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PLANETARY NEBULAE IN LOCAL GROUP GALAXIES. V. THE ANDROMEDA GALAXY

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ABSTRACT

We present identifications of 315 planetary nebulae in seven fields of M31. The nebulae are isolated by comparing pairs of λ5007 on-line and off-line image intensifier photographs of fields along the major axis and minor axis of M31. Equatorial coordinates are derived for the nebulae; an *x-y* projection of the coordinates shows the strong concentration of the planetary nebulae to the center of M31. Photoelectric photometry of typical bright planetary nebulae in M31 yields $F_\lambda 5007 \sim 2 \times 10^{-14}$ ergs cm^{-2} s^{-1}. The difference between the brightest and faintest identified nebulae is approximately 3 mag. We correct the observed numbers of nebulae in four fields for interstellar extinction in the disk of M31 to estimate the true numbers. A derived planetary count-to-luminosity ratio (PLR) is roughly constant across M31 and indicates a total of 2700 planetary nebulae in M31 within 3 mag of the brightest nebula. A simple model for the luminosity evolution of planetary nebulae is used to predict a lower limit of 5400 planetary nebulae in M31 with radii less than 0.6 pc. Comparison of the number of bright planetary nebulae in M31 with the luminosity function of solar-neighborhood planetary nebulae results in an estimate of 7,000–27,000 planetary nebulae in M31 with radii less than 0.6 pc, depending on the distance scale used. We conclude that the number will be much closer to 10,000 than to 30,000. The PLR is used to predict 775 planetary nebulae in the nuclear bulge within 3 mag of the brightest. For an assumed time of 14,700 years to evolve from the brightest planetary nebula to the faintest, the stellar death rate in the nuclear bulge is estimated to be 5.3×10^{-2} stars yr^{-1}. The resultant mass loss rate in the nuclear bulge is $2.6 \times 10^{-2}\ M_\odot$ yr^{-1}. Mass lost from evolving stars is sufficient in 2×10^9 years to account for the observed H I mass in the nuclear disk. We conclude that the gas and dust in the nuclear disk originate in evolving stars in the nuclear bulge. We show that it is plausible that ~25% of the mass of the original nuclear bulge may now be in the nuclear disk.

Subject headings: galaxies: individual — galaxies: stellar content — galaxies: structure — nebulae: planetary — stars: mass loss

I. INTRODUCTION

The identification and observation of planetary nebulae in the Andromeda galaxy (M31) provide a powerful means of studying its 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 in M31.

The number of planetary nebulae found in M31 is a direct check of theoretical estimates of the death rate of old stars. The number of planetary nebulae in the nuclear bulge provides an observational basis for estimating the production rate of an interstellar medium in the center of a spiral galaxy.

The identification of planetary nebulae in M31 leads to a better understanding of the spatial distribution and luminosity function of planetaries in our Galaxy. Unlike 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. Because of the lack of accurate distances to planetary nebulae in our Galaxy, their luminosity function is poorly determined. The identification of a large number of planetaries at the well determined distance of M31 permits the determination of an accurate luminosity function.

Previous papers of this series presented identifications and observations of the planetary nebulae in the elliptical companions of M31: M32 (Ford, Jenner, and Epps 1973 [Paper I]; Ford and Jenner 1975 [Paper II]; Ford and Jenner 1976 [Paper III], NGC 205 (Paper I), and NGC 185 and NGC 147 (Paper I and Ford, Jacoby, and Jenner 1976 [Paper IV]). In this paper we summarize our identifications of 315 planetary nebulae in M31. Previously Baade

(Baade 1955; Baade and Swope 1963) identified five planetary nebulae in a field 90′ southwest of the center of M31.

In § II we discuss the observations and present representative photographs of fields centered along the major axis and centered on the nucleus. In § III we present monochromatic photoelectric [O III] λ5007 fluxes for eight planetary nebulae in M31. In § IV we estimate the total number of planetary nebulae in M31 to a given limiting magnitude and the rate at which the planetary nebulae in M31's nuclear bulge produce an interstellar medium.

In future papers we will present finding charts and coordinates for the planetary nebulae identified in M31, discuss radial velocity observations of the nebulae, and determine a luminosity function for the nebulae.

II. IDENTIFICATIONS

The planetary nebulae in M31 were identified by isolating the emission line [O III] λ5007 with pairs of on-line and off-line photographs. The photographs were taken with a Westinghouse WL-30677 image intensifier at the f/5 prime focus of the Lick Observatory 120 inch (3 m) telescope. The central wavelengths (λ_c) and the full widths at half-maximum transmission (FWHM) of the filter pair are λ_c5010 (23 Å FWHM) and λ_c5300 (200 Å FWHM). The identification technique and the characteristics of the image intensifier and interference filters are discussed in detail in Papers I and II.

Exposures of the major and minor axis fields were typically 45 minutes with IIa-D photographic plates and the on-line filter. Figure 1 (Plate 16) reproduces the on-line and off-line photographs of a major axis field centered at $\alpha(1975.0) = 00^h41^m42^s.9$ and $\delta(1975.0) = 41°13'06''$. In a system of nebular coordinates centered on the nucleus with X along the major axis and positive to the northeast, Y positive to the southeast, and the position angle of the major axis taken to be 37°.7, the coordinates of the center of Figure 1 are $X = 6'.46$ and $Y = -0'.09$. The 95 planetary nebulae identified in this field are marked with arabic numerals in Figure 1. A low-surface-brightness diffuse nebula near the northwest edge of the field is identified as an H II region. The elliptical isophotes and shadow of a mask at the edge of the field show that the background in Figure 1 is the stellar continuum of the nuclear bulge seen through the 23 Å FWHM filter.

Figure 2 (Plate 17) shows identifications of 49 planetary nebulae in a major axis field centered at $\alpha(1975.0) = 00^h42^m08^s.8$ and $\delta(1975.0) = 41°19'01''$. The nebular coordinates of the field are $X = 14'.12$ and $Y = 0'.13$. There are seven identifications in common in the small overlap of Figures 1 and 2.

The brightness of the stellar continuum transmitted by the 23 Å FWHM filter determines the limiting magnitude of the planetaries in the different fields. In order to identify planetaries throughout the bright central field ($r \approx 900$ pc) we took a sequence of 10 minute, 20 minute, and 40 minute photographs with the high information capacity IIIa-J plate. The center of the plate is not saturated with the shortest exposure; consequently planetaries could be identified to within 5″ (17 pc in projection) of the nucleus. The longer exposures, which saturate the central region, progressively reveal fainter planetaries in the unsaturated portions of the plate.

