PLANETARY NEBULAE IN THE ANDROMEDA GALAXY AND ITS COMPANIONS

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1. INTRODUCTION

The identification and observation of planetary nebulae in the Andromeda galaxy (M31) and its companions provide a powerful means of studying their old stellar populations. The direct determination of chemical abundances and radial velocities for even the brightest individual old stars is impossible at the distance of M31. The strongest emission lines of planetary nebulae are as bright as the entire visual continuum of the most luminous giants. Consequently, spectrophotometry of planetary nebulae presently provides the only direct measure of chemical abundances, and, with the exception of globular clusters, the only radial velocity determinations for the old populations.

Chemical compositions give data on nucleosynthesis in sequential generations of stars and the dependence of nucleosynthesis on the mass of the parent galaxy. The helium abundance in planetary nebulae in low mass ellipticals may determine the cosmic abundance of helium at the time the galaxies formed.

Kinematical studies in galaxies such as M32 and NGC 205 allow the determination of halo velocity dispersions and consequently virial masses which are largely model independent. Comparison of halo and nuclear velocity dispersions, in combination with a light distribution, allows the testing of dynamical models of galaxies and the validity of commonly used methods of estimating the masses of galaxies.

The number of planetary nebulae found in a galaxy provides an observational basis for estimating the death rate of old stars and the rate at which they produce an interstellar medium.

The identification of planetary nebulae in M31 leads to a better understanding of the spatial distribution and luminosity function of planetary nebulae in our galaxy. Unlike the planetary nebulae in the heavily obscured center of our galaxy, those in the center of M31 can be identified optically to within a few parsecs from the nucleus. The

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identification of a large number of planetary nebulae at the well determined distance of M31 will permit the determination of an accurate luminosity function.

Baade (Baade 1955; Baade and Swope 1963) used broad band filters and direct photography to identify five planetary nebulae in a field 90' southwest of the center of M31. Swope (1963) measured their mean photographic magnitude as 22.3. The advent of sophisticated interference filter and image intensifier technology has made it possible to greatly extend Baade's identifications.

2. THE IDENTIFICATION OF PLANETARY NEBULAE IN ANDROMEDA AND ITS COMPANIONS

Planetary nebulae were first identified in NGC 185(4), NGC 205(12), and M32(10) by Ford, Jenner, and Epps (1973). Refinement of the identification technique permitted an extension of the identifications in M32(21) (Ford and Jenner 1975), led to the first identifications in NGC 147(5) (Ford, Jacoby, and Jenner 1977), and permitted the identification of 307 planetary nebulae in 7 fields of M31 (Jacoby and Ford 1976, and Ford and Jacoby 1977).

These surveys utilized a Westinghouse WL-30677 image intensifier at the f/17 prime focus of the Lick Observatory 120-inch (3-m) telescope. The 40 mm photocathode of the image intensifier is electrostatically imaged onto the 25 mm anode; this reduction gives the 120-inch telescope an effective focal ratio of f/3.2. There is almost no measurable geometrical distortion in the image intensifier. This greatly simplifies the determination of accurate coordinates for the nebulae, which are essential for spectrophotometry or radial velocity observations.

The identifications (Ford, Jenner, and Epps 1973) were made by isolating Hα or the [OIII] λ5007 line in the nebulae with a pair of plates taken sequentially through on-line and off-line interference filters. The central wavelengths (λ_c) and the full widths at half-maximum transmission (FWHM) of the filter pairs were λ_c 5020 (50 Å FWHM)/λ_c 5300 (200 Å FWHM) and λ_c 6570 (50 Å FWHM)/λ_c 6065 (175 Å FWHM). The off-line filters transmit in spectral regions that are free of strong lines from the nebula, from the night sky, and from mercury and neon in city lights. The exposures were balanced for each plate pair to give equal sky densities. To minimize the effect of spatial variation of photocathode sensitivity on images near the plate limit the exposures of an on-line/off-line pair were made with the image of the galaxy in the same position on the photocathode. Thirty minutes was typically required for the dark sky through the λ_c 5020 (50 Å FWHM) filter to give a density of 0.6 on a IIa-D plate.

The technique was refined (Ford and Jenner 1975, and Ford and Jacoby, 1977) by more effectively isolating the emission lines with narrower bandpass filters and by using baked IIIa-J plates for surveys of the bright centers of M31 and M32. The characteristics of the new

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filters are λ_c 6565 (21 Å FWHM) and λ_c 5010 (23 Å FWHM). The limiting monochromatic magnitude for λ5007 emission corresponds approximately to V = 23.5.

The preceding technique in combination with the criteria that planetary nebulae must appear stellar and must not show any continuum on the off-band plate results in highly reliable identifications. Planetary nebulae are identified in NGC 185(5), NGC 147(5), and NGC 205(22) where there is no possibility of HII regions or confusion with nebulae projected from M31. Seventeen of the 21 nebulae in M32, 11 of the 22 nebulae in NGC 205, and 5 out of 5 of the nebulae in NGC 185 are identified on two or more plates (often in λ5007 and Hα). The survey of M31 gave 75 redundant identifications in the overlap of the fields. Spectrophotometric scans and photoelectrically determined monochromatic magnitudes of the brightest nebulae in each galaxy show that they are planetary nebulae.

