PLANETARY NEBULAE IN LOCAL GROUP GALAXIES

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ABSTRACT

Recent surveys for planetary nebulae have given the first identifications in Fornax, NGC 6822, M33, IC 10, Leo A, Sextans A, Pegasus, WLM, NGC 404, and M81, and extended the identifications in the SMC, the LMC, and M31. Observations of planetaries have established chemical compositions in old or intermediate age populations in 8 Local Group galaxies. The chemical compositions show that i) the helium abundance is higher in planetary nebulae than in H II regions in the same galaxy, and ii) nitrogen is overabundant relative to H II regions by factors of 4 to 100. Planetary nebulae are not a major source of helium in star-forming galaxies, and are a major source of nitrogen. The planetary in Fornax has a relatively high O abundance, and, together with Fornax's carbon stars, establishes the presence of at least 2 stellar populations. The abundance gradient derived from 3 planetaries in M31 is very shallow, and gives high abundances at ~ 20 kpc. By using planetary nebulae as standard candles, upper and lower distance limits have been set for 10 Local Group candidates, and a new distance estimated for M81.

1. RECENT SURVEYS FOR PLANETARY NEBULAE

New surveys for planetary nebulae in Local Group Galaxies have significantly extended the identifications reviewed by Ford (1978). These searches are important because they pinpoint stars that can be used to study the chemical composition and kinematics of otherwise mostly inaccessible populations. The surveys and their pertinent characteristics are summarized in Table 1. The galaxies in Table 1 are grouped according to certain, possible, or non-membership in the Local Group. The latter two groups will be discussed in Section 3.

The survey by Danziger et al. (1978) is noteworthy because it establishes the only identification of a planetary nebula in a spheroidal galaxy. It is not surprising that Fornax, the most massive of the spheroidal galaxies ($M \sim 2\text{x}10^7\ M_\odot$), has a planetary nebula. Using Jacoby's (1980) mass specific number, $2.1\text{x}10^{-7}$ planetary nebulae $M_\odot^{-1}$, we expect roughly 4 nebulae in Fornax. From another point of

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view, Fornax's mass is comparable to the mass of the galaxy's globular cluster system, wherein there is one luminous planetary in M15, and a faint planetary possibly associated with NGC 6401 (Peterson, 1977). Danziger et al. surveyed Fornax in Hα, and sampled approximately 2.3 magnitudes of the luminosity function. Because [OIII] λ5007 is typically 2 to 5 times brighter than Hα (c.f. Table 2), a deep survey in [OIII] λ5007 might reveal one or two more faint nebulae.

Killen and Dufour (1982) searched NGC 6822 for planetary nebulae and H II regions. They used Hα, [OIII] λ5007, and continuum plates taken with the CTIO 4-m telescope to find emission line sources and estimate their excitation. They found 31 diffuse nebulae and 36 stellar nebulae, and singled out 8 of the latter as possible planetary nebulae. Dufour and Talent (1980) used spectrophotometry to confirm that one of the nebulae (S 33) is indeed a planetary (cf. Section 2). The author used an unpublished survey by Sedwick and Ford (1976) to confirm that five of Killen and Dufour's candidates (S 10, S 14, S 16, S 29, and S 33) are probably planetary nebulae. One of their candidates, S 26, most likely is a star, and another, S 23, isn't on either Lick Hα or [OIII] λ5007 image tube plates, even though they appear to reach a fainter limiting magnitude than Killen and Dufour's plates. The last Killen and Dufour candidate, S 30, which is not in the area surveyed by Sedwick and Ford, probably is a planetary nebula. Sedwick and Ford found two additional faint candidates, which brings the total number of identifications back to 8. Killen and Dufour noted that the planetary nebulae are mostly in or near NGC 6822's bar, which presumably contains old stars.

Lawrie and Ford (1982) used a Velocity Modulating Camera (VMC) to isolate planetary nebulae in the central 250 parsecs of M31 and M32. By combining the slow f/17 Lick 3-m Cassegrain focus with a very narrow band (2.1Å FWHM) [OIII] λ5007 filter, they were able to suppress the galaxy's light and detect planetary nebulae to within a few arc seconds (a few tens of parsecs) of their nuclei. The VMC photographs revealed 42 nebulae in the center of M31, including 19 new identifications, and 5 new nebulae in the central 8" (r = 25 pc) of M32. Ford and Jenner confirmed the 5 new nebulae (and found still another, #28) with a video camera picture which is reproduced in Figure 1. Nebula number 27 projects 3.75" (12 pc) from M32's nucleus. The number of new nebulae (6) in M32's center is equal to the number predicted from the number per unit light in the outer regions. We expect that there are one to two more nebulae in the saturated core shown in Figure 1.

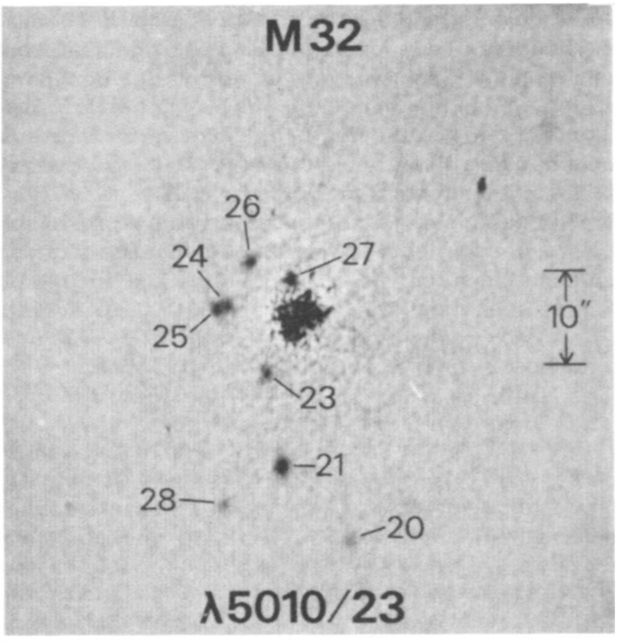

Figure 1. Planetary nebulae in the center of M32. The picture is a 12.5-min exposure with the video camera on the KPNO 4-m telescope. Galaxy light was removed by subracting a smoothed and normalized off-band picture. The dark area in the center is due to camera saturation rather than [OIII] emission.