Figure 3 (Plate 18) is a reproduction of the 10 minute photograph. Sixty-eight planetary nebulae were identified with this short exposure. The most luminous planetaries in M31 will be among these identifications.

Our assertion that the stellar nebulae in Figures 1–3 are in fact planetary nebulae is based on several considerations. The magnitudes of the brightest nebulae and the magnitude range of the nebulae are approximately equal to those found in the elliptical companions of M31 where there is no possibility of confusion with H II regions or peculiar young stars. In galaxies such as NGC 6822 and M33 where the nebulae are predominantly H II regions we find that the H II regions typically are resolved and show a weak continuum on the off-line plates. Finally, the nebulae show no tendency to form a spiral pattern or associate with the dust seen in Figure 1.

We derived equatorial coordinates for 315 nebulae on nine plates using the procedure described in Paper II. For 75 nebulae, identifications and positions were independently determined from two or more plates. This redundancy gives us considerable confidence in the reality of the identifications and in the accuracy of the derived coordinates.

Plotting the positions in an x-y projection (standard coordinates) provides a convenient means of illustrating the distribution of the planetary nebulae in M31. Figure 4 shows a plot of the 315 planetary nebulae identified in M31, 19 planetary nebulae identified in the elliptical companion NGC 221 (M32), and 21 planetary nebulae identified in the elliptical companion NGC 205. 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 4 as solid lines. This shows the distribution of the planetary nebulae relative to the large scale structure of M31.

The apparently L-shaped distribution of planetary nebulae in Figure 4 resulted from our decision to use a limited amount of telescope time to sample the major and minor axes. In particular, we chose to photograph the region between M31 and NGC 205 to establish if there is any significant projection of planetary nebulae from the disk of M31 onto NGC 205. It is evident from Figure 4 that the majority of nebulae in NGC 205 are intrinsic to that galaxy.

Figure 5 clarifies the manner in which the apparent distribution of nebulae in Figure 4 has been determined by the choice of fields. The centers of the fields are marked by crosses and the boundaries by dashed circles. As in Figure 4, Arp's (1964) logarithmic fit to the spiral arms is represented by solid lines.

It is apparent from Figures 4 and 5 that the planetary nebulae in M31 are strongly concentrated to its center.

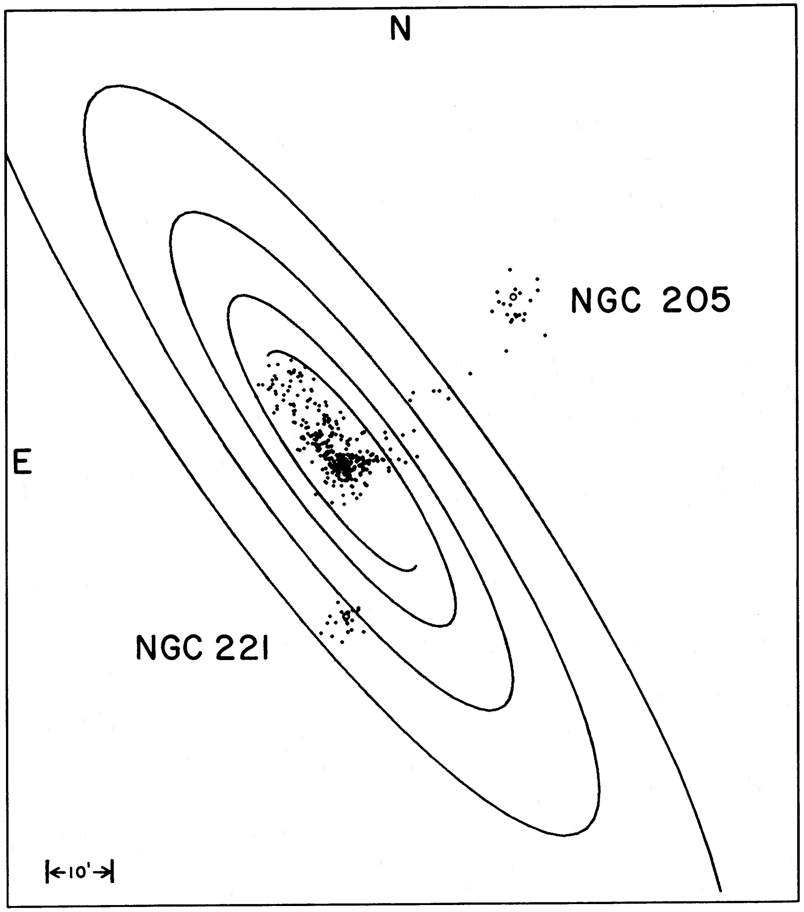

FIG. 4

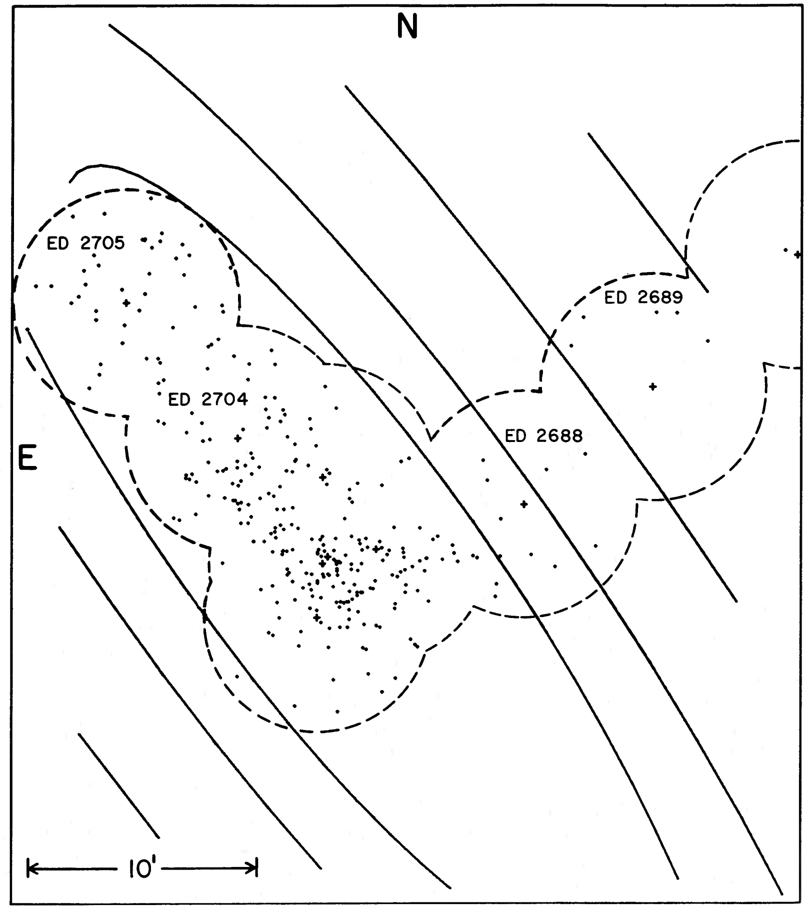

FIG. 5

FIG. 4.—Positions of 315 planetary nebulae in M31 and its elliptical galaxy companions NGC 205 and NGC 221 (M32). The centers of NGC 205 and NGC 221 are marked with small circles. The logarithmic spiral arms are Arp's (1964) fit of the optical arms.

