KINEMATIC EVIDENCE FOR DIFFERENT PLANETARY NEBULA POPULATIONS IN THE ELLIPTICAL GALAXY NGC 4697

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ABSTRACT

We have analyzed the magnitudes, kinematics, and positions of a complete sample of 320 planetary nebulae (PNs) in the elliptical galaxy NGC 4697. We show the following. (1) The PNs in NGC 4697 do not constitute a single population that is a fair tracer of the distribution of all stars. The radial velocity distributions, mean velocities, and dispersions of bright and faint subsamples differ with high statistical confidence. (2) Using the combined data for PNs brighter than 26.2, we have identified a subpopulation of PNs that is azimuthally unmixed and kinematically peculiar, and thus neither traces the distribution of all stars nor can be in dynamical equilibrium with the galaxy potential. (3) The planetary nebula luminosity functions (PNLFs) of two kinematic subsamples in NGC 4697 differ with 99.7% confidence, ruling out a universal PNLF. We estimate that the inferred secondary PN population introduces an uncertainty in the bright cutoff magnitude of ~0.15 mag for this galaxy. We argue that this secondary PN distribution may be associated with a younger, ≥1 Gyr old stellar population, perhaps formed in tidal structures that have now fallen back onto the galaxy, as has previously been suggested for the X-ray point sources in this galaxy, or coming from a more recent merger/accretion with a red galaxy. The use of PNs for extragalactic distance determinations is not necessarily compromised, but their use as dynamical tracers of dark halos will require deep observations and careful analysis of large PN samples.

Key words: galaxies: distances and redshifts — galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 4697) — galaxies: kinematics and dynamics — planetary nebulae: general

Online material: color figures

1. INTRODUCTION

Planetary nebulae (PNs) have become increasingly important in extragalactic astronomy for distance determinations via their luminosity functions (LFs) (Jacoby 1989; Ciardullo et al. 1989; Jacoby et al. 1990; Méndez 1999; Ferrarese et al. 2000; Ciardullo 2003 and references therein), as kinematic tracers of the dark halos of galaxies (Arnaud et al. 1998; Saglia et al. 2000; Méndez et al. 2001; Romanowsky et al. 2003), and as tracers of the distribution and kinematics of the diffuse stellar population in galaxy clusters (Feldmeier et al. 1998, 2004; Arnaud et al. 2002, 2004; Gerhard et al. 2005). Due to their strong narrow-line emission at [OIII] λ5007, PNs can be easily detected out to distances beyond 20 Mpc with narrowband photometry and slitless spectroscopy (Feldmeier et al. 1998; Arnaud et al. 2002; Méndez et al. 2001; Douglas et al. 2002), and to ~100 Mpc with multislit imaging spectroscopy (Gerhard et al. 2005). Moreover, they are observed in elliptical and spiral galaxies, making them an indispensable tool for supporting distances obtained by other methods (such as Cepheids, surface brightness fluctuations, the Tully-Fisher relation, and Type Ia supernovae) and measuring the kinematics of stellar populations whose surface brightness is too faint for absorption-line spectroscopy.

For distance determinations the planetary nebula luminosity function (PNLF) is normally modeled as having a universal shape that depends only on the absolute bright magnitude cutoff $M^*$:

$$N(M) \propto e^{0.307(M - M^*)},$$

where $N(M)$ is the number of PNs with absolute magnitude $M$ (Ciardullo et al. 1989). Observationally, the cutoff magnitude $M^*$ has a quasi-universal value of ~4.5, with only a weak dependence on the host-galaxy metallicity expressed by the system’s oxygen abundance, which can be compensated for by a quadratic relation in [O/H] (Dopita et al. 1992; Ciardullo et al. 2002). In practice, the PN magnitudes $m(5007)$, after correcting for the interstellar reddening, are fitted to the model PNLF of equation (1) convolved with the photometric error profile, yielding a value of the distance modulus (Ciardullo et al. 1989). The absence of any systematic variations in $M^*$ and the PNLF shape has been verified in galaxies with significant population gradients and among galaxies of different morphologies within galaxy clusters/groups up to Virgo (Jacoby 1997; Ciardullo 2003 and references therein).