3. PLANETARY NEBULAE IN M32

Three Hα plates and two λ5007 plates were used to identify 21 planetary nebulae in M32. Figure 1 is a reproduction of a 45-minute exposure with a λ_c 6565 (21 Å FWHM) filter and image intensifier using a IIa-D plate. Seventeen stellar nebulae and seven diffuse nebulae were identified on this plate.

The heliocentric radial velocity of M32 is approximately -190 km/s, whereas the combined systemic and projected rotational velocity of M31 in the M32 field is approximately -370 km/s. The large difference between the two velocities provides a straightforward basis for using radial velocities to establish the origin of nebulae in the M32 field. Radial velocities of 14 planetary nebulae were observed with the Image Tube Scanner (Robinson and Wampler 1972 a,b) on the Lick Observatory 120-inch telescope. The radial velocities of 2 HII regions were observed with the Intensified Image Dissector Scanner on the Kitt Peak 4-m telescope.

Ford and Jenner (1975) concluded that the planetary nebulae M32-4 (-409 km/s), M32-17 (-423 km/s), and M32-12 (-664 km/s) belong to M31. The remarkable velocity of M32-12 was determined from the lines [NII] λ6548, Hα, and [NII] λ6548, and was observed during two separate observing runs. Ford and Jenner (1976) concluded that the diffuse nebulae M32 HII-1 (-354 km/s) and M32 HII-4 (-323 km/s) are HII regions in the M31 spiral arm which projects across the M32 field.

Ford and Jenner (1975) concluded that M32-16 is a possible plate flaw, and that M32-18 and M32-19 may belong to M31. Of the remaining 19 certain identifications, 3 clearly belong to M31, 11 clearly belong to M32, and the remaining 6 are plausibly associated with M32. In summary, there are 16 planetary nebulae which are probable members of M32.

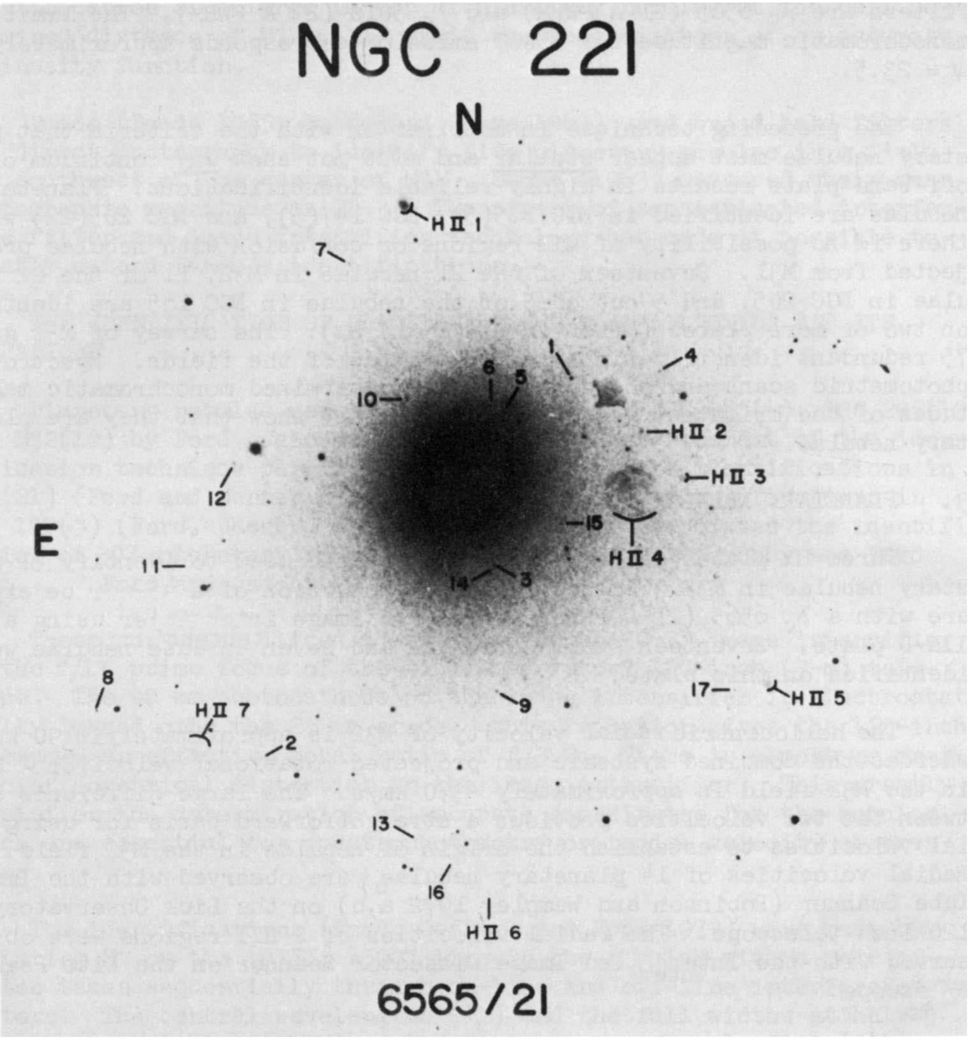

Figure 1. 17 planetary nebulae and 7 HII regions in NGC 221 (M32).