FIG. 5.—Positions of planetary nebulae in M31. Crosses mark the centers of the fields photographed along the major and minor axis of the galaxy. Solid lines mark Arp's (1964) logarithmic fit of the optical spiral arms. The prefixed numbers are the plate numbers of the four fields discussed in text. The increasing surface brightness in the center of the galaxy results in a decreasing limiting magnitude toward the center of the galaxy. Consequently the concentration of planetary nebulae to the center of M31 is even stronger than indicated by this figure.

The concentration is even stronger than that indicated by the observed distribution since the limiting magnitude on our survey plates rapidly decreases as the bright center of the galaxy is approached. Consequently, the fraction of the luminosity function which is sampled steadily decreases toward the center. Allowance for this effect will be made in the estimates of the total number of nebulae in M31.

III. PHOTOMETRY

Photoelectric fluxes of planetary nebulae in M31 allow a comparison of the nebulae with planetary nebulae in other galaxies. Fluxes for eight planetary nebulae have been obtained at the f/17 Cassegrain focus of the Lick 120 inch (3 m) telescope with a pulse-counting EMI 9658 photomultiplier cooled to dry-ice temperature. The same interference filter used for the photographic identifications was again used to isolate the emission at λ5007. Aperture sizes of 10″ or 6″ were used to observe the stellar planetary nebulae in M31. Observations are referenced to the Galactic nebula IC 351 which has a measured flux of 4.9×10^{-11} ergs cm^{-2} s^{-1} in [O III] λ5007 (Collins, Daub, and O'Dell 1961). This planetary nebula, observed through a 25″ aperture, was used as a flux standard since it has a small angular diameter of 8″. The flux calibrated stars HZ 15 and BD +25°3941 (Stone 1974) were also observed as an additional check on the flux of IC 351. Corrections for atmospheric extinction were made with mean extinction coefficients for Lick Observatory.

Observed fluxes for eight planetary nebulae in M31 are presented in Table 1. Column (1) is the designation for the nebula, column (2) is the total observing time for that nebula, column (3) is the logarithm of the flux, column (4) is the estimated error in the logarithmic flux, based on multiple measurements, and column (5) is the number of independent observations. The error is the internal error derived from variations in the 10 s integrations which constitute an observation. The error in converting count rates to energy units through IC 351 adds 0.05 to the error of the logarithmic flux. This is due to the uncertainty in the absolute flux of IC 351 and the errors in observation and extinction.

The brightest planetary nebula in Table 1 (M31–116) has a [O III] λ5007 flux of 1.8×10^{-14} ergs cm^{-2} s^{-1}.

TABLE 1

PHOTOMETRY OF PLANETARY NEBULAE IN M31

Object M31– (1)	Observation Time (s) (2)	Log $F_{\lambda 5007}$ (ergs cm^{-2} s^{-1}) (3)	Error (4)	N (5)
116.....	720	−13.74	0.03	1
240.....	1600	−13.86	0.02	3
245.....	960	−14.20	0.11	1
251.....	720	−14.24	0.05	1
252.....	560	−14.18	0.09	1
256.....	480	−14.15	0.10	1
270.....	880	−14.57	0.15	1
290.....	880	−14.51	0.14	2

The flux of the brightest planetary in the Large Magellanic Cloud (Webster 1969) would be 2.8×10^{-14} ergs cm^{-2} s^{-1} at the distance of M31. Although M31–116 is at the bright end of the luminosity function for M31 planetary nebulae, some of the planetary nebulae identified in Figure 3 are probably even brighter. Table 1 shows that the difference between the brightest and faintest planetary nebulae is more than 2 mag. Reliable photometry of the faintest identified nebulae is unobtainable at this time, but the photographic data indicate that the identifications extend about 1 mag fainter than the faintest nebula in Table 1. This difference of 3 mag compares well to the estimate of 2.5 mag made for the planetary nebula identifications in M32 (Paper II).

IV. DISCUSSION

a) *Estimated Number of Planetary Nebulae in M31*

To estimate the total number of planetary nebulae in M31 we first determine the number of nebulae in two major-axis and two minor-axis fields. These numbers are then corrected for nebulae which are fainter than the limiting magnitude of the plate because of interstellar extinction in the disk of M31. The corrected number in each field is divided by the integrated luminosity of the field to obtain a planetary count-to-luminosity ratio (PLR). An adopted PLR is then multiplied by the integrated luminosity in any particular area of M31 to estimate the number of nebulae in that area.

In fields centered on or near the nucleus of M31 the limiting magnitude of the photographs decreases at the same rapid rate that the brightness increases toward the nucleus. Rather than try to deal with the large corrections required to account for this effect, we chose to use major and minor axis fields where the limiting magnitude is relatively constant across the field.

The plate numbers, dates, and exposure times of the four fields are given in the column headings of Table 2. The equatorial coordinates of the field centers are given in the first two rows of Table 2; the nebular coordinates, in the third and fourth rows. The fifth row gives the number of planetary nebulae identified in each field. Figures 1 and 2 correspond respectively to plates ED 2704 and ED 2705.