This universality of the PNLF and the cutoff magnitude $M^*$ must be considered surprising, given that the PN luminosity in the [OIII] λ5007 line depends on the mass and metallicity of the central star, as well as on the electron gas temperature, optical thickness, and dust extinction of the surrounding nebula. Indeed, some current semianalytic simulations of the PNLF seem to be at odds with the observational trends. Méndez et al. (1993) and Méndez & Soffner (1997) indicate small possible dependencies of $M^*$ on the...
total size of the PN population, on the time elapsed since the last episode of star formation, and on how optically thin the PNs are, concluding, however, that only careful studies would detect such effects in the observed PNLF. In contrast, more recent PNLF simulations by Marigo et al. (2004) contradict the observed narrow spread in $M^*$ and predict large variations of several magnitudes depending on a variety of realistic star formation and evolution scenarios. So is the PNLF truly quasi-universal and its cutoff magnitude nearly independent of population age and metallicity?

PNs are also important as test particles to study the kinematics and dark matter distribution in the halos of elliptical galaxies. Since the PN population is expected to arise from the underlying galactic stellar distribution, their radial velocities can be used as effective kinematic tracers of the mass distribution. However, the required PN sample sizes are many hundreds (Merritt & Saha 1993), or at least 100 or more in conjunction with absorption-line spectroscopy, which has limited this application to only a few nearby galaxies (Hui et al. 1995; Arnaboldi et al. 1998; Saglia et al. 2000; Méndez et al. 2001; Romanowsky et al. 2003; Peng et al. 2004). In recent simulations of disk-galaxy mergers involving dark matter, stars, and gas, Dekel et al. (2005) predict that the young stars formed in the merger have steeper density profiles and larger radial anisotropy than the old stars from the progenitor galaxies, and they argue that if the PNs observed in elliptical galaxies were to correspond to the young population rather than to all stars in the simulations, their velocity dispersion profile would match the measured dispersion profiles of Romanowsky et al. (2003). So do PNs really trace the stars and their kinematics in elliptical galaxies?

Different stellar populations may have, and in general would have, different phase-space distributions in the same galaxy potential. The simplest approach for dynamical modeling, taking the PN velocities as a random sampling of the stellar velocities, is, however, valid only when the PN population properties and their kinematics are uncorrelated. Except in special cases, this also requires that the PNLF be independent of the stellar population. Vice versa, if there existed differences in the PNLF or the bright cutoff magnitude for different stellar populations, they would best be identified by studying the correlations between PN magnitudes and kinematics or positions of these tracers in a single galaxy where all PNs are at the same distance.

In this paper, we report on such a study in the elliptical galaxy NGC 4697, an excellent target for this purpose because of the large sample of PN velocities known from Méndez et al. (2001).

Our analysis shows the existence of distinct PN populations that differ in their kinematics, brightnesses, and spatial distributions. This suggests that the answer to both the questions posed above may be “no”: in general, different stellar populations may have slightly different PNLFs, and the observed PN population in elliptical galaxies may not be a fair tracer of their stars. The paper is organized as follows. In § 2 we review the properties and PN data of this galaxy and discuss the magnitude and velocity completeness of our sample. Our statistical analysis of these data is given in § 3, where we demonstrate the inhomogeneity of the sample in the space of velocities, magnitudes, and positions. Sections 4 and 5 conclude our work, giving also a brief discussion of its implications.

2. NGC 4697: PROPERTIES AND PN SAMPLE

NGC 4697 is a normal, almost edge-on E4–5 galaxy located along the Virgo southern extension. From the multicolor CCD photometry of Goudfrooij et al. (1994), the effective radius is $R_{\text{eff}} = 95''$, the mean ellipticity is 0.45, and the position angle (P.A.) is constant, consistent with a near-axisymmetric luminosity distribution. Isothermal analysis shows that this galaxy has a positive $a_{\phi}$ coefficient, suggesting a disklike structure within $0.6R_{\text{eff}}$ (Carter 1987; Scorza & Bender 1995).

From optical spectroscopy, its dominant stellar population has an age of ~9 Gyr (Trager et al. 2000), consistent with the red mean $B - V = 0.91$ color. Stellar absorption-line kinematics along the major axis ($P.A. = 66^\circ$) of NGC 4697 have been reported by Binney et al. (1990) and Dejonghe et al. (1996); these velocity data can be well described by dynamical models based on the luminous mass distribution only.

Méndez et al. (2001) detected and measured radial velocities of 531 PNs extending out to 300'' (~3$R_{\text{eff}}$) in this galaxy, with observational errors of ~40 km s$^{-1}$. Via dynamical analysis, they determined a constant mass-to-light ratio $Y_B = 11$ within ~300'', which is consistent with a 10 Gyr old stellar population with a Salpeter mass function and slightly supersolar metallicity.