The VMC survey swept velocity space in the centers of M31 and M32 with a sequence of photographs taken through a temperature tuned 2.1 Å interference filter. Lawrie (1978, 1983) used the photographs to measure the radial velocities of 30 planetary nebulae within 250 parsecs of M31's nucleus, and to place velocity limits on 10 more. He used a maximum likelihood method to derive a radial velocity dispersion of 155 ± 22 km s^{-1}, which he combined with the virial theorem and light distribution to calculate a mass-to-light ratio for the inner nuclear bulge, $M/L_V = 9.6 \pm 3.6$. His M/L_V agrees with previous results based on dynamical studies of galaxy nuclei (Faber and Jackson, 1976; Williams, 1977), but is inconsistent with the large M/L_V predicted by dwarf-enriched stellar population models (Spinrad and Taylor, 1971; Williams, 1976).

Ford, Jacoby, and Jenner (1983) extended previous surveys of M31 (cf. Ford, 1978) to large distances from the center. Using the KPNO 0.9-m and 4-m telescopes, they found planetaries out to projected distances of 34 kpc. They have measured radial velocities of 49 of the most distant nebulae, and Jacoby and Ford (1983) have determined chemical abundances in planetary nebulae at 10 kpc, 17 kpc, and 34 kpc (cf. Section 2).

Eason and Ford (1983) used a long exposure (165-min) [OIII] λ5015/32 KPNO 4-m plate of M33 to improve the limited coverage of an earlier unpublished Lick survey by Ford and Jenner which identified 20 planetaries. The distribution of 58 planetary nebulae in M33 is shown schematically in Figure 2. The schematic representation of the spiral structure was taken from Sandage and Humphreys (1980). The H II regions in M33 are not very bright in [OIII] λ5007. Consequently, the detection limit was relatively constant across the galaxy. The nebulae do not show a strong concentration toward the center, reflecting the absence of a nuclear bulge which in the Milky Way Galaxy and M31 gives rise to a strong central concentration.

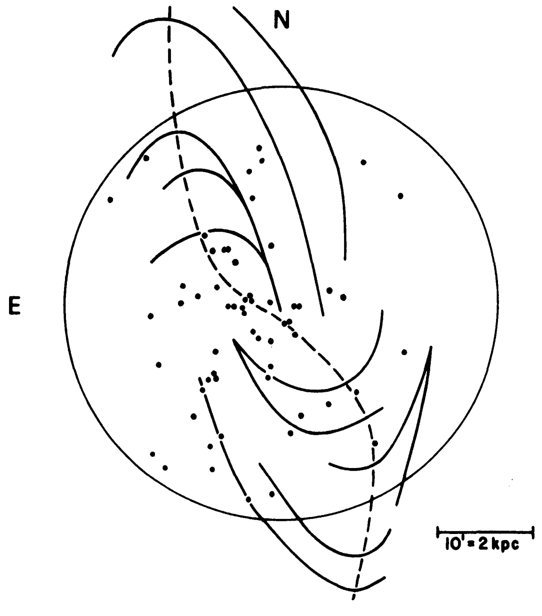

Figure 2. A schematic representation of the distribution of planetary nebulae in M33. The schematic spiral arms were taken from Sandage and Humphreys (1980). The distribution is noticeably asymmetrical about the major axis. The circle delimits the field of the 4-m telescope.

The planetary nebula distribution in Figure 2 is strikingly asymmetrical about M33's major axis. The ratio of the number on the SE side to the number on the NW side is between 1.7 and 1.8, depending on the value of the major-axis position angle. The binomial probability of observing a chance ratio greater than 1.5 is 0.1, which suggests that the distribution may have a physical origin. The asymmetry can be understood if we idealize the distribution of nebulae as a uniform density ellipsoid that is bisected by a thin sheet of dust which obscures the far side. Let q be the number of far side nebulae which can be seen through the disk divided by the number which can be seen on the near side. The ratio of the number of nebulae which project across the major axis onto the far side to the number which project onto the near side is then given by

$$R = \frac{\pi - (1-q)\cos^{-1}\theta(b/a,i)}{q\pi + (1-q)\cos^{-1}\theta(b/a,i)} \qquad (1)$$

where b/a is the ratio of the ellipsoid's minor axis to major axis, i is the inclination of the minor axis to the line of sight and θ is given by

$$\theta = \frac{(b/a)\tan i}{\sqrt{1 + (b/a)^2\tan^2 i}} \qquad (2)$$

The optical depth through M33's disk can be estimated from the average H I column density ($\sim 9.5 \times 10^{20}$ atoms cm^{-2}; Rogstad and Shostak, 1972), using $A(V) = 3 \times n(H\ I) \times 1.69 \times 10^{-22}$ mag cm^2 (Spitzer, 1978), A(V) = 0.5 mag. If we assume that the planetary luminosity function n(m) is constant, the value of q is 0.28. We can now solve equation (1) for the b/a which gives the observed R for a specified position angle and inclination i.

In reality, M33's geometry is rather more complicated than our simple geometrical model. Sandage and Humphreys (1980) have shown that the position angle and inclination respectively change from 49°/40° in the inner 2 kpc to 15°/65° in the outer parts of the galaxy. The respective solutions are b/a = 1.0 and b/a = 0.5. Because our symmetrical model does not represent the bent galaxy, we cannot derive a unique b/a. We can, however, conclude that the planetaries must have an inflated distribution. A thin bent disk cannot reproduce the observed distribution other than by chance.