The number of planetaries identified in a field to a given limiting magnitude is less than the true number to the same limiting magnitude because of the interstellar extinction suffered by those nebulae which are on the far side of M31. In the nuclear bulge, and probably throughout the disk of M31, the scale height of the planetaries will be much larger than the scale height of the interstellar dust. We adopt an idealized model in which the dust is continuously distributed in a thin sheet with half the planetaries on the far side of the sheet. If the extinction in the sheet is so large that the brightest farside planetary is fainter than the limiting magnitude of the plate, then only the nearside planetaries will be seen. Thus, it is clear

TABLE 2

Planetary Nebulae in Four Fields of M31

Parameter	ED 2688 1973 Sept. 27/28 30^m	ED 2689 1973 Sept. 27/28 45^m	ED 2704 1973 Sept. 28/29 45^m	ED 2705 1973 Sept. 28/29 45^m
α(1975.0)	00^{h}40^{m}36^{s}7	00^{h}40^{m}06^{s}4	00^{h}41^{m}42^{s}9	00^{h}42^{m}08^{s}8
δ(1975.0)	41°10′12″	41′15′19″	41°13′06″	41°19′01″
$X_{\rm Nebular}$	−3′44	−2′86	6′46	14′12
$Y_{\rm Nebular}$	−8′17	−15′81	−0′09	0′13
N(PN, observed)	20	7	95	49
$\tau_{5007\,Å}$	1.14	1.02	0.46	0.68
N_0(PN, estimated)	31	11	118	66
L_B(integrated)	0.820	0.221	2.512	1*
N_0(PN)/L_B	38	50	47	66

* The integrated luminosity adopted for $m_B = 8.37$.

that the true number of planetaries can exceed the observed number by as much as a factor of 2.

We shall now derive the relationship between the true number of planetary nebulae N_0(PN) and the observed number N(PN, observed). We first derive the relationship between the true brightness density function $n_0(l)$ and the observed brightness density function $n(l)$, where $n(l)\,dl$ is the observed number of nebulae with a monochromatic brightness between l and $l + dl$. We denote the brightness of the brightest nebulae by l_1 and the brightness of nebulae at the plate limit by l_2. Because approximately half the nebulae will be dimmed by the factor $e^{-\tau}$, the observed density will be one half of the true density for brightnesses between l_1 and $l_1e^{-\tau}$; that is,

$$n(l) = \tfrac{1}{2}n_0(l), \qquad l_1e^{-\tau} \leq l \leq l_1 . \tag{1}$$

At a brightness l fainter than $l_1e^{-\tau}$ the observed density is again depleted by a factor of 2 relative to the true density. However, the density at brightness l is enhanced by the half of the true density at le^{τ} which now appears at brightness l due to the extinction $e^{-\tau}$. We thus have

$$n(l) = \tfrac{1}{2}n_0(l) + \tfrac{1}{2}n_0(le^{\tau}), \quad l_2 \leq l < l_1e^{-\tau} . \tag{2}$$

The true number of nebulae between l_1 and l_2 will be

$$\int_{l_2}^{l_1} n_0(l)\,dl$$

and the observed number will be

$$\int_{l_2}^{l_1} n(l)\,dl .$$

As previously noted, if the plate limit is not faint enough to see the farside planetaries ($l_2 > l_1e^{-\tau}$), we will have $N_0 = 2N_{\rm obs}$, no matter what form the density function has. When the plate limit is faint enough to see the farside, we must know the functional form of the density to evaluate the integral of equation (2).

If we assume the luminosity function of planetary nebulae is uniformly populated [$n_0(l)$ = constant], integration of equation (2) gives

$$N_0(\mathrm{PN}) = \frac{N(\mathrm{PN,\ observed})}{1 - \frac{1}{2}[l_1/(l_1 - l_2)](1 - e^{-\tau})}, \quad l_2 \leq l_1e^{-\tau} . \tag{3}$$

Alternatively, if we assume that the luminosity function is a Gaussian density function, we obtain an expression of Gaussian distribution functions which is similar to equation (3). Because the functional form of the planetary nebula luminosity function is not well determined, we make the simple assumption that the luminosity function is constant and use equation (3) in subsequent calculations.

To estimate τ we first assume a relationship between the color excess $E(B - V)$ and the projected neutral hydrogen density. We use

$$E(B - V) = 0.2\ \mathrm{mag} \times 10^{-21}\ \mathrm{cm}^2\ \mathrm{per\ atom}\,, \tag{4}$$

which is typical in our Galaxy (Spitzer and Jenkins 1975). Following Roberts (1966), the projected neutral hydrogen density in M31 is given by

$$n_{\rm H\,I} = 1.83 \times 10^{18} \int_{-\infty}^{\infty} T_B\,dv\,, \tag{5}$$

where T_B is the antenna brightness temperature. When equations (2) and (3) are combined with $A_{5007\,Å} = 3.36E(B - V)$, we obtain

$$\tau_{5007} = 1.13 \times 10^{-3} \int_{-\infty}^{\infty} T_B\,dv\,. \tag{6}$$

The values of the integral in equation (5) were obtained by plotting the centers of the fields in Table 2 onto Roberts's (1966) contour map of the integrated 21 cm brightness temperature in M31. The resultant values of τ are given in the sixth row of Table 2.

In § III we estimated that the difference between the brightest and faintest planetary nebula is approximately a factor of 16 (3 mag), which gives $l_1 = 16l_2$. Equation (3) can now be used with the optical depth τ to estimate the number of nebulae which are within

3 mag of the brightest planetary nebula. These numbers, N_0(PN, estimated), are given in the seventh row of Table 2.

The integrated blue light (L_B) in each field was obtained by numerically integrating de Vaucouleurs's (1958) luminosity profiles for M31. The normalized integrated luminosities are given in the eighth row of Table 2; a value of unity was adopted for $m_B = 8.37$. The estimated number of planetary nebulae in each field was divided by the luminosity (L_B) to give the PLR tabulated in the ninth row of Table 2.

The minor axis field of plate ED 2688 has a PLR (38) which is 34% less than the average PLR of the two major-axis fields. This difference is probably due to the fact that the exposure time for ED 2688 was two-thirds that of the major-axis fields. The PLR (50) for the minor-axis field ED 2689 agrees reasonably well with those of the major-axis fields. However, the statistical uncertainty in the small number of planetaries (7) in that field does not allow a reliable comparison with the other fields.

As previously noted, the limiting magnitude in a field decreases as the galaxy light increases. Since the average surface brightness in field ED 2704 is approximately 1.0 mag brighter than in field ED 2705, the limiting magnitude will be correspondingly brighter. If the planetary luminosity function is uniformly populated and the PLR is constant, the observed PLR in field 2704 will be approximately 16% less than in field 2705. This accounts for half of the difference between the two fields; the remaining difference is possibly due to effects such as a nonuniform distribution of the dust.