X-ray observations with ROSAT (Sanson et al. 2000) show only small amounts of hot gas in the halo of this galaxy. Using more recent Chandra data, Sarazin et al. (2000) could resolve most of the X-ray emission into nonuniformly distributed X-ray binary point sources, suggesting that NGC 4697 has lost most of its interstellar gas. Although NGC 4697 does not show any signature of recent interactions, Zezas et al. (2003) present evidence that the distribution of these X-ray sources is inconsistent with the optical morphology of NGC 4697, and propose that these sources are mostly high-mass X-ray binaries associated with young stellar populations related to fallback of material in tidal tails onto a relaxed merger remnant or to shock-induced star formation along tidal tails. They estimate typical fallback times of such tidal tails to be much longer than the settling timescale of the remnant and expect similar results for other elliptical galaxies with populations of ~10 Gyr age.

For the work in this paper we use the PN sample presented by Méndez et al. (2001). After removing the possible contaminants and unclear detections, they report unambiguous detection of 535 PNs. However, only 526 of them have confirmed measurements of velocity and magnitude, and we use these in our analysis. In order to determine the PNLF, it is crucial to estimate the magnitude at which PN detection incompleteness sets in. Detectability of a PN varies with the background-galaxy surface brightness; for a statistically complete sample the surface number density of PNs should be directly proportional to it. Méndez et al. (2001) show that their PN sample is statistically complete down to $m(5007) = 27.6$ mag outside an elliptical region of semi-major axis 60''. In our analysis, we have thus defined two data sets: a “complete sample” (with PNs brighter than 27.6, outside the central ellipse of semi-major axis 60'') and a “total sample” (consisting of all PNs with measured magnitude and radial velocity). The total number of PNs in these data sets is 320 and 526, respectively.

The systemic velocity ($V_{\text{sys}}$) of NGC 4697, obtained by averaging the observed velocity of all 526 PNs, is 1274 km s$^{-1}$, which agrees with the values quoted in the literature (Méndez et al. 2001 and references therein). The on-band filter configuration used to detect and measure velocities of these PNs has a peak wavelength of 5028 Å, peak transmission of 0.76, equivalent width of 48.5 Å, and FHWM of 60 Å (Méndez et al. 2001). The FHWM corresponds to a velocity range of ±1800 km s$^{-1}$ around the systemic velocity of NGC 4697. Thus, the filter transmission width is large enough to facilitate observations of PNs with all velocities bound to NGC 4697, irrespective of their magnitude. Indeed, even at magnitudes as faint as $m(5007) = 28$ in the total sample, PNs with large velocities of ~300 km s$^{-1}$ are detected. Thus, the velocity coverage in both samples (total and complete) is not biased with respect to the PN magnitudes.
The PN magnitudes were measured by Méndez et al. (2001) from their undispersed images; they are accurate to 0.1 and 0.2 mag for $m(5007)$ brighter and fainter than 26.5, with systematic effects below 2%. As a further test relevant for the present work, Méndez et al. (2001) used the redundancy provided between their east and west fields: plotting magnitude differences between the two measurements (east and west) of PN candidates as a function of difference in distance from the center of the CCD, they found a scatter diagram without any evidence of correlation. Méndez et al. (2001) estimated the errors in the PN velocities from calibration, image registration, spectrograph deformation, and guiding errors to be 40 km s$^{-1}$. The velocities of 165 PNs were measured independently in the east and west fields of Méndez et al. (2001); these velocities agree within a standard deviation of 36 km s$^{-1}$. In order to check whether a systematic difference between the velocities of bright and faint PNs could be introduced by an asymmetric point-spread function (PSF) (a possibility suggested by K. Freeman), we have superposed the PSFs of three groups of 10 of the brightest PNs: one selected at random and two selected among those PNs with the highest and lowest radial velocities. In the three cases we estimated the shift of the centroid of the entire PSF with respect to the centroid of the upper part. The shifts were smaller than 10 km s$^{-1}$, and in some cases they were in the opposite sense compared to the results discussed below.