Jacoby's (1978, 1980) Magellanic Clouds survey, which is reviewed elsewhere in this volume, established the [OIII] planetary nebula luminosity function over a six magnitude range. Jacoby noted that in the absence of strong central star evolution over the 20,000-year nebula lifetime, the [OIII] luminosity evolution will be controlled by the nebula's expansion velocity (i.e. the rate of change of the density). There is relatively strong observational evidence that both the form (approximately uniform magnitude density) and the scaling of luminosity functions are similar from one galaxy to another. Jacoby and Lesser (1981) and Ford and Jenner (1979) found that the dispersion in the magnitudes of the brightest planetaries in M31, M32, NGC 185, NGC 205, the LMC, and the SMC is less than 25%. Jacoby found that the LMC and SMC luminosity functions are statistically indistinguishable, and Lawrie and Ford (1982) showed that the first three magnitudes of the luminosity function in the center of M31 matches that of the Clouds.

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Jacoby (1980) estimated the total number of planetaries (within an 8-mag interval) in Local Group galaxies by using his luminosity function to extrapolate from the observed bright end to the unobserved faint end. He showed that the derived luminosity-specific number of planetary nebulae per unit luminosity is approximately consant in 8 galaxies, with a value of 6.1×10^{-7} planetaries $L_{\odot}^{-1}$.

2. CHEMICAL COMPOSITIONS

Chemical abundances have been measured in planetary nebulae in 8 Local Group galaxies. Because the nebulae in the more distant galaxies are very faint, there is considerable variation in the observational uncertainties and the number of atomic species measured. In spite of these difficulties, some interesting trends appear to be emerging.

The data are summarized in Tables 2, 3, and 4. Table 2 is a compilation of reddening corrected line intensities for Fornax (Danziger et al., 1978), NGC 185 (Jenner and Ford, 1976), M32 (Jenner and Ford, 1978), NGC 6822 (Dufour and Talent, 1980), and M31 (Jacoby and Ford, 1983). The line intensities in NGC 185 and M31 are published here for the first time. The Hβ fluxes and luminosities of the nebulae are given in the last row of Table 2. Many of the fluxes were measured through small spectroscopic apertures, and thus are lower limits. It is evident that the Hβ luminosities of the brighter planeteries in galaxies of widely differing masses are relatively constant.

The ionic abundances of the nebulae are given in Table 3. Both Danziger et al. (1978) and Dufour and Talent (1980) calculated ionic abundances for the case of a uniform temperature and the case of temperature fluctuations represented by Piembert and Costero's (1969) fluctuating temperature with $t_2 = 0.035$. All of the ionic abundances in Table 3 are based on a uniform temperature throughout the nebula. Table 3 shows that the O^{++} abundances of oxygen are relatively high in the Fornax planetary and in the M31 10 kpc and 17 kpc planetaries. Consequently, independent of the ionization correction scheme which is used, the abundance of oxygen must be relatively high in those planetaries.

Atomic abundances are given in Table 4. I have included the abundances of H II regions in those galaxies where data is available. In addition to the average abundances of planetary nebulae in the SMC and LMC, I have included N67 and N97, helium and nitrogen-rich nebulae in the respective galaxies which Dufour and Talent considered most similar to the planetary observed in NGC 6822.

Before discussing abundances in Table 4, I will first briefly discuss the ages, or equivalently the masses, of the progenitor stars. Planetary nebulae near the sun have an average distance from the plane $\langle|z|\rangle = 150$ pc (Osterbrock, 1974), which corresponds to precursor masses $M \simeq 1.5 M_{\odot}$ (Peimbert, 1978) and ages of $\sim 2 \times 10^{9}$

years. Peimbert (1978) used chemcial composition and kinematics to classify galactic planetary nebulae into the following 4 types: Type I, nebulae which are helium and nitrogen rich and that appear to originate in young stars; Type II, an intermediate population with a characteristic mass of $M \sim 1.5\ M_{\odot}$; Type III, which have $|\Delta V| > 60$ km s^{-1} and $|z| > 0.8$ kpc; and Type IV, a metal-deficient halo population. Tinsley (1978) used models to show that a steady star formation rate in the galaxy will yield approximately equal numbers of 0.9 to 1.2 $M_{\odot}$, 1.2 to 2 $M_{\odot}$, and 2 $M_{\odot}$ to 5 $M_{\odot}$ progenitors. That distribution apparently does not represent galactic planetary precursors, because the majority of planetaries are Type II. If there is a declining star formation rate the respective intervals will provide 65%, 20%, and 15% of the precursors. From an observational point of view, several arguments suggest that planetary nebulae in Local Group galaxies primarily derive from old and intermediate age populations. The stars in M32 and in M31's and the galaxy's nuclear bulges produce planetary nebulae copiously. There is no evidence for recent star formation in either the galaxy's or M31's nuclear bulge, nor in M32, which has no detectable gas (cf. Ford and Jenner, 1975) and has not had star formation more recently than 5×10^{9} years (O'Connell, 1980). Feast (1968) has shown that planetaries in the LMC have approximately twice the velocity dispersion of extreme Population I stars. The planetary nebulae in M33, which has vigorous star formation, may be distributed in an ellipsoidal distribution (cf. Section 1) rather than in a thin disk. There is no star formation in Fornax, although the carbon star population (Frogel et al., 1981) shows that there has been star formation within the last 2 to 8 billion years. In view of these considerations, we conclude that planetary progenitors are typically 2 or more billion years old $M \leq 1.5\ M_{\odot}$).