We conclude that our data from major and minor axis fields are consistent with the hypothesis that the planetary count-to-luminosity ratio is constant throughout M31. We adopt the value of 66 planetary nebulae for an integrated luminosity which corresponds to $m_B = 8.37$ mag. For the integrated magnitude of M31 we use de Vaucouleurs's (1958) value $m_B = 4.36$. Combining this with our adopted PLR = 66, we estimate that there are 2700 planetary nebulae in M31 within 3 mag of the brightest planetary nebula.

To estimate a lower limit to the number of planetary nebulae in M31 we follow the analysis presented by Alloin, Cruz-González, and Peimbert (1976). This analysis, when based on Cudworth's (1974) distance scale for Galactic planetary nebulae, assumes that planetary nebulae brighten during an initial optically thick phase until they reach maximum brightness and become optically thin at $r \approx 0.12$ pc. With the assumptions 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 $L \propto M^2 t^{-3}$. If the central star fades with a time scale $\sim$30,000 years or the expanding shell accelerates, this analysis will underestimate the number of faint nebulae.

We assume that all nebulae have the same mass M and the same expansion velocity of 20 km s^{-1}, which is the value appropriate for most Galactic planetary nebulae (Wilson 1950; Bohuski and Smith 1973). The time from birth to 3 mag below maximum brightness is then 14,700 years, and the time to expand to $r = 0.6$ pc ($\sim$6 mag below maximum) is 29,300 years. Because surveys for planetary nebulae near the Sun are complete only for nebulae with $r \lesssim 0.6$ pc (Alloin, Cruz-González, and Peimbert 1976), 29,300 years is a convenient baseline for computing the total number of nebulae. It follows that approximately 50% of the nebulae (both optically thick and optically thin) are within 3 mag of the brightest, and that the total number in M31 with radii less than 0.6 pc is equal to or greater than 2700/0.5 = 5400 nebulae. This number is close to Alloin, Cruz-González, and Peimbert's (1976) estimated lower limit (5000) to the number of planetary nebulae ($r \leq 0.6$) in our Galaxy.

Alternatively, the ratio of the total number of nebulae to bright nebulae in M31 can be directly estimated from a luminosity function for planetary nebulae. Ideally the luminosity function should be obtained from homogeneous photometry to a specified limiting magnitude of a group of planetary nebulae at a well determined distance (e.g., the planetary nebulae in the Magellanic Clouds). To date, however, the luminosity function must be constructed from the heterogeneous photometry of galactic planetaries whose distances are not well determined.

With these problems in mind, we proceed to determine a luminosity function from a list of 41 nearby Galactic planetary nebulae presented by Cahn and Wyatt (1976). The nebulae were selected by those authors to constitute a complete list of all optically thin nebulae with radii in the range 0.08–0.4 pc and a projected distance from the Sun less than 1.1 kpc using the Seaton distance scale (Seaton 1968). Hβ luminosities for the nebulae were taken from Cahn's (1977) revision of Cahn and Kaler's (1971) catalog of distances to planetary nebulae. We expect the resultant luminosity function to be similar to the [O III] luminosity function which would be appropriate for our λ5007 identifications. The Hβ luminosity function has 16 of the 41 nebulae within 3 mag of the brightest nebula. This implies that our estimate of 2700 nebulae within 3 mag of the brightest should be multiplied by a factor of 2.6 to obtain an estimate of 7,000 planetary nebulae in M31.

A considerable error can result from this procedure if the sample of 41 nearby planetary nebulae does not contain nebulae as luminous as those in the M31 fields which were used to determine the PLR. A comparison of the luminosities of the two brightest nebulae in Table 1 with the two most luminous nebulae in Cahn and Wyatt's list (NGC 7009 and NGC 6302) shows that in fact the former are approximately 1.1 mag more luminous than the latter, provided the Seaton distance scale is used. If the volume near the Sun is increased enough to include nebulae which are as luminous as those in M31, the ratio of the total number of nebulae to bright nebulae becomes 10 (Cahn and Wyatt 1977).

Though we cannot rule out a ratio of 10, we think that a ratio that large is unlikely. Such a large ratio requires a luminosity function which rises steeply toward the faint end. Contrary to this, our plates do not show a large number of planetaries near the plate limit (cf. Figs. 1 and 2). In Paper II it was noted that the luminosity function in M32 does not appear to rise steeply toward the faint end. This conclusion was based on the fact that an Hα photograph with a 20 Å bandpass which was clearly deeper than a 50 Å bandpass Hα photograph did not result in any additional identifications.

Cudworth (1974) has developed a distance scale for planetary nebulae which is based on statistical parallaxes. The ratio of Cudworth's distance scale to Seaton's scale is 1.43. Consequently, with the Cudworth scale the brightest planetaries in Cahn and Wyatt's list have luminosities which are nearly equal to those of the brightest planetary nebulae in Table 1. If the Cudworth scale is correct, the estimate of 7000 planetary nebulae in M31 should be reasonably correct.

We conclude that the number of planetary nebulae in M31 is between 5400 and 27,000, with a likely value which will be much closer to 10,000 than to 30,000. This unsatisfactorily large range is very close to that estimated by Alloin, Cruz-González, and Peimbert (1976) for our Galaxy. Our estimates are on the low side of Cahn and Wyatt's (1976) estimate of 38,000 $\pm$ 12,000 nebulae in the Galaxy. We think that a definitive estimate of the number of planetary nebulae in M31 will require the determination and comparison of the luminosity functions in M31 and the Magellanic Clouds.

b) Mass Loss in the Nuclear Bulge of M31

The spectral energy distributions and light distributions in the bulges of spiral galaxies are similar to those in elliptical galaxies. On the basis of these similarities Faber and Gallagher (1976) suggested that the mass lost from evolving stars in the bulges of spirals may be disposed of by the same processes proposed for elliptical galaxies. These processes include supernova-powered winds (Mathews and Baker 1971) and formation of low-mass stars (Faber and Gallagher 1976). Jura (1977) has discussed the latter proposal quantitatively. Though either or both processes may occur in the bulges of spiral galaxies, we suggest that in the bulge of M31 the majority of the mass shed by evolving stars accumulates in the nuclear disk.

Prominent spiral arms, as marked by H II regions and O and B stars, can be traced to 20′ from the nucleus of M31 (Baade 1963; Arp 1964). This distance approximately corresponds to the extent of the nuclear bulge. Interior to 20′ the presence of a disk is revealed by 21 cm emission (Roberts 1966) and spiral structure marked by dust lanes (Baade 1963; cf. Fig. 1). The presence of the dust suggests that the disk had its origin in mass lost from stars. The identification of planetary nebulae in the bulge provides an observational basis for testing the plausibility of the hypothesis that mass lost from evolving stars in the nuclear bulge accumulates in the nuclear disk.