3. THE DISTRIBUTION OF NGC 4697 PNs IN VELOCITY, MAGNITUDE, AND POSITION

In this section, we search for stellar population effects in the kinematics of the PNs in NGC 4697 by analyzing the total and complete data sets with respect to their three observables: velocity, magnitude, and position. For both data sets, we convert the observed PN radial velocities into corotating or counterrotating velocities as follows. With the galaxy center at the origin of the reference frame and the $x$-axis oriented along the major axis (P.A. = 66$^\circ$), the absorption-line stellar-kinematic data predict positive line-of-sight mean velocity with respect to the galaxy systemic velocity, at slit positions toward the southwest of the center with $x$-coordinate $> 0$, and vice versa. We denote this sense of rotation as “corotating” and the opposite sense as “counterrotating.” By definition, the major-axis absorption-line data are corotating.

3.1. Subpopulations of PNs in the Velocity-Magnitude Plane

After subtracting the systemic velocity from the PN radial velocities, we define reduced velocities $U = (V - V_{sys}) \text{sgn}(x)$ and denote the PNs with $U > 0$ as corotating and those with $U < 0$ as counterrotating. By definition, the major-axis absorption-line data have $U > 0$. The resulting values of $U$ are displayed against the observed magnitudes in Figure 1. Even at magnitudes as faint as $m(5007) = 28$ in the total sample, PNs with large velocities of $\sim 300$ km s$^{-1}$ are detected, showing that there is no kinematic bias at faint magnitudes. Henceforth, unless stated otherwise, we always use the complete sample for our analysis.

Figure 1 shows that the complete PN sample appears to exhibit a correlation between magnitudes and kinematics, with faint PNs showing more corotation than bright PNs. We have performed several statistical tests to verify the significance and look for the origin of this correlation. Table 1 shows the results of Pearson's

![Figure 1](image-url)

**TABLE 1**

| Sample               | $r$       | $P_r$       |
|---------------------|-----------|-------------|
| Corotating          | -3.5 x 10^{-2} | 0.64        |
| Counterrotating     | 0.24      | 5.8 x 10^{-3} |

**Notes.**—Shown are the results of Pearson’s $r$-test for linear correlation of PN magnitudes with reduced velocity $U$ for the complete sample and the corotating and the counterrotating subsamples. Values of $r$ close to 1 indicate a strong linear correlation; values close to 0 indicate little or no correlation. $P_r$ is the probability that two uncorrelated variables would give an $r$-coefficient as large as or larger than the measured one, for a normal distribution of $r$. Small values of $P_r$ imply significant correlation.
TABLE 2

MEAN REDUCED VELOCITY AND DISPERSION

| Sample          | \( \bar{U} \)   | \( \sigma \) | \( t \) | \( P_t \) | \( F \)  | \( P_F \) |
|-----------------|------------------|--------------|--------|----------|---------|---------|
| \( m(5007) \geq 26.9 \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) |
| \( m(5007) \leq 26.2 \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) | \( \ldots \ldots \) |

Notes.—Shown are the mean reduced velocity (\( \bar{U} \)) and dispersion (\( \sigma \)) of the brightest and faintest PNs, along with the results from Student’s \( t \)-test and the \( F \)-test. Very small values of \( P_t \) and \( P_F \) imply that the differences between the observed \( U \) and \( \sigma \) are statistically significant.

Fig. 2.—Cumulative velocity distribution of the brightest PNs (\( m \leq 26.2 \); dashed line), faintest PNs (\( m \geq 26.9 \); dot-dashed line), and entire complete sample (solid line). The entire velocity range is shown in the top left panel. In the top right panel the velocities are divided according to their sense of rotation. The bottom panel shows the cumulative distribution (shown from \( +ve \) to \( -ve \) values), normalized at \( U = 0 \). The K-S probabilities show that the brightest counterrotating PNs have a significantly different velocity distribution from the rest of the PNs. [See the electronic edition of the Journal for a color version of this figure.]
r-test for correlated data. Velocities of counterrotating PNs are strongly linearly correlated with their brightness, while those of corotating PNs are almost independent of their magnitude distribution. Further, we divided our sample into three equal-magnitude bins each of size \( \Delta m = 0.7 \), hereafter referred to as the “faintest,” “intermediate,” and “brightest” PNs, and computed the mean reduced velocity and its dispersion in each of these bins, along with the significance of their differences. As shown in Table 2, the faint- and bright-PN subsamples defined through these bins have different mean reduced velocities and dispersions at 94% and 99.3% confidence, respectively. In Figure 2 we have plotted the cumulative velocity distribution of PNs in the brightest and faintest magnitude bins. There is a visible excess of bright PNs with counterrotating velocities. It is particularly evident from this figure that the brightest counterrotating PNs display a velocity distribution that differs from the rest of the PNs in the complete sample with high confidence.