Turning now to Table 4, I first note, as have many previous authors, that the helium abundance in planetary nebulae is typically higher than in H II regions in the same galaxy. There can be little doubt that planetary shells are helium enriched. However, if we use Tinsley's (1978) criterion that X(PN)/X(ISM) be greater than 7 for planetaries to produce most of an element in our galaxy, it does not appear that planetary nebulae are a major source of helium in star-forming galaxies. Table 4 also shows that the nitrogen abundance in planetaries is consistently higher than in H II regions, by factors of 4.0, 4.5, 5.5, 4.2, and 123 in the galaxy, M31, the SMC, the LMC, and NGC 6822. The average abundances in Table 4 are based on "typical" planetaries. In addition to these there are populations of helium-rich and nitrogen-rich planetaries in the galaxy (Peimbert's Type I; Peimbert, 1978), the LMC (N97, P07, and P09; Osmer, 1976; Dufour and Killen, 1977; and Aller, 1983), the SMC (N67; Osmer, 1976; Dufour and Killen, 1977) and NGC 6822 (Dufour and Talent, 1980). Between the "typical" planetaries, which have a nitrogen enrichment of 4 to 5 relative to the ISM, and the smaller populations of helium-rich planetaries, which have nitrogen enrichments of 20 to 100, there is ample data to substantiate earlier conclusions (e.g. Tinsley, 1978) that planetary nebulae are most likely a major source of nitrogen enrichment in galaxies. The only qualification of this conclusion is William's (1982) demonstration that novae may return even more nitrogen to the interstellar medium than planetaries.

There are no obvious trends in the oxygen abundance. Oxygen is underabundant in the planetaries studied in NGC 185 and NGC 6822, and in some planetaries such as the helium-rich planetaries in the Clouds. There are weak correlations between N/O and He/H and between N/O and O/H, which suggest that nitrogen is at least partially a secondary product of nucleosynthesis (cf. Danziger et al., 1978 ; Talbot and Arnett, 1974).

I will now consider the galaxies in Table 4 individually. The analysis by Danziger et al. (1978) of the Fornax planetary shows that there are at least two stellar populations in Fornax. The first population is characterized by Fornax's 4 globular clusters, which are clearly old, metal-deficient clusters that are similar to M15 and M92 (van den Bergh, 1969; Danziger, 1973; Zinn and Persson, 1981). By analogy with the galaxy (cf. Sandage, Freeman, and Stokes, 1970), this old population presumably had its genesis during Fornax's earliest star-formation epoch. In contrast to the metal-poor globular clusters, the Fornax planetary nebula has a nearly normal oxygen abundance, which is unlike the oxygen-deficient planetary K648 in M15 and the galactic halo planetaries PK 49+88°1 and 108-76°1 (Hawley and Miller, 1978). The discovery of carbon stars in Fornax (Frogel et al., 1982) with probable ages between 2 and 8 billion years (inferred from comparison with carbon stars in the Magellanic Clouds; Mould and Aaronson, 1980) establishes star formation and continuing metal enrichment long after the globular clusters formed. Although the detailed evolution from red giants to planetary nebulae is poorly understood, it seems likely that carbon stars and the carbon-rich protoplanetary nebulae discussed by Zuckerman (1978) are two links in the evolutionary chain. Consequently, it is plausible to suppose that the Fornax planetary and the carbon stars are members of the same intermediate age population.

The considerable metal enrichment revealed by the presence of the oxygen-enriched planetary and the carbon-enriched carbon stars points to an origin in nucleosynthesis-enriched gas, rather than in primordial gas that was retained or captured by Fornax. The mass loss rate from stellar evolution in Fornax, estimated from comparison with NGC 147 (Ford, Jacoby, and Jenner 1977), is $\sim 3 \times 10^{-5}$ $M_{\odot}$ yr^{-1}. Consequently, even if Fornax did not retain any gas after the first star formation epoch, it produces enough gas to fuel star formation. However, planetary nebula shells, which have expansion velocities larger than the escape velocity ($v_{escap} \lesssim 10$ km s^{-1}), may be able to power a cool thermal wind (cf. Ford, et al., 1977) that would keep the galaxy relatively gas free. If the mass loss rate is too high for planetary shells to power a warm wind, Fornax may be an example of an elliptical galaxy which accumulates gas until star formation begins and is subsequently quenched by a supernova-powered, hot-pulsed wind (Sanders, 1981).

Dufour and Talent (1980) have shown that there is an extreme overabundance of nitrogen in the NGC 6822 planetary. Although considerable uncertainty in the nitrogen abundance is introduced by correction for unseen N^{++}, Dufour and Talent note that N^+, O^+, and S^+ have similar ionization potentials, and thus originate in the same regions of the nebulae. Consequently, the great strength of the [NII] lines in the NGC 6822 planetary must point to a nitrogen overabundance relative to galactic planetaries. A similar argument applies to the planetaries in M32, which have stronger nitrogen lines that galactic planetaries. Although Jenner and Ford (1979) could not derive O and N abundances because of the difficulty of measuring the planetary's temperature (which suggests a high O abundance), the similarity of the line intensities in M32-1 and the NGC 6822 planetary suggests a considerable overabundance of nitrogen. In spite of the possibly similar overabundances of nitrogen, the ages of the progenitor stars in the two galaxies may be very different. Because of the NGC 6822 planetary's similarity to galactic helium and nitrogen-rich stars, Dufour and Talent conclude that it derives from a young star. By contrast, O'Connell's (1980) spectral synthesis of M32 suggests that there has not been any star formation in M32 more recently than 5×10^9 years ago.

The planetary in NGC 185 has a high helium and nitrogen abundance relative to the nebulae in Fornax and typical nebulae in the clouds. Although the nitrogen abundance is very uncertain because of a large ionization correction, the nebulae may be a helium and nitrogen-rich planetary that had its origin in one of NGC 185's small population of OB stars (Baade, 1951; Hodge, 1963) rather than the old, metal poor populations which produce most of NGC 185's light.

The M31 abundances reveal several interesting facts. First, the oxygen abundance in an old star(i.e a planetary nebula) and an H II region (No. 685; Baade and Arp, 1964) are surprisingly high at 17 kpc from the center. The oxygen abundances are very nearly equal to those in the Orion nebulae. Blair et al. (1982) used empirically calibrated abundances in H II regions and also found high abundances at large radii. Jacoby and Ford's (1983) oxygen abundance in the H II region is a direct determination based on a well-measured temperature, and falls near the mean fit of O/H versus R (Blair et al., 1982), thereby supporting their empirical calibration at 17 kpc.