De Vaucouleurs (1958) showed that the light distribution in the bulge of M31 can be decomposed into a flat component which represents the disk, and a spheroidal component which closely follows the distribution of light in elliptical galaxies. We define the extent of the nuclear bulge as the major axis radius where the two components are equally bright. De Vaucouleurs's elliptical isophote ($2a \times 2b = 31' \times 12'.4$) through this radius ($15'.5 = 3100$ pc) includes more than 99% of the light of the spheroidal component. The integrated magnitude of the light within this isophote is $m_B = 5.695$. Using our estimate of 66 planetary nebulae for $m_B = 8.37$, we estimate that there will be 775 planetary nebulae in the nuclear bulge which are within 3 mag of the brightest planetary nebula. This number is very reasonable in view of the fact that our incomplete survey of the bulge resulted in identifications of 300 planetary nebulae (cf. Figs. 3 and 4).

We assume that every evolving star in the nuclear bulge goes through a planetary nebula stage. With this assumption and our previous estimate of 14,700 years for a planetary nebula to evolve 3 mag in brightness (cf. § IV*a*), the death rate of stars in the nuclear bulge is $\chi_{\text{death}} = 5.3 \times 10^{-2}$ stars yr^{-1}. Since stars at the main-sequence turnoff will have a mass of $\sim 1.1\ M_\odot$ and white dwarfs a mass of $\sim 0.6\ M_\odot$, each star loses $\sim 0.5\ M_\odot$ during its evolution. The resultant rate of mass loss in the nuclear bulge is $\dot{M} = 2.6 \times 10^{-2}\ M_\odot$ yr^{-1}. The most uncertain quantity in this estimate is the evolution time.

The mass of gas in the nuclear disk, determined from Rubin and Ford's (1970) interpretation of Roberts's (1966) 21 cm observations of M31, is $M_{\text{H I}} \geq 6 \times 10^7\ M_\odot$. This is almost certainly a lower limit to the mass of the disk since molecular hydrogen is usually associated with dust. Scoville, Solomon, and Jefferts (1974) estimate that the mass of molecular hydrogen in the center of our Galaxy exceeds the H I mass by a factor of 20 to 50. If this is also true in M31, the mass of the nuclear disk will be $\sim 10^9\ M_\odot$, which is approximately 25% of the total mass in the nuclear bulge indicated by the nuclear rotation curve (Rubin and Ford 1970).

Our estimated rate of mass loss will provide the observed mass of gas in the nuclear disk in 2×10^9 years. To account for the more likely value of $\sim 10^9\ M_\odot$, we must show that $\sim 25\%$ of the original stellar mass in the nuclear bulge has been lost through stellar evolution. Though we do not know the precise form of the initial mass function (IMF) in the nuclear bulge, we can show that such a figure is plausible. Tinsley and Gunn (1976) showed that evolution of the power law IMF,

$$\frac{dN}{dm} = Am^{-1}\,, \quad 0.1\ M_\odot \leq m \leq 2.0\ M_\odot\,, \tag{7}$$

can adequately represent the present colors of elliptical galaxies. In view of the fact that the spectral energy distribution of the nucleus of M31 is very similar to those of giant elliptical galaxies (Schild and

Oke 1971), we will use equation (7) for the IMF in the nuclear bulge of M31.

We assume that all stars between 2 $M_\odot$ and the present main-sequence turnoff of $m \sim 1.1\ M_\odot$ evolve to white dwarfs with masses $m_{\rm wd} = 0.6\ M_\odot$. The fraction of the initial stellar mass which is shed by dying stars will then be

$$R = \frac{\int_{1.1}^{2.0} (m - 0.6)m^{-1}\, dm}{\int_{0.1}^{2.0} dm} = 0.28\,. \quad (8)$$

Thus we see that with a plausible IMF $\sim$25% of the initial stellar mass will be returned to the interstellar medium. This amount is sufficient to account for the likely mass of the nuclear disk. We conclude that this is in fact the origin of the nuclear disk in M31.

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REFERENCES

Alloin, D., Cruz-González, C., and Peimbert, M. 1976, *Ap. J.*, **205**, 74.
Arp, H. 1964, *Ap. J.*, **139**, 1045.
Baade, W. 1955, *A.J.*, **60**, 151.
———. 1963, *Evolution of Stars and Galaxies* (Cambridge: Harvard University Press).
Baade, W., and Swope, H. H. 1963, *A.J.*, **68**, 435.
Bohuski, T. J., and Smith, M. G. 1973, *Bull. AAS*, **5**, 13.
Cahn, J. H. 1977, private communication.
Cahn, J. H., and Kaler, J. B. 1971, *Ap. J. Suppl.*, **22**, 319.
Cahn, J. H., and Wyatt, S. P. 1976, *Ap. J.*, **210**, 508.
———. 1977, private communication.
Collins, G. W., Daub, C. T., and O'Dell, C. R. 1961, *Ap. J.*, **133**, 471.
Cudworth, K. M. 1974, *A.J.*, **79**, 1384.
de Vaucouleurs, G. 1958, *Ap. J.*, **128**, 465.
Faber, S. M., and Gallagher, J. S. 1976, *Ap. J.*, **204**, 365.
Ford, H. C., Jacoby, G., and Jenner, D. C. 1976, *Ap. J.*, **213**, 18 (Paper IV).
Ford, H. C., and Jenner, D. C. 1975, *Ap. J.*, **202**, 365 (Paper II).
———. 1976, *Ap. J.*, **208**, 683 (Paper III).
Ford, H. C., Jenner, D. C., and Epps, H. W. 1973, *Ap. J. (Letters)*, **183**, L73 (Paper I).
Jura, M. 1977, *Ap. J.*, **212**, 634.
Mathews, W. G., and Baker, J. C. 1971, *Ap. J.*, **170**, 241.
Roberts, M. S. 1966, *Ap. J.*, **144**, 639.
Rubin, V. C., and Ford, W. K. 1970, *Ap. J.*, **159**, 379.
Schild, R., and Oke, J. B. 1971, *Ap. J.*, **169**, 209.
Scoville, N. Z., Solomon, P. M., and Jefferts, K. B. 1974, *Ap. J. (Letters)*, **187**, L63.
Seaton, M. J. 1968, *Ap. Letters*, **2**, 55.
Spitzer, L., and Jenkins, E. B. 1975, *Ann. Rev. Astr. Ap.*, **13**, 133.
Stone, R. P. S. 1974, *Ap. J.*, **193**, 135.
Tinsley, B. M., and Gunn, J. E. 1976, *Ap. J.*, **203**, 52.
Webster, B. L. 1969, *M.N.R.A.S.*, **143**, 79.
Wilson, O. C. 1950, *Ap. J.*, **111**, 279.

