ± 0.3 Mpc (Herrnstein et al. 1999). The galaxy's PNLF distance is 7.5 ± 0.3 Mpc (Ciardullo et al. 2002). Although this $\sim 1\sigma$ difference is a bit concerting, it should be noted that the galaxy's Cepheid distance is also slightly high, 7.7 ± 0.3 Mpc (Freedman et al. 2001). Since the PNLF distance scale is set by the Cepheids, it is likely that the discrepancy lies with the Cepheids, rather than the planetaries.

3. Why it Works

The effectiveness of the PNLF technique has surprised many people. After all, a PN's [O III] $\lambda 5007$ flux is directly proportional to the luminosity of its central star, and this luminosity, in turn, is highly dependent on the central star's mass. Since the distribution of central star masses depends on stellar population (via the initial mass-final mass relation), the PNLF should be population dependent.

Fortunately, this does not appear to be the case, and, in retrospect, the invariance is not difficult to explain. First, consider the question of metallicity. The [O III] $\lambda 5007$ flux of a bright PN is proportional to its oxygen abundance, but since $\sim 15\%$ of the central star's flux comes out in this line, the ion is the nebula's primary coolant. Consequently, if the abundance of oxygen is decreased, the nebula's electron temperature will increase, and the number of collisional excitations per ion will increase. The result is that the flux in [O III] $\lambda 5007$ depends only on the square root of the nebula's oxygen abundance.

Meanwhile, the PN's core reacts to metallicity in the opposite manner. According to the models of Lattanzio (1986), if the abundance of metals in a central star is decreased, then the lower bound-free opacity will result in a slightly larger UV flux. The energy deposited in the nebula therefore goes inversely as the cube-root of metallicity. When combined with the abundance dependence of the nebula, this result implies that the PNLF should be almost independent of metallicity. The detailed models of Dopita, Jacoby, & Vassiliadis (1992) confirm this behavior.

Now consider the reaction of the PNLF to population age. According to the initial mass-final mass relation (*e.g.*, Weidemann 2000), young populations produce high-mass central stars that are extremely bright in the UV. The PN associated with these objects should therefore be extremely luminous in [O III] $\lambda 5007$. In fact, this does happen. However, the initial mass-final mass relation also predicts that the envelopes surrounding these stars will be very massive, and their circumstellar dust will produce a significant amount of extinction. This effect is exacerbated by the sensitivity of the central star's evolutionary timescale to mass: high mass cores fade quickly before their circumstellar envelopes have time to disperse. As a result, PN that are intrinsically more luminous than M^* will be extincted below the PNLF cutoff. Observational evidence for this comes from the correlation between core mass and extinction derived for [O III]-bright in the Magellanic Clouds and M31 (Ciardullo & Jacoby 1999).

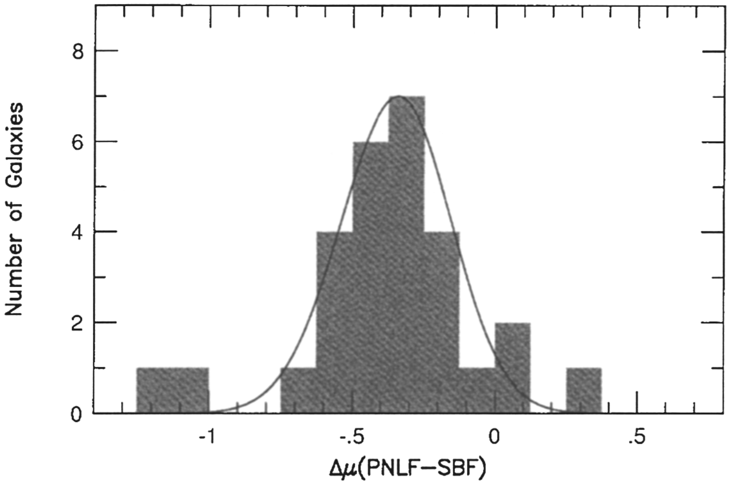

Figure 4. A histogram of the difference between the PNLF and SBF distance moduli. The two worst outliers are the edge-on galaxies NGC 4565 and NGC 891; the curve represents the expected dispersion of the data.