Oxygen and neon, and probably nitrogen, are relatively underabundant in the planetary at 34 Kpc. The oxygen abundance is a little less than in PK 49+88° 1, a galactic halo planetary (Hawley and Miller, 1978). We believe the remote 34 kpc nebula is a member of a metal-poor halo population in M31.

Although an abundance gradient based only on the three planetary nebulae in Table 4 cannot be considered well determined, there is as yet no other data available. Abundance gradients in M31 and the galaxy are summarized in Table 5. The reader should note that different investigators derive widely differing galactic abundance gradients. Barker (1978) found weak evidence for a nitrogen abundance gradient, and gave a formal value of approximately half that in Table 5. Aller and Czyzak (1982) find little evidence for a galactic nitrogen abundance gradient. Table 5 shows that the gradient in both the gas and stars is very shallow in M31, and much shallower than in the galaxy.

3. PLANETARY NEBULAE AS STANDARD CANDLES

Ford and Jenner (1979) used unpublished KPNO 4-m telescope video camera photographs to show that the dispersion in the reddening corrected [OIII] λ5007 magnitudes of the brightest planetary nebulae in M31, M32, NGC 205, and NGC 185 is ~ 25%. This relative luminosity constancy in galaxies with a wide range in chemcial composition and number of nebulae suggests that planetaries may be useful as standard candles. In particular, it is reasonable to suppose that a comparison of two well-populated homogeneous populations, such as those found in the nuclear bulges of two nearly identical spirals, will lead to an even smaller dispersion between the first ranked nebulae, or some combination of brightest nebulae. Following this line of reasoning, Ford and Jenner (1979) used video camera [OIII] λ5007 on-band/off-band pictures to find and measure the magnitudes of planetary nebulae in the nuclear bulges of M81 (Sb, inclination = 58°) and M31 (Sb, inclination = 77°).

Figure 3 shows the sum of twelve 12.5-min on-band pictures and an equivalent sum of off-band pictures. Both pictures have been flattened by subtracting a smoothed off-band picture. Using the criterion that a nebula must appear in each of three on-band pictures taken on three separate nights, there are eight very faint, but definite identifications.

The galactic-extinction corrected differences between the 1st brightest nebulae, the average of the 2nd through 4th nebulae, and the cumulative luminosity distributions lead to preliminary M81 to M31 distance ratios, which do not include corrections for internal extinction, of 4.0, 3.6, and 3.5. These ratios are significantly lower than those determined by Sandage and Tammann (4.9; 1974) and de Vaucouleurs (5.3; 1979).

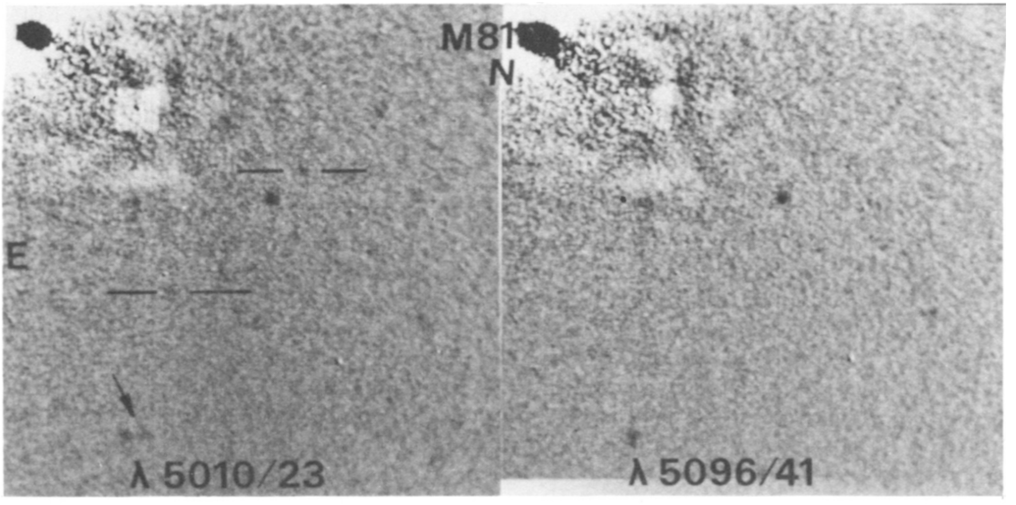

Figure 3. Three planetary nebulae in M81's nuclear bulge. The pictures are a superposition of 12 12.5-min KPNO telescope video camera exposures. The galaxy light has been removed by subtracting a smoothed off-band summation.

Jacoby and Lesser (1980) looked for planetary nebulae in 10 galaxies whose Local Group membership is uncertain. Using the video camera on the KPNO 2.1-m telescope, they found 7 planetaries in 5 of the galaxies (cf. Table 1). Because planetaries are faint during most of their lifetime (Jacoby 1980), they could not derive reliable distances from the observed fluxes of one or two nebulae in a sparsely populated galaxy. However, they were able to place upper limits on the distances by assuming that the nebulae are as intrinsically luminous as the planetaries in well populated galaxies such as M31 and the Magellanic Clouds. These upper limits suggest that IC 10 is a definite Local Group member and that Sextans A and WLM could be Local Group members. In those galaxies where they did not detect planetaries, they were able to set rough lower limits to the distances by finding the distance at which at least one planetary should have been found. Their lower limits allow them to exclude Sextans B, NGC 3109, and NGC 6946 from Local Group membership. The membership designations in Table 1 are based on Jacoby and Lesser's survey and the kinematical considerations which they cited. Finally, we note that Ford and Jenner used KPNO video camera pictures to find 2 faint planetary nebulae and extended high excitation nuclear emission in NGC 404, a galaxy excluded from Local Group membership by kinematical considerations (Yahil et al., 1977). The 2 nebulae and the asymmetrical, extended nuclear emission are shown in Figure 4.