The number of nebulae detected in M32 is less than the true number for several reasons. First, nebulae cannot be detected in the saturated image of the central part of M32, and the fainter nebulae are lost in the bright, unsaturated portions of the image of the galaxy's envelope. Second, the galaxy is larger than the field of the plates. Finally, part of the nebular luminosity function is fainter than the limiting magnitude of the plates. Allowance for the first two effects results in an estimate of 34 planetary nebulae which are brighter than the faintest detected planetary. Ford and Jenner (1975) estimated that there are 2.3 mag difference between the brightest and faintest nebulae. Ford and Jacoby (1976) used photoelectric photometry to show that

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nebulae in M31 which are well above the plate limit are 2 mag fainter than the brightest nebulae. They conclude that nebulae at the plate limit are approximately 3 mag fainter than the brightest nebulae.

Surveys for planetary nebulae near the sun are thought to be complete for optically thin nebulae with a radius less than 0.4 pc (Seaton distance scale, Seaton 1968) or 0.6 pc (Cudworth scale, Cudworth 1974). Alloin, Cruz-Gonzalez, and Peimbert (1976) use a simple model to extrapolate the estimated 34 nebulae in M32 to the total number with a radius less than 0.6 pc. In their model, planetary nebulae brighten during an initial optically thick phase until they reach maximum brightness and become optically thin at $r \simeq 0.12$ pc. With the assumption that the flux of ionizing radiation from the central star remains constant and the nebulae expand at uniform velocity, the nebulae will fade rapidly with $L \propto M t^{-3}$. If all nebulae have the same mass M and the same expansion velocity of 20 km/s, the time from birth to 3 mag below maximum brightness is 14,700 years, and the time to expand to r = 0.6 pc (~ 6 mag below maximum) is 29,300 years. It follows that approximately 50% of the nebulae (both optically thick and thin) are within 3 mag of the brightest. The total number in M32 with a radius less than 0.6 pc is then equal to or greater than 64 nebulae. If, as assumed by Alloin et. al, (1976), the nebulae suddenly appear with r = 0.12 pc, the corresponding number will be 90 (the 120 estimated by Alloin et. al, 1976, is based on 2.3 mag). These estimates will be lower limits to the total number if the central star fades with a time scale ~30,000 years or the expanding shell accelerates.

Alternatively, the ratio of the total number of nebulae to bright nebulae can be estimated from a luminosity function for planetary nebulae. Ford and Jacoby (1977) determined an Hβ luminosity function from a list of 41 nearby galactic planetary nebulae presented by Cahn and Wyatt (1976). With the Cudworth distance scale the luminosity function requires that the number of bright nebulae in M32 be multiplied by 2.6 to give an estimate of 88 for the total number of nebulae. If the Seaton distance scale is used the brightest nebulae in M32 are approximately 1 mag brighter than the brightest nebulae in Cahn and Wyatt's list. The volume near the sun must then be increased to include nebulae as bright as those in M32. When this is done Cahn and Wyatt (1977) find that the ratio of the total number of nebulae to bright nebulae is 10.

A ratio as large as ten requires a luminosity function which rises steeply toward the faint end. Ford and Jenner (1975) noted that a 20 Å bandpass Hα photograph of M32 (Figure 1) which was clearly deeper than a 50 Å bandpass Hα photograph did not result in any additional identifications. This, plus the fact that the majority of the identifications are not near the plate limit, suggests the ratio is not as large as 10.

In summary, the lower limit to the number of planetary nebulae in M32 with a radius less than 0.6 pc is 64 to 88. A galactic planetary luminosity function based on the Cudworth distance scale results in an

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estimate of 88 nebulae; the Seaton scale results in an estimate as large as 340. Though this author thinks the number will be closer to 100 than to 300, a definitive estimate awaits better determinations of a planetary nebula luminosity function.

The identifications of planetary nebulae provide a direct observational basis for estimating the stellar death rate and the rate at which mass returns to the interstellar medium in M32. If planetary nebulae are within three magnitudes of maximum brightness during most of the optically thick phase, the appropriate evolutionary time is 14,700 years. The corresponding stellar death rate is $\chi_{pn} \geq 2.3 \times 10^{-3}$ per yr. If planetary nebulae are too faint to be detected during most of the optically thick phase, as implied by Alloin, et. al (1976), the death rate will be $\chi_{pn} \geq 3.9 \cdot 10^{-3}$ per yr. Either evolution of the central star or acceleration of the planetary shell will increase these estimates. Hills (1977) used theoretical considerations to estimate $\chi_{M32} = 5.4 \times 10^{-3}$. Hills uses this death rate and the observed number of planetary nebulae in M32 to calculate 6300 years for the time required for the nebulae to fade 3 mag. This value would require considerable evolution of the central star in the corresponding time.

The production rate of an interstellar medium can be directly estimated by assuming each planetary nebula represents the loss of 0.5 M⊙, which is the difference between the present main sequence turn-off mass $M \sim 1.1$ M⊙ and $M_{w.d.} \sim 0.6$ M⊙. The resultant mass loss rate is $\dot{M} \geq 1.2 \times 10^{-3}$ M⊙ per yr. The true value probably lies between this value and the value inferred from Hills' death rate, $\dot{M} = 2.7 \times 10^{-3}$ M⊙ per yr.