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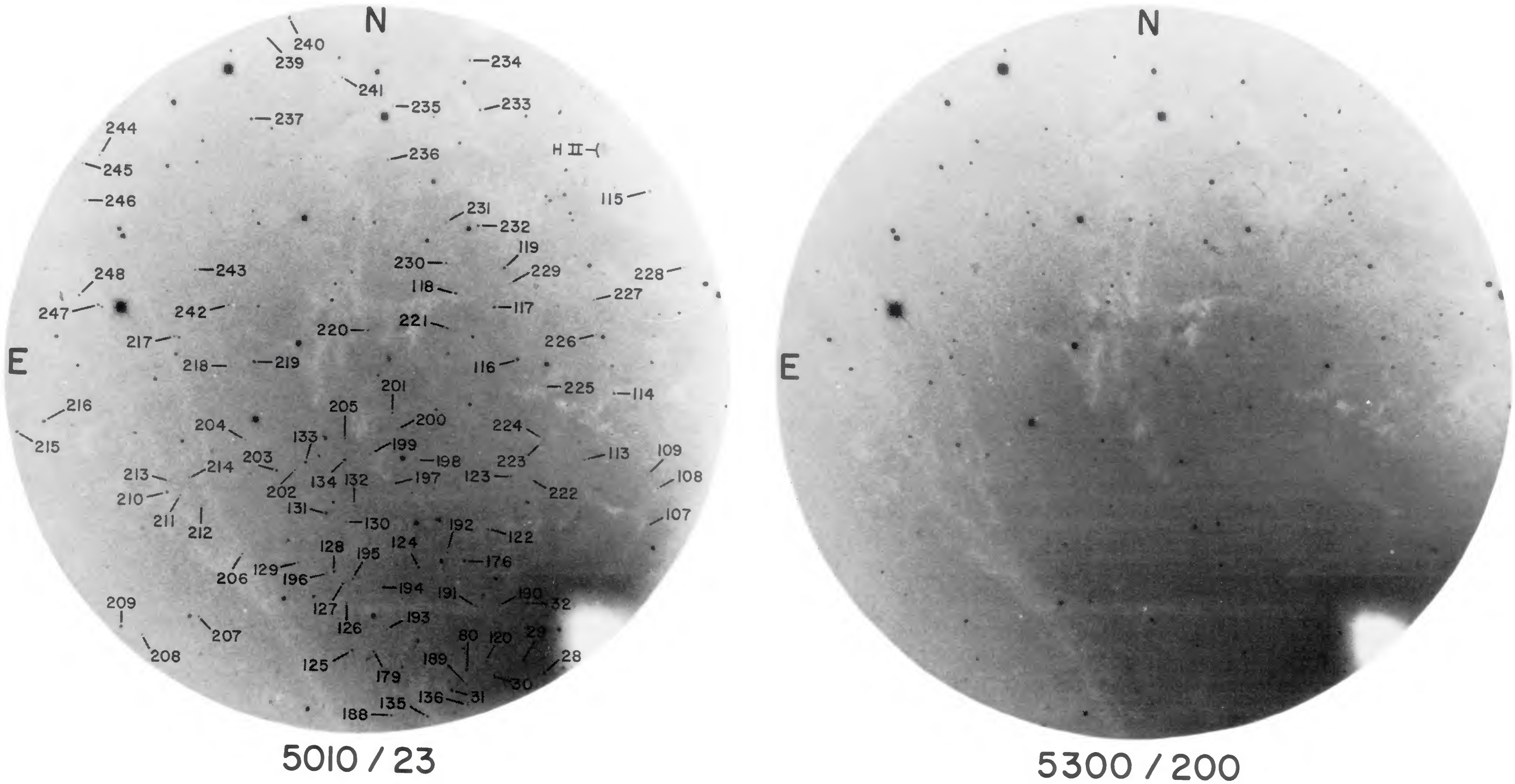

FIG. 1.—A pair of on-line and off-line photographs of a field on the major axis of M31. The center of the field in nebular coordinates (see § II) is $X = 6'.46$, $Y = -0'.09$. The IIa-D on-line plate isolates [O III] λ5007 with the interference filter λ_c5010 (23 Å FWHM). The identifications of 95 planetary nebulae are marked with arabic numerals. A spectral region which is free of emission lines was isolated by the off-line IIa-D plate and the interference filter λ_c5300 (200 Å FWHM). The diameter of the field is 9'.3.