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Table 1

Recent Surveys For Planetary Nebulae

Galaxy	Telescope	Detector or Plates	Filters: On-Line ion, λ_c/FWHM	Filters: Off-Line λ_c/FWHM	Nebulae Found	Membership	References
			Local Group Members				
Sculptor Fornax	UK 1.2-m	098	Hα + [NII] interference filter	RG 630	0 1		Danziger, Dopita, Hawarden, and Webster (1978)
NGC 6822	CTIO 4-m	IIIa-J 127 04	[OIII] λ5000/70 Hα + [NII] λ6560/120	GG 385, GG 495 GG 385, GG 495	8		Killen and Dufour (1982)
M32 Nucleus M33	Lick 3-m KPNO 4-m	Velocity Modulating Camera IIIa-F IIa-D	[OIII] $\lambda_c$tuneable/2.1 [OIII] λ 5015/32	$\lambda_c$tunable/2.1 OG 570	6 (new) 58		This paper. Eason and Ford (1983)
M31 Nucleus M31 Halo	Lick 3-m KPNO 4-m	Velocity Modulating Camera IIIa-J, IIa-D IIIa-F, IIa-D	[OIII] $\lambda_c$tuneable/2.1 [OIII] GG 475 [OIII] λ5015/23	$\lambda_c$tuneable/2.1 OG 570 OG 570	19 (new) 47		Lawrie and Ford (1982) Ford, Jacoby, and Jenner (1983)
M31 Disk and Halo	KPNO 0.9-m	KPNO Image Intensifier	[OIII] λ5007/21	λ5300/130	40		Ford and Jacoby (1983)
			Possible Local Group Members			**Membership**	
IC 10	KPNO 2.1-m	Video Camera	[OIII] λ5007/21	λ5300/130	1	yes(?)	Jacoby and Lesser (1981)
Leo A	"	"	"	"	2	yes(?)	"
Sextans A	"	"	"	"	1	(?)	"
Pegasus	"	"	"	"	1	(?)	"
WLM	"	"	"	"	2	yes(?)	"
			Galaxies Beyond the Local Group				
IC 342	KPNO 2.1-m	Video Camera	[OIII] λ5007/21	λ5300/130	0	no	Jacoby and Lesser (1981)
Sextans B	"	"	"	"	0	no(?)	"
NGC 3109	"	"	"	"	0	no	"
GR 8	"	"	"	"	0	no(?)	"
NGC 6946	"	"	"	"	0	no	"
NGC 404	KPNO 4-m	Video Camera	[OIII]5007/20	λ5300/200	2	no	This paper
M 81	"	"	"	"	8	no	Ford and Jenner (1979)

Table 2

Reddening Corrected Line Intensities in Local Group Planetary Nebulae

Ion	λ	Fornax	NGC 185	M32	NGC 6822	M31		
						10 kpc	17 kpc	34 kpc
[OII]	3727	25.2	< 7	63	43.8	117	144	34:
[NeIII]	3869	35.7	45	-	30.5	74	143	128
HeI	3889	14.4	21	96	-	-	16:	64:
Hε + [NeIII]	3970	21.0	-	-	31.0	31	-	88
Hδ	4102	26.1	-	30:	25.4	27	-	80:
Hγ	4341	47.3	52	36	47.1	57	57	48
[OIII]	4363	3.9	30	-	39.1	9.4:	15	26
HeI	4471	5.5	-	-	-	-	-	-
HeII	4686	-	<10	<15	71.9	-	-	-
Hβ	4861	100.0	100	100	100.0	100	100	100
[OIII]	4959	200.8	327	292	410.0	355	500	375
[OIII]	5007	579.5	967	897	1160.0	1079	1471	1122
HeI	5876	16.3	25	12	14.6	22:	26:	-
[NII]	6548	0.2	-	94	134.0	-	31:	-
Hα	6563	290.1	280	264	272.0	281	290	302
[NII]	6584	7.1	23	250	399.0	57	84:	<35
HeI	6678	6.0	-	-	-	-	-	-
[SII]	6724	<2.2	-	94:	<10	-	-	-
[ArIII]	7136	4.5	31	-	-	-	-	-
[OII]	7324	<2.2	< 7	-	-	-	-	-
Distance (kpc)		190	~600	<652	557		652	
log F(Hβ) ergs $cm^{-2}s^{-1}$		-13.8	-14.24	-14.75	-14.83	-15.09	-15.20	-15.44
log L(Hβ) ergs s^{-1}		34.8	>34.3	<35.0	34.7	>34.6	>34.51	>34.27

TABLE 3

Local Group Planetary Nebulae Ionic Abundances
Relative to H by Number

Ion	Fornax	NGC 185	M32	NGC 6822	M31 10 Kpc	M31 17 Kpc	M31 34 Kpc
He^+	0.13	0.21	0.089	0.12	0.16:	0.21:	-
He^{++}	0.00	< 0.009	$\leq$ 0.0012	0.066	-	-	-
O^+	1.4×10^{-5}	$< 7.7 \times 10^{-7}$	-	0.51×10^{-5}	7.6×10^{-5}	2.8×10^{-5}	0.62×10^{-5}
O^{++}	1.99×10^{-4}	7.3×10^{-5}	-	0.81×10^{-4}	3.05×10^{-4}	3.1×10^{-4}	1.16×10^{-4}
N^+	0.15×10^{-5}	1.4×10^{-6}	-	0.24×10^{-5}	3.3×10^{-5}	1.2×10^{-5}	$<2.2 \times 10^{-6}$
Ne^{++}	3.8×10^{-5}	6.4×10^{-6}	-	0.50×10^{-5}	6.05×10^{-5}	7.0×10^{-5}	0.28×10^{-5}
Ar^{++}	0.54×10^{-6}	9.5×10^{-6}	-	-	-	-	-
S^+	$<0.12 \times 10^{-6}$	-	-	$<0.12 \times 10^{-6}$	-	-	-
S^{++}	-	-	-	$<1.86 \times 10^{-6}$	-	-	-