The total mass lost in M32 during a Hubble time can be obtained by assuming the mass loss rate has been constant (cf. Ford and Jenner 1975). The resultant mass, $M = 1.2 \times 10^7$ M⊙, is a lower limit since the product of the mass lost per star and the death rate decreases with time. Ford and Jacoby (1977) showed that with a plausible initial mass function ~25% of the original stellar mass will have been lost during a Hubble time. The value of 10^8 M⊙ (or 1.2×10^7 M⊙) is considerably larger than the upper limit of 1.5×10^6 M⊙ of HI set by Emerson's (1974) 21-cm observations of M32, or the upper limit of 10^4 M⊙ of ionized gas set by Hills and Klein's (1973) 3.8-cm observations of M32. Various possibilities for disposal of the gas are efficient low-mass star formation (Gallagher 1972; Jura 1977), stellar winds which exceed the escape velocity in M32 (Hills and Klein 1973), or loss from a supernova-heated galactic wind (Mathews and Baker 1971). The difficulty of applying the latter mechanism to M32 has been discussed by Ford and Jenner (1975). Understanding the disposal of mass lost from evolving stars in elliptical galaxies is an outstanding problem at this time.

Spectrophotometry of eleven nebulae in M32 (Jenner and Ford 1977) shows that the average nebula has comparatively strong [NII] λ6584 emission relative to Hα. Nine out of 11 nebulae have $I(\lambda6584)/I(H\alpha) \geq 0.4$. The average value of the ratio for the 11 nebulae is $0.62 \pm 0.4(\sigma)$. In contrast to M32, average nebulae in NGC 185 and NGC 205 have small values for this ratio. The stars which produce the nebulae in the three galaxies most likely have the same ages and the same masses. Consequently, though the enhancement of the nitrogen lines in M32 may be caused directly by excitation and/or density-fluctuation effects, the ultimate difference between the nebulae in M32 and those in NGC 185 and NGC 205 is probably due to differences in chemical composition.

The radial velocities of the planetary nebula can be used to estimate a virial mass for M32 which is largely model independent. The technique of measuring radial velocities with the Robinson-Wampler Image Tube Scanner on the Lick Observatory 120-inch telescope is described by Ford, Jacoby, and Jenner (1977). The weighted mean heliocentric radial velocity for eleven planetary nebulae is -194 km/s, and the weighted dispersion about the mean is 36.3 km/s. The weights were assigned according to a subjective estimate of the signal-to-noise ratio in the $H\alpha$ + [NII] lines, which were used for the velocity measurements. The dispersion of five independent measurements (different nights and different months) of M32-1 is 5.5 km/s. The average dispersion about the mean derived from the six nebulae with two or more measurements is 8.5 km/s. Adopting the latter for the dispersion due to instrumental and measuring errors, the true dispersion of the nebulae is σ_o = 35.3 km/s.

To derive a virial mass from the velocity dispersion three assumptions are made: the velocity distribution is isotropic, the observed separations result from randomly oriented true separations, and rotation is unimportant. The virial mass is then 3.8×10^8 M⊙. The true mean reciprocal radius is 1/440 pc; the mass is thus derived from halo objects which move under the gravitational influence of the majority of the mass of M32. Correction for the approximately 20% of the mass which is external to the planetaries results in a preliminary estimate of 4.8×10^8 M⊙ for M32. This is a substantial revision of previous estimates (e.g. Richstone and Sargent 1972). The most serious problem with the virial mass is the assumption that the velocities are isotropic. Additional radial velocities will be required to resolve this question.

Baade (cf. Schwarzschild 1954) noted that M32 is progressively less well resolved into stars on the northern side of the galaxy. Based on this he concluded that M32 must lie behind the M31 spiral arm which projects across the northern side of the M32 field. If the question is asked, "how much absorption is there if M32 is behind M31?", it quickly becomes apparent what observations will determine M32's position relative to M31. M32 projects very close to the ridgeline of maximum 21-cm brightness in M31 (cf. Roberts 1966; Emerson 1974). Assuming the average gas-to-dust ratio in M31 is the same as in our galaxy, the 21-cm brightness at the position of M32 can be used to predict a Balmer decrement of 5.8 for a farside nebula and 3.2 for a nearside nebula. Ford, Jacoby, and Jenner (1978) measured a Balmer decrement of 2.7 in M32-1. The difference between the observed value and the nearside value is within the observational errors for such a faint object. It should also be noted that 21-cm brightness variations across the M32 field predict a visual absorption variation from 1.4 mag to 1.0 mag across M32, and an

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E(B-V) variation from 0.48 mag to 0.33. The absence of such color gradients or perturbations in the isophotes and the absence of any small scale dust clouds projected against M32 strengthen the conclusion that M32 must be in front of M31.

4. PLANETARY NEBULAE IN NGC 185 AND NGC 147

Two λ5007 plates were used to identify 5 planetary nebulae in NGC 185 (Ford, Jenner, and Epps 1973; Ford, Jacoby, and Jenner 1977). A single Hα plate was used to identify 5 planetary nebulae in NGC 147 (Ford, Jacoby, and Jenner 1977).