Thus, it is clear that the observed correlation between the PNs’ kinematics and their magnitudes is compelling, and it arises because the faintest and brightest PNs have significantly different velocity distributions. There appears to exist an additional component of bright, counterrotating PNs with respect to the overall sample.

### 3.2. Spatial Distribution

If these correlations have a physical origin, they should also be manifest in the spatial distribution of these PNs. Thus, we now enquire whether the PN kinematics and magnitudes depend on their spatial location in the galaxy.

In Figure 3 we plot the spatial locations of all 526 PNs in this galaxy. The central incompleteness ellipse is also displayed. PNs brighter than \( m = 26.2 \) (which is 0.71 mag deeper than the brightest PN) are shown as squares (corotating PNs) and triangles (counterrotating PNs). Inside the incompleteness ellipse, the distribution of bright PNs appears to be concentrated around a nearly elliptical annulus. However, we did not find any kinematic evidence (such as a rotation curve signature) relating these bright PNs to the central stellar disk: either they are not physically related to the disk, or the evidence from the data is inconclusive.

Outside the incompleteness ellipse, the distribution of bright PNs does not follow the surface brightness of the host galaxy: there is a significant left-right asymmetry, with more bright PNs to the right side of the galaxy minor axis (27 ± 5) than to the left side (15 ± 4). Méndez et al. (2001) discuss at length the possible differences in their east and west fields and are convinced that the maximum systematic errors in the measured photometry, positions, and radial velocities are below 2%, 0′06, and 20 km s⁻¹,
respectively. Hence, we conclude that the left-right asymmetry in number counts of bright PNs is not affected by detection uncertainties.

Subsequently, we carried out several tests to check whether the brightest and faintest PNs, or the co- and counterrotating PNs, are distributed differently in the galaxy. It turns out that the radial PN distribution is independent of their sense of rotation. However, the distribution of PN distances from the galaxy midplane differs for co- and counterrotating PNs at a confidence level of 73%.

The left-right asymmetry is confirmed by inspecting the azimuthal distribution of the faint and bright PNs. In the literature we found a related analysis by Zezas et al. (2003), who compared the azimuthal distribution of Chandra X-ray point sources with the optical surface brightness of NGC 4697. We follow their P.A. convention and plot the cumulative angular distributions of the bright, intermediate, and faint PNs in our complete sample in Figure 4. For comparison, the right panel of Figure 2 from Zezas et al. (2003) is also shown. The angular distribution of all PNs in the complete sample has a shape somewhere between that of the X-ray point sources and that of the optical light. The brightest PNs are in complete disagreement with either of these distributions; they seem to be more concentrated in a narrow angular sector in the range $110^\circ \leq P.A. \leq 150^\circ$ (see Fig. 3), with only a 1.9% probability that the faint- and bright-PN subsamples are drawn from the same azimuthal distribution. At the same time, the radial distributions of the faint and bright subsamples are not significantly different (Fig. 5).

The velocity distribution of the brightest PNs is also correlated with their azimuthal distribution. In Figure 6 we plot the mean radial velocity and its dispersion in angular sectors containing an approximately constant number of PNs from the bright subsample, as well as an angular running average of their mean radial velocity. Along both sides of the major axis of the galaxy, the brightest PNs have positive velocity while showing a relatively low velocity dispersion, perhaps due to infall as suggested for...
mean velocities, consistent with \( v \approx 0 \). In the outer parts, the velocity asymmetry in the bright PNs leads to a positive mean velocity on both sides of the galaxy center. Both the faint/intermediate sample and the entire PN sample also show some asymmetry; the outer mean velocities on the \( x < 0 \) side reach zero, but not the negative values expected from reflecting the positive values at \( x > 0 \). This confirms that also the intermediate/faint subsample contains a fraction of PNs stemming from the out-of-equilibrium population traced by the bright PNs. However, the streaming velocity of the majority of the faint PNs does appear to decrease on both sides of the center. Similarly contaminated results could be expected for the derived velocity dispersions.