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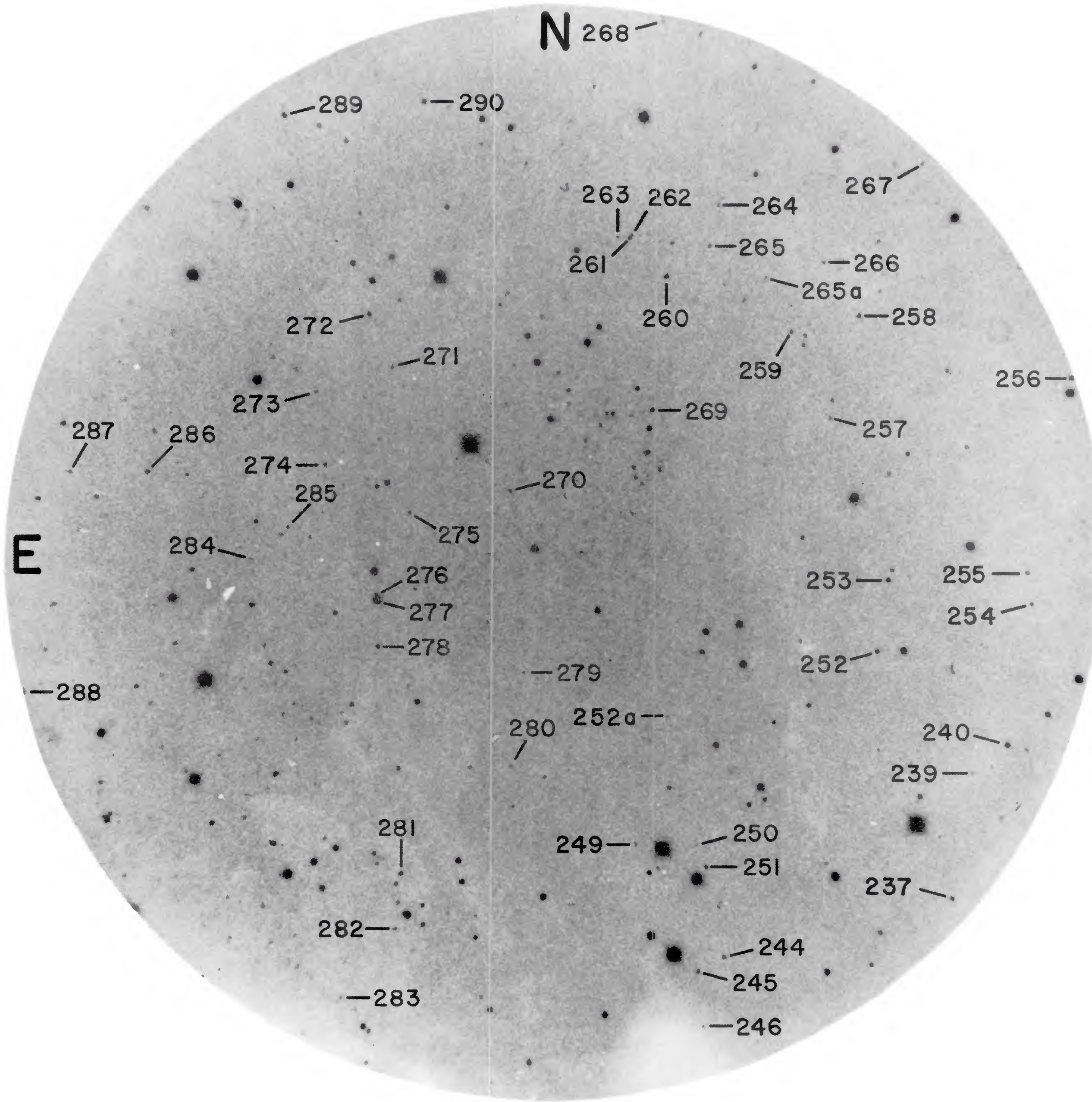

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FIG. 2.—Identifications of 49 planetary nebulae in a field on the major axis of M31. The center of the field is $X = 14'.12$, $Y = 0'.13$. The exposure time was 45 minutes with a IIa-D plate.

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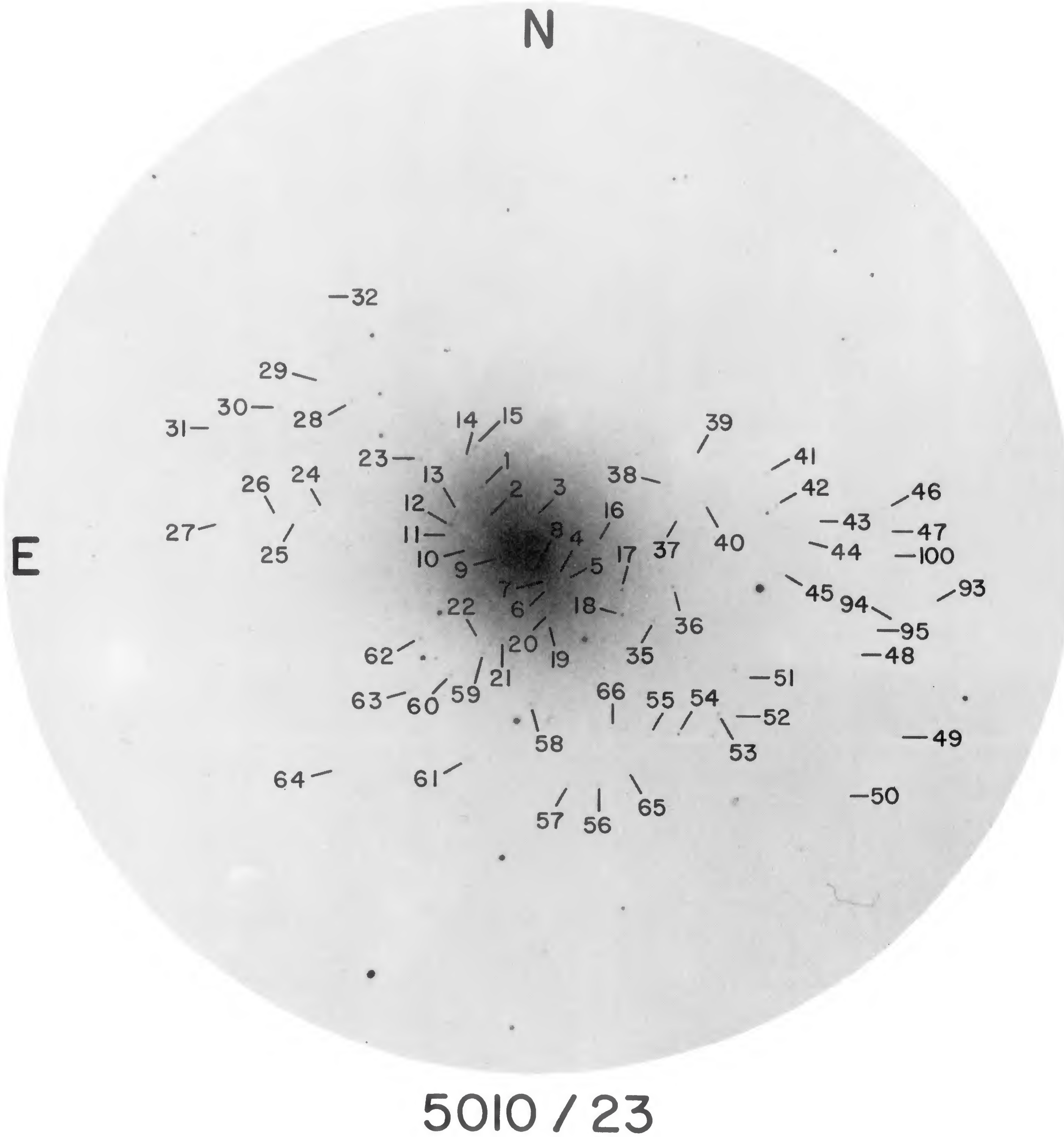

FIG. 3.—Identifications of 68 planetary nebulae in a field centered on the nucleus of M31. The exposure time was 10 minutes with a baked IIIa-J plate. The fainter nebulae are more easily seen on longer exposure plates.

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