Jenner and Ford (1977, 1978) have used spectrophotometry of the brightest nebula in NGC 185 to determine the chemical abundances of He, O, and N. Because of the faintness of the weak lines the determinations are difficult. With a large telescope the critically important diagnostic line [OIII]λ4363 gives a few detected counts per minute. The problem of obtaining a reliable ratio of I(λ4363) to I(λ4959) + I(λ5007) is further exacerbated by the apparent blue shift of NGC 185 which shifts λ4363 onto the cityglow line Hgλ4358.

Three independent scans were used to derive the temperature in NGC 185-1 from the ratio of I(λ4363) to I(λ4959) + I(λ5007). The temperature derived from the best Lick scan agrees well with the temperature derived from a Kitt Peak scan. Because of the problem of Hgλ4358 at Lick Observatory, the Kitt Peak scan had the largest weight. The nebular temperature is 17,900 K $\pm$ 1600 K. The resultant logarithmic oxygen and nitrogen abundances relative to hydrogen are 7.9 and $\geq$ 8.1. [OII] is very weak in the nebula; consequently the O abundance is not very dependent on corrections for ionization and thus should be reliable. Conversely the N abundance is very uncertain since it is strongly dependent on corrections for unobserved NIII.

The O abundance in NGC 185-1 is like the values obtained for the galactic halo planetaries 49 + 88°1 (8.01, Miller 1969), K 648 (7.67, Peimbert 1973), and 108-76°1 (7.44, Boeshaar, G. O. and Bond, H. E. 1977). Hawley and Miller (1977) have redetermined abundances for these nebulae using homogeneous spectrophotometric data and confirm the low O abundances. The O abundance in NGC 185-1 is quite low relative to the average galactic disk planetary (8.69, Aller 1977; 8.6 Osmer 1976). Jenner and Ford (1978) conclude that NGC 185-1 is an extreme Population II nebula and by inference that the chemical abundances in NGC 185 as a whole are extreme Population II.

The helium abundance is relatively insensitive to temperature and, in NGC 185-1, is primarily in one stage of ionization. The primary uncertainty in the abundance results from the faintness of the line λ5876. The abundance by number relative to hydrogen, determined from 4 independent scans, is 0.24 $\pm$ 0.08. The abundance differs by more than a standard deviation from the average value for galactic planetary nebulae (0.11) and probably reflects a true high abundance of helium in the nebula. Osmer (1976) found high helium abundances in some planetary nebulae in the Magellanic Clouds; however, Webster (1976) finds normal helium abundances in the planetary nebulae in the Clouds. The interpretation of the helium abundance in NGC 185-1 in terms of the cosmic abundance at the time NGC 185 formed will require careful consideration of mixing in the envelope of the star prior to the ejection of the planetary shell (cf. Torres-Peimbert and Peimbert 1971).

The mass loss rate in NGC 147 and NGC 185 can be estimated as for M32 (cf. § 3). The result is $\dot{M} \geq 1.7 \times 10^{-4}$ M⊙/yr. Ford, Jacoby, and Jenner (1977) estimated that a typical escape velocity in NGC 147 is 13 km/s. They showed that the expanding planetary shells can interact, thermalize, and power a thermally steady cool wind ($t \sim 10^4$ K) if the shells expand at ~20 km/s, as is typical in our galaxy (Wilson 1950; Bohuski and Smith 1973). If supernovae occur with a rate within an order of magnitude of one per 50 years per 10^{11} stars the cool wind will be heated sufficiently for a hot ($t \sim 10^7$ to 10^8 K) wind to blow.

The scenario of filling a galaxy with a thermally stable gas which can be heated by supernovae does not work in NGC 185 and M32. In the absence of supernovae the gas will rapidly cool and accumulate in the center of the galaxy. In the presence of supernovae the history of planetary shells will be a statistical sequence of interactions with a distribution of sizes of planetary and supernovae shells. Determination of the fate of the shells will require an analysis of these interactions.

It is interesting to note that two of the four elliptical companions of M31 - NGC 185 and NGC 205 - have conspicuous dust clouds and OB stars (Baade 1944, 1951; Hodge 1963, 1973). Hodge (1963) estimated 2×10^5 M⊙ for the mass of OB stars and gas in NGC 185. In the absence of disposal mechanisms such as galactic winds the planetary nebulae can provide the necessary mass in ~10^9 yr.

Baade (1944) estimated a distance of 204 kpc to NGC 185 and NGC 147. At this distance their projected separation (58!2) corresponds to 3.5 kpc. Based on this implied close proximity, Baade concluded that the two galaxies "obviously form a physical pair." Modern estimates of the distance to NGC 185 and NGC 147 (~600 kpc, Hodge 1963) make Baade's conclusion less obvious.

Ford, Jacoby, and Jenner (1977) used the newly determined radial velocities of NGC 147 (-168 km/s) and NGC 185 (-208 km/s) to investigate the gravitational binding of the pair. They showed that binding of NGC 185 and NGC 147 requires that the mass-to-light ratio (MLR) of the pair be at least 17 times larger than the MLR of M32. The small differences between the colors of the three galaxies (Sandage 1972; Hodge 1973b) severely constrain any attempt to account for the large MLR by postulating differences between the luminosity functions of the pair and M32. Alternatively, the assumption that the pair is bound and has the same MLR as M32 requires the observed velocity difference to be

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less than 9.7 km/s. This is incompatible with the observed difference of 40 km/s by approximately 3σ. Ford, et. al concluded that NGC 185 and NGC 147 are not a gravitationally bound system.