Table 4

Chemical Abundances in Local Group Planetary Nebulae and H II Regions

Element	Fornax	NGC 185	M32	NGC 6822		SMC			LMC			Galaxy		M31			
				PN	HII	N67	Avg	HII	N97	Avg	HII	PN	Orion	10 kpc PN	17 kpc PN	17 kpc HII	34 kpc PN
He	11.08	11.32	11.00:	11.27	10.92	11.27	11.02	10.92	11.26	11.07	10.97	11.04	11.00	11.20	11.32:	10.93	-
O	8.51	7.88	-	8.12	8.4	7.7	8.16	8.10	7.8	8.34	8.43	8.9	8.7	8.58	8.66	8.52	8.09
N	7.41	>8.14	-	8.79	6.7	7.6	7.19	6.45	8.3	7.64	7.02	8.3	7.7	8.22	7.90	7.25	<7.6
Ne	-	6.81:	-	6.91	7.7	-	7.60	7.58	8.0	7.64	7.77	8.3	7.9	7.88	8.09	7.63	6.47
A	5.91	7.02	-	-	-	-	-	-	-	6.41	6.35	-	-	-	-	-	-
Abundance Sources	1	2	3	4	5	6	7	8	6	9	8	10	10	11	11	11	11
Galaxy Mass	~2×10^{7} (1)	~2×10^{8} (1)	5×10^{8} (3)	1.4×10^{9} (2)		1.5×10^{9} (2)			6×10^{9} (2)			1.8×10^{11} (4)		1.85×10^{11} (5)			
Galaxy Type	Spheroidal	dE0	E2	Ir IV-V		Ir IV			SBc III-IV			Sbc		Sb			

Abundances with considerable uncertainty are marked with a colon.

Mass References

1. Derived from the luminosity by assuming that it has the same mass-to-light ratio as M32.
2. van den Bergh (1968)
3. Ford (1978)
4. Schmidt (1965)
5. Rubin and Ford (1970)

Abundance References

1. Danziger et al., 1978
2. Jenner and Ford, 1978
3. Jenner, Ford, and Jacoby, 1979
4. Dufour and Talent, 1980
5. Lequeux et al., 1979
6. Osmer 1976, Dufour and Killen, 1977
7. Aller et al., 1981
8. Aller, Keyes, and Czyzak, 1979
9. Aller, 1983
10. Peimbert, 1978
11. Jacoby and Ford, 1983

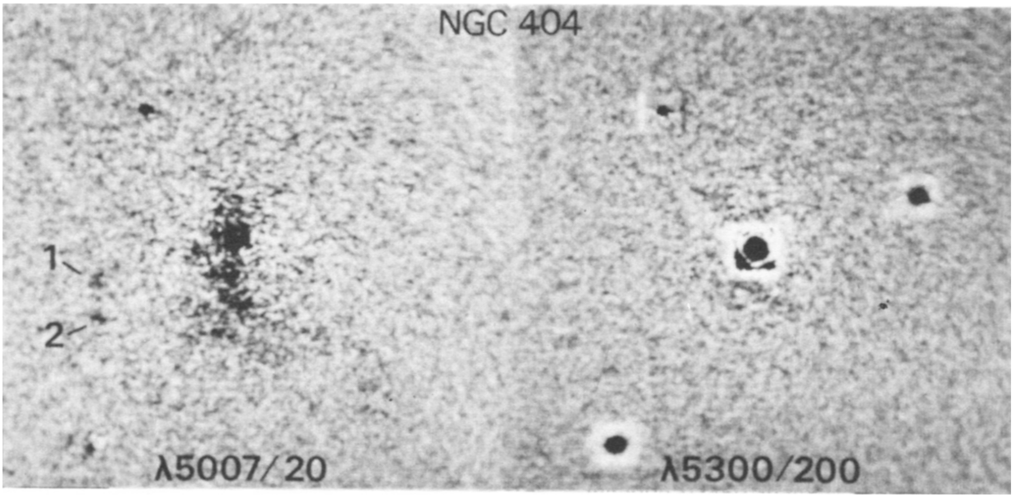

Figure 4. An [OIII] λ5007 pair of on-band off-band pictures of NGC 404. Two candidate planetary nebulae are marked. The on-band picture shows [OIII] emission extending asymmetrically out of the nucleus.

Table 5

Abundance Gradients in M31 and the Milky Way Galaxy

	M31 PN	M31 HII	MWG PN	MWG HII
$\frac{d \log (O/H)}{dR}$	-0.023	-0.029	-0.06	-0.13
$\frac{d \log (N/H)}{dR}$	$\leq$-0.024	-0.027	-0.18	-0.23
Source	1	2	3	3

1. Jacoby and Ford, 1983
2. Blair, Kirshner, and Chevalier, 1982
3. Peimbert, 1978

REFERENCES

Aller, L. H. 1983, This volume.