4. Comparing the Pop I and Pop II Distance Scales

Can PN successfully link the Pop I and Pop II distance scales? To address this question, we consider three techniques: the PNLF, the surface brightness fluctuation (SBF) method, and Cepheids. The PNLF is calibrated via 13 galaxies with Cepheid distances (Freedman et al. 2001); the SBF system of Tonry et al. (2001) is zero-pointed by 6 Cepheid galaxies. (Four Cepheid galaxies are common to both systems.) Figure 4 compares these two distance scales using 28 galaxies measured by both methods. There are three important items to note.

First, the curve plotted in Figure 4 is not a fit to the data: it is instead the *expected* scatter in the measurements, as determined by propagating the uncertainties associated with the PNLF distances, the SBF distances, and Galactic reddening (see Ciardullo, Jacoby, & Tonry 1993 for an explanation of the latter component). It is obvious that the derived curve is in excellent agreement with the observations. This demonstrates that the quoted errors of both methods are reasonable.

A second feature of the figure is the presence of three outliers. The two worst offenders are NGC 4565 (−0.8 mag from the mean) and NGC 891 (+0.7 mag from the mean). Both are edge-on spirals — the only two edge-on spirals in the sample. Clearly one (or both) methods has trouble measuring the distances to such objects. Given the sensitivity of the SBF technique to color gradients, it is likely that the problem with these galaxies lies there.

The most important fact displayed in the figure, however, is the mean of the distribution. SBF distances are, on average, 0.34 ± 0.05 mag larger than PNLF distances. Since the formal uncertainties of the PNLF and SBF zero points are ~ 0.05 mag, this offset is extremely significant!

Where is the problem? The residuals between the PNLF and Cepheid distance moduli exhibit no significant trend with galactic distance, absolute magnitude, inclination, or metallicity (as determined from the emission lines of H II regions). Similarly, the PNLF-SBF residuals do not correlate with galactic distance, absolute magnitude, color, or PN sample size. Thus, the offset cannot be attributed to PNLF errors arising from background galaxy contamination, a metallicity dependence, or an incorrect form for the empirical PNLF.

There are only two possibilities. An analysis of the PNLF-SBF residuals reveals that the PNLF of star-forming disks is systematically 0.14 ± 0.10 mag fainter than that measured in old stellar populations. If real (and if the SBF distances are correct), this may mean that PN measurements in disks are slightly affected by internal extinction. Support for this idea comes from PN in M31: the PNLF of the galaxy's disk has a slightly fainter cutoff (~ 0.1 mag) than that of the galaxy's bulge or halo. This offset is only marginally significant, however, and Monte Carlo simulations suggest that dust is unlikely to shift the PNLF by more than ~ 0.1 mag (Feldmeier, Ciardullo, & Jacoby 1997).

The second possibility is the presence of a systematic error in the Cepheid distances. The ~ 0.05 mag uncertainties associated with the SBF and PNLF zero points assume only the formal distance errors of the calibrating galaxies. If additional uncertainties exist, then these errors will be underestimates.

One example of such an effect is the dependence of Cepheid distances on galaxy metallicity. There are several metallicity laws in the literature, most of which range from -0.3 mag dex^{-1} to $+0.4$ mag dex^{-1} (*e.g.,* Feast 1999). In their final distance scale paper, Freedman et al. (2001) adopt a metallicity slope of $+0.2$ mag dex^{-1}. If this law is used, then the systematic offset between the PNLF and SBF distances is cut in half, due mostly to a change in the SBF zero point. Obviously, the PNLF can play a useful role in constraining this value.

5. Conclusion

The PNLF's ability to work in both spiral and elliptical galaxies makes it an important tool with which to search for systematic errors in the extragalactic distance ladder. This is evidenced by the results of the PNLF-SBF-Cepheid comparison: an analysis of 13 Cepheid galaxies with PNLF measurements, 6 Cepheid galaxies with SBF measurements, and 28 PNLF galaxies with SBF measurements demonstrates that the three distance scales are not self-consistent. The cause of the discrepancy may be due to a combination of factors, including a metallicity dependence in the *HST* $V - I$ period-luminosity relation, and the effect of internal extinction on the PNLF. The offset illustrates how difficult it is to securely calibrate rungs on the distance ladder.

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