5. PLANETARY NEBULAE IN NGC 205

Two $\lambda 5007$ plates and two Hα plates were used to identify 22 nebulae in NGC 205 (Ford, Jenner, and Epps 1973; Ford and Jacoby 1978). Figure 2 is a reproduction of a 45-minute exposure with a λ_c 6565 (21 Å FWHM) filter and image intensifier plus a IIa-D plate. Nineteen planetary nebulae are identified with arabic numbers.

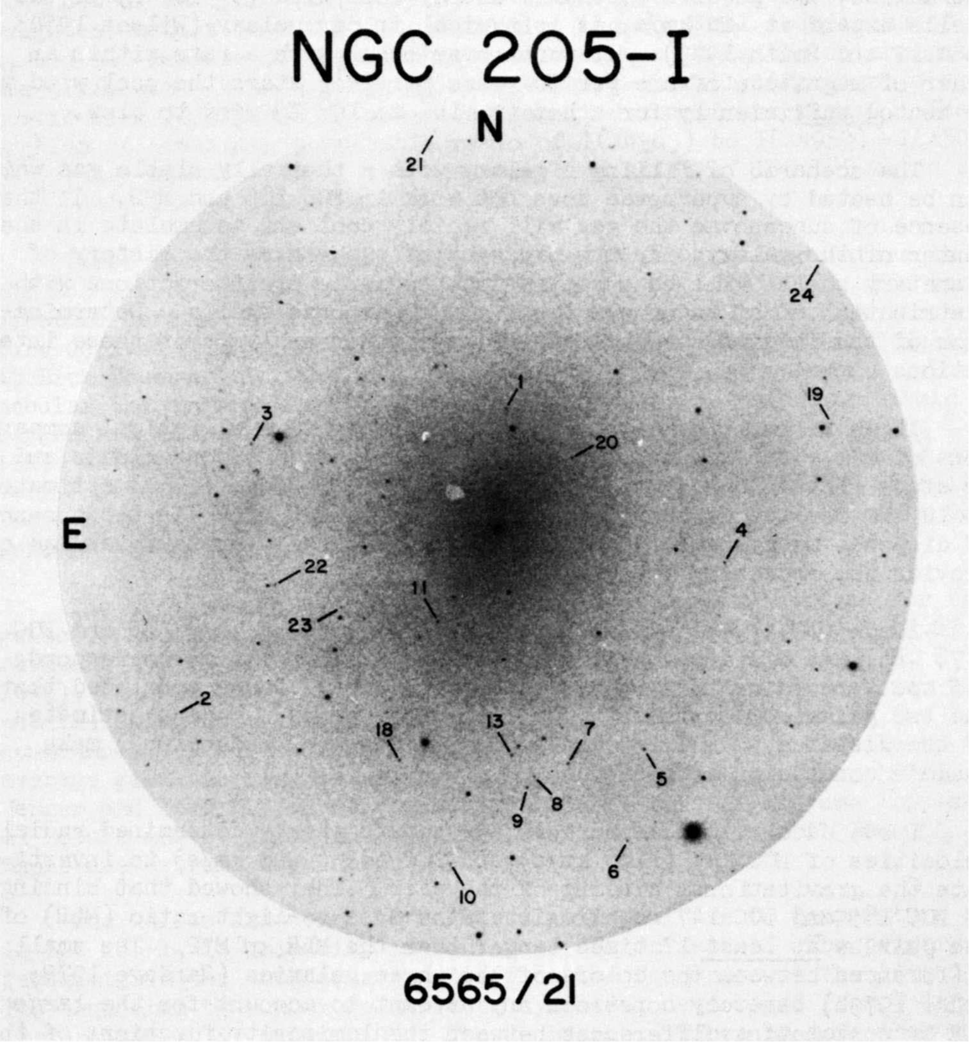

Figure 2. Identifications of 19 planetary nebulae in NGC 205.

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Two characteristics of the distribution of nebulae in NGC 205 are evident from Figure 2. First, the nebulae are not strongly concentrated to the center of the galaxy as in M32. The low surface brightness of NGC 205 would allow detections in the center of the galaxy. Consequently no correction to the observed number is required as in M32. Second, the nebulae are clumped on the side of NGC 205 toward M31. This may be simply a statistical effect. A series of photographs along the minor axis of M31 (cf. § 6 and Figure 3) shows that the nebulae belong to NGC 205 and are not the top of a halo of nebulae in M31 projected onto NGC 205. This conclusion is supported by the radial velocities of the nebulae.

The estimated number of planetary nebulae in NGC 205 with a radius less than 0.6 pc can be obtained by multiplying the estimates for M32 (cf. § 3) by 22/34. The lower limit to the number is then 41 to 57 nebulae; the latter number is equal to the estimate obtained from a galactic planetary luminosity function based on the Cudworth (1974) distance scale. Though Cahn and Wyatt's (1977) interpretation of the galactic luminosity function results in an estimate as large as 220 nebulae, this author thinks the number will be nearer the lower estimates (50 to 60) for the reasons stated in 3.