Aller, L. H. and Czyzak, S. J. 1982, Ap. J. Suppl., in press

Aller, L. H., Keyes, C. D., and Czyzak, S. J. 1979, Proc. Natl. Acad. Sci. USA, 76, 1525

Aller, L. H., Keyes, C. D., Ross, J. E., and O'Mara, B. J. 1981, Mon. Not. R. Astr. Soc., 194, 613

Barker, T. 1978, Ap. J., 220, 193

Baade, W. 1951, Pub. University of Michigan 10, 7

Baade, W. and Arp, H. 1964, Ap. J. 139, 1027

Blair, W. P., Kirshner, R. P., and Chevalier, R. A. 1982, Ap. J., 254, 50

Danziger, I. J. 1973, Ap. J., 181, 641

Danziger, I. J., Dopita, M. A., Harwarden, T. G., and Webster, B. L. 1978, Ap. J., 220, 458

Dufour, R.J. and Killen, R. M. 1977, Ap. J., 211 68

Dufour, R. J. and Talent, D. L. 1980, Ap. J., 235, 22

Eason, E. L. E. and Ford, H. C. 1983, in preparation

Faber, S. M. and Jackson, R. E. 1976, Ap. J., 204, 668

Feast, M. W. 1968, Mon. Not. R. Astr. Soc., 140, 345

Ford, H. C. 1978, in Planetary Nebulae (I.A.U. Symp. No. 76), p. 19, ed. Y. Terzian

Ford, H. C. and Jacoby, G. H. 1978, Ap. J. 219, 437

Ford, H. C., Jacoby, G. H., and Jenner, D. C. 1977, Ap. J. 213, 18

Ford, H. C., Jacoby, G. H., and Jenner, D. C. 1979, Ap. J. 227, 391

Ford, H. C, Jacoby, G. H., and Jenner, D. C. 1983, in preparation

Ford, H. C. and Jenner, D. C. 1975, Ap. J., 202, 365

Ford, H. C. and Jenner, D. C. 1979, B.A.A.S, 10, No. 4, 665

Frogel, J. A., Blanco, V. M., McCarthy, M. F., and Cohen, J. G. 1982, Ap. J., 252, 133

Hawley, S. A. and Miller, J. S. 1978, Ap. J., 220, 609

Hodge, P. W. 1963, A. J., 68, 691

Jacoby, G. H. 1978, Ap. J. 226, 540

Jacoby, G. H. 1980, Ap. J. Suppl., 42, 1

Jacoby, G. H. and Ford, H. C. 1983, in preparation

Jacoby, G. H. and Lesser, M. P. 1981, A. J., 86, 185

Jenner, D. C. and Ford, H. C. 1978, in Planetary Nebulae (I.A.U. Symp. No. 76), p. 246, ed. Y. Terzian

Jenner, D.C., Ford, H. C. and Jacoby, G. H. 1979, Ap. J., 227, 391

Killen, R. M., and Dufour, R. J. 1982, Pub. Astr. Soc. Pac. (June)

Lawrie, D. G. 1978, Ph.D. Thesis, Univ. of Calif., Los Angeles

Lawrie, D. G. 1983, in preparation

Lawrie, D. G. and Ford, H. C. 1982, Ap. J., 256, 120

Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A., and Torres-Peimbert, S. 1979, Astr. Ap.,

Mould, J. and Aaronson, M. 1980, Ap. J., 240, 464

O'Connell, R. W. 1980, Ap. J., 236, 430

Osterbrock, D. E. 1974, Astrophysics of Gaseous Nebulae, W. H. Freeman and Co., San Francisco

Peimbert, M. 1978, in Planetary Nebulae (I.A.U. Symp. No. 76), p. 215, ed, Y. Terzian
Peimbert, M. and Costero, R. 1969, Bol. Obs. Tonantzintla y Tacubaya, 5, 3
Peterson, A. W. 1977, Pub. Astr. Soc. Pac., 89, 129
Rogstad, D. H. and Shostak, G. S. 1972, Ap. J., 176, 315
Sandage, A., Freeman, K. C., and Stokes, N. R. 1970, Ap. J., 160, 831
Sandage, A., and Humphreys, R. M. 1980, Ap. J. (Letters), 236, L1
Sandage, A. and Tammann, G. A. 1974, Ap. J., 190, 525
Sanders, R. H. 1981, Ap. J., 244, 820
Sedwick, K. E. and Ford, H. C. 1976, Bull. Am. Astr. Soc., 8, 568
Spinrad, H. and Taylor, B. J. 1971, Ap. J. Suppl., 22, 445
Spitzer, L. 1978, Physical Processes in the Interstellar Medium, Wiley, New York
Talbot, R. J., Jr., and Arnett, W. D. 1974, Ap. J., 190, 605
Tinsley, B. 1978, in Planetary Nebulae (I.A.U. Symp. No. 76), p. 341, ed. Y. Terzian
van den Bergh, S. 1969, Ap. J. Suppl., 14, 145
Williams, T. B. 1976, Ap. J., 209, 716
Williams, T. B. 1977, Ap. J. 214, 685
Williams, R. E. 1982 (preprint)
Yahil, A., Tammann, G. A., and Sandage, A. 1977, Ap. J., 217, 903
Zinn, R. and Persson, S. E. 1981, Ap. J., 247, 849

FLOWER: Which lines are available for abundance determinations?

FORD: The ionization corrections are based on [O II] λ 3727 and [O III] λ 5007 and are applied to [N II] λ 6584 and [Ne III] λ 3868.

PAPP: I would like to point out that the distribution of PN you have found in the outer disk of M 31 follows very well the observed H I and optical warp.

REAY: From the relatively high signal/noise of the spectrum which you showed, it appears that it would be possible, at higher dispersion, to use velocity measurements to discriminate against background sources.

FORD: The photon rate is about 2 s^{-1} in [O III] λ 5007 for the brighter PN when using a 4 m telescope. Although the shells could be resolved, we believe that there is little or no confusion with H II regions. The [O III] magnitudes and absence of a stellar continuum in our spectrophotometric scans support this conclusion.

DOPITA: The metallicity gradient of M 31 has recently been derived (Dopita, Binette, d'Odorico and Benvenuti, Ap. J., in press) from the data of Blair, Kirshner and Chevalier. Our result is a gradient of -0.05 ± 0.02 dex kpc^{-1}.

FORD: Although your result is somewhat larger than the values given in my Table 5, it is still relatively shallow.

ZUCKERMAN: I hope that observations of PN will be extended to more distant PN, perhaps using the Space Telescope.

LAWRIE: Observations of PN are already being extended outwards using ground-based instruments. John Graham and I have identified 9 strong PN candidates in the Sculptor group, NGC 300. We hope to obtain [O III] λ 5007 magnitudes for these objects in the autumn.