The lower limit to the mass loss rate in NGC 205 will be $\dot{M} = 7.1 \times 10^{-4}$ M⊙/yr. This mass loss rate is sufficient to account for Hodge's (1973) estimated mass for the OB stars, 2×10^5 M⊙ to 2×10^6 M⊙, in ~1.5×10^9 yr. The presence of OB stars and dust clouds in NGC 185 and NGC 205 and the relative short time required to account for the mass suggests that galactic winds have not been blowing in these galaxies in the recent past.

6. PLANETARY NEBULAE IN THE ANDROMEDA GALAXY

Ford and Jacoby (1977) used λ5007 photographs to identify 307 planetary nebulae in 7 fields of M31. Equatorial coordinates have been derived for the nebulae (Ford and Jacoby 1977). Figure 3 shows an x-y projection of 307 planetary nebulae in M31, 22 nebulae in NGC 205, and 21 nebulae in M32. The centers of NGC 205 and M32 are marked with small circles. Arp's (1964) logarithmic spiral fit of the optical arms is plotted in Figure 3 as solid lines. The figure shows the distribution of planetary nebulae relative to the large scale structure of M31.

The apparently L-shaped distribution of planetary nebulae in Figure 3 resulted from a decision to use a limited amount of telescope time to sample the major and minor axes. In particular it was decided to photograph the region between M31 and NGC 205 to establish if there is any significant projection of planetary nebulae from the disk or halo of M31 onto NGC 205. It is evident from Figure 3 that the majority of nebulae in NGC 205 are intrinsic to that galaxy.

It is apparent from Figure 3 that the planetary nebulae in M31 are strongly concentrated to its center. The concentration is even stronger

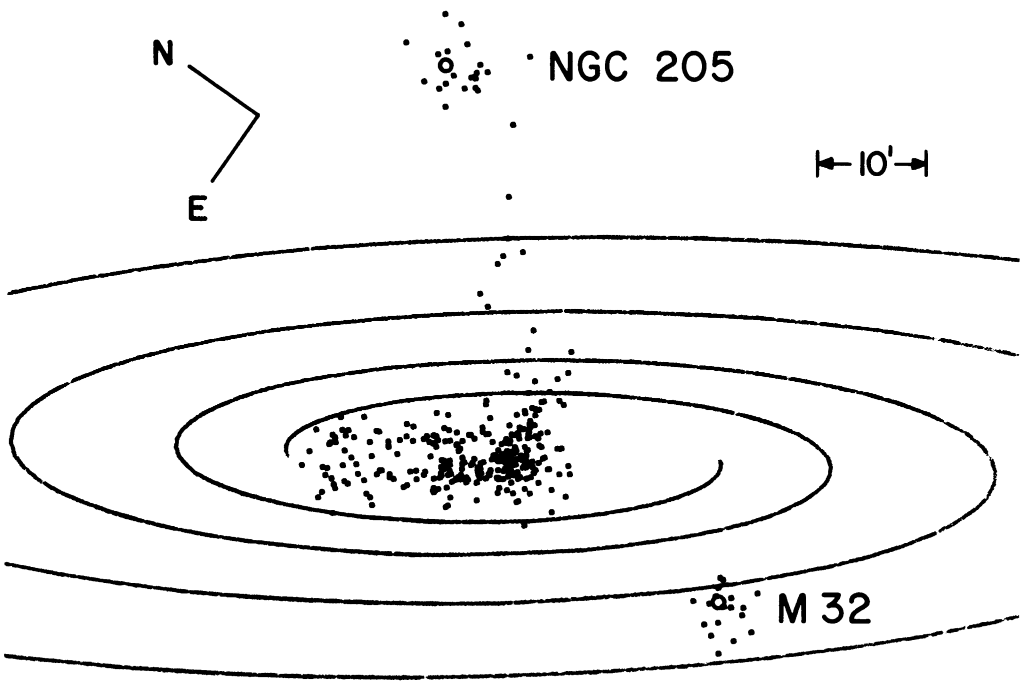

Figure 3. Positions of planetary nebulae in M31, M32, and NGC 205.

than that indicated by the observed distribution because the limiting magnitude on the survey plates rapidly decreases as the bright center of the galaxy is approached.

Ford and Jacoby (1977) obtained λ5007 monochromatic fluxes for 8 planetary nebulae in M31. The fluxes allow a comparison of the nebulae with planetary nebulae in other galaxies. The brightest nebula observed (M31-116) has a [OIII] λ5007 flux of 1.8×10^{-14} ergs/cm^2/s. The flux of the brightest planetary in the Large Magellanic Cloud (Webster 1969) would be 2.8×10^{-14} ergs/cm^2/s at the distance of M31. Although M31-116 is at the bright end of the luminosity function for M31 planetary nebulae, some of the nebulae near the center of M31 are probably even brighter. The difference between the brightest and faintest nebulae which were observed photoelectrically is more than 2 mag. The photographic data indicate that the identifications extend about 1 mag fainter; thus the identifications span approximately 3 mag.

Radial velocities have been measured for 15 planetary nebulae with the Image Tube Scanner on the 120-inch telescope. Nebulae near the minor axis of M31 were chosen in order to minimize the effects of rotation on the observed velocity dispersion. A preliminary analysis of the data gives a mean heliocentric velocity $v_{\odot} = -312$ km/s and a dispersion about the mean $\sigma = 112$ km/s (Ford and Jacoby 1978). The correction for the instrumental dispersion (~10 km/s) is negligible. A velocity dispersion determined from planetary nebulae avoids the uncertainties associated with dispersions determined from the composite spectrum of M31 (cf. Morton and Elmergreen 1976 for a discussion of such problems). The velocity dispersion determined from the planetary nebulae agrees well with Morton, Andereck, and Bernard's (1977) visually determined value of 110 km/s for the nuclear bulge of M31. Using the same technique they visually determine a velocity dispersion of 120 km/s for the nucleus of M31. The present data supports the visually determined velocity dispersions (125 km/s, Williams 1975; 120 km/s, Morton and Thuan 1973) rather than those determined from Fourier techniques (165 km/s, Sargent, Schechter, Boksenberg, and Shortridge 1977; 190 km/s, Faber and Jackson 1976).

Ford and Jacoby (1977) estimated there are a total of 2700 planetary nebulae in M31 within 3 mag of the brightest nebula. To derive this estimate they first corrected the number of nebulae in two major axis fields and two minor axis fields for those nebulae which are fainter than the limiting magnitude of the plate because of interstellar extinction in the disk of M31. The extinction was estimated from Roberts (1966) 21-cm brightness map of M31 and the assumption that the gas to dust ratio in M31 is the same as in our galaxy. The corrected number of nebulae in each field was divided by the integrated luminosity of the field to obtain a planetary nebula count-to-luminosity ratio (PLR). The data indicate that the PLR is roughly constant across M31. The PLR they adopted is 66 planetary nebulae for an integrated luminosity m(B) = 8.37 mag. An estimate of 2700 nebulae results when this value is combined with de Vaucouleur's (1958) integrated magnitude of M31, m(B) = 4.36.

Alloin et al. (1976) and Cahn and Wyatt (1976) estimated the total number of planetary nebulae in our galaxy which have a radius less than 0.6 pc. Ford and Jacoby's (1977) estimate of the equivalent number in M31 follows the analysis used for M32 (cf. § 3). The estimated lower limit to the number is 5400 to 7200 nebulae. The number estimated from a galactic planetary luminosity function based on the Cudworth (1974) distance scale is 7000 nebulae. Cahn and Wyatt's (1977) interpretation of the galactic luminosity function results in an estimate as large as 27,000 nebulae. For the reasons stated in 3, this author thinks the number will be nearer to the lower estimates than to the upper estimate.

Ford and Jacoby (1977) used the PLR to predict 775 nebulae in the nuclear bulge of M31 within 3 mag of the brightest. This is a reasonable estimate in view of the fact that an incomplete survey of the nuclear bulge (cf. Figure 3) resulted in the detection of ~300 nebulae.

For an assumed evolutionary time of 14,700 years the stellar death rate in the nuclear bulge is $\chi(\text{bulge}) \geq 5.3\times10^{-2}$ stars per yr. The resulting mass loss rate in the nuclear bulge is $\dot{M} \geq 2.6\times10^{-2}\ M_\odot$ per yr.

The mass of HI gas in the nuclear disk, determined from Rubin and Ford's (1970) interpretation of Roberts (1966) 21-cm observations of M31, is $M(HI) \geq 6\times10^{7}\ M_\odot$. Mass lost from evolving stars is sufficient in 2×10^{9} years to account for the observed HI mass in the nuclear disk. Prominent dust lanes in the nuclear disk of M31 (Baade 1963; Johnson and Hanna 1972) suggest there may be a considerable mass of molecular hydrogen in the nuclear disk of M31. Scoville, Soloman, and Jefferts (1974) estimate that the mass of molecular hydrogen in the center of our galaxy exceeds the HI mass by a factor of 20 to 50. If this is also true in M31 the mass of the nuclear disk will be $\sim10^{9}\ M_\odot$, which is approximately 25% of the total mass in the nuclear bulge indicated by the nuclear rotation curve (Rubin and Ford 1970). Ford and Jacoby (1977) show that it is plausible that $\sim$25% of the mass of the original nuclear bulge may now be in the nuclear disk.

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DISCUSSION

Peimbert, M.: Have you looked at the variation of the ratio of planetary nebulae count to local mass density as a function of distance to the center of M31?

Ford: We have avoided making planetary-to-light or planetary-to-mass estimates in the very center of M31 because of the differentiation of the luminosity function that resulted from our procedure of taking successively shorter exposures as we approach the center. We have plans to use different techniques to avoid the latter problem.

Cudworth: With so few planetaries observed with radial velocities in NGC 147 and 185 and with large velocity dispersions in the Galaxy and in M31, should we take the velocity of a planetary as the velocity of the galaxy?

Ford: We used radial velocities of eleven planetaries in M32 to determine a velocity dispersion of 35 kms^{-1}. We have used the light distributions, integrated magnitudes, and the assumption of a constant mass-to-light ratio to virially scale the velocity distribution in M32 to these two galaxies. The result is $\sim$8 kms^{-1} in the line of sight for NGC 147 and 17 kms^{-1} for NGC 185. With two velocities in the latter, the dispersion should introduce almost no uncertainty in our mean velocity.

Dufour: Have you attempted or had any success in finding planetary nebulae in the Local Group irregular galaxies NGC 6822 or IC 1613?

Ford: We identified approximately five planetary nebulae in NGC 6822 and didn't find any in IC 1613. We found as many as 10 planetaries in M33.