Several important conclusions can be drawn from these figures. (1) The bright PNs as defined in § 3.1 and Figure 1 do not trace the azimuthal distribution of light in NGC 4697. (2) They do not trace the fainter PNs in their azimuthal kinematics; thus, a large fraction of them must belong to a separate PN subcomponent originating from a separate stellar population. (3) They are not in dynamical equilibrium in the gravitational potential of NGC 4697. (4) Because this subpopulation does not trace the stars, including its PN velocities in a dynamical analysis of the galaxy will lead to significant errors in the results.

3.3. Kinematic Dependence of PNLF

What can we learn about the luminosity functions of the two kinematic components of the PN system in NGC 4697? The cumulative magnitude distributions of the corotating and counterrotating subsamples in Figure 1 have only a 28% Kolmogorov-Smirnov (K-S) probability of stemming from the same distribution (Fig. 8, top). However, the fact that there are both corotating and counterrotating bright PNs in the bright sample whose azimuthal distribution is unmixed shows that counterrotation is not a clean discriminator after all for the secondary population of PNs in NGC 4697. Thus, the luminosity functions of the main and secondary PN populations in this galaxy may be a lot more different than this figure of 28% would suggest.

From Figure 6 we estimate that the main population of PNs in NGC 4697 has a mean radial velocity \( \bar{v}_{\text{faint}} \approx 45 \text{ km s}^{-1} \) sin (P.A. \( -24^\circ \)), with a dispersion of \( \sigma_{\text{faint}} \gtrsim 120 \text{ km s}^{-1} \), so its reduced mean velocity is \( 0 \text{ km s}^{-1} < U_{\text{faint}} \lesssim 45 \text{ km s}^{-1} \). Thus, in the bottom panel of Figure 8 we show the cumulative magnitude distribution of the PNs in the velocity range \(-100 \text{ km s}^{-1} < U < 200 \text{ km s}^{-1}\) and compare it with the cumulative distribution of the PNs with \( U < -100 \text{ km s}^{-1}\). These velocity ranges are dominated by the main and secondary PN populations in the sample, respectively. Now the K-S significance test shows that the magnitude distributions from these sections of Figure 1 have only a probability of 0.3% of being drawn from the same distribution. This result is strong enough to imply that the PNLF cannot be universal; the PNLF in NGC 4697 depends on a kinematic selection.

In the following, we use the velocity range \(-100 \text{ km s}^{-1} < U < 200 \text{ km s}^{-1}\) as an approximate kinematic selection criterion for the main PN population in NGC 4697. The luminosity function of the strongly counterrotating PNs in Figure 1 — a first approximation to the luminosity function of the secondary PN population in NGC 4697 — differs from that of the main PN distribution so defined in the sense that it contains more bright PNs near the cutoff and fewer faint PNs than the main population (see Fig. 8). Now an important question is, in what proportion do both populations contribute to the brightest PNs, and do they have different cutoff magnitudes?

To investigate this, we show in Figure 9 the velocities, magnitudes, and position angles of the entire bright-PN subsample (see...
Figs. 1 and 6). The top panel shows the following. (1) Thirteen of 16 of the bright PNs, whose radial velocities differ most from those of the faint population, are counterrotating. This explains the differences between the velocity distributions of co- and counterrotating PNs that first suggested more than one PN population in Section 3.1. (2) Also, even in the kinematically normal bright PNs, there is a large overdensity (10 of 12) in the angular range P.A. = 100° − 150°. The bottom panel shows in addition that many of the brightest PNs are either kinematic outliers or are found in the overdense angular region. [See the electronic edition of the Journal for a color version of this figure.]

Figs. 8.—Top: Cumulative distributions of PN magnitudes for all (solid line), corotating (dotted line), and counterrotating (triple-dot–dashed line) PNs in NGC 4697. The magnitude distributions of co- and counterrotating PNs are similar, with only 28% probability. Bottom: Cumulative magnitude distributions of the main PN sample (−100 km s^{-1} ≤ U ≤ 200 km s^{-1}; dotted line) and the extreme counterrotating sample (U < −100 km s^{-1}; triple-dot–dashed line) defined in the text, along with that of the total sample (solid line). The first two luminosity functions are different with 99.7% confidence; thus, the PNLF cannot be universal. [See the electronic edition of the Journal for a color version of this figure.]

Figs. 9.—Disentangling the bright-PN subsample from radial velocities, luminosities, and position angles on the sky. Top: Radial velocity–position angle plane. Squares and diamonds show PNs whose reduced velocities are respectively outside and within −100 km s^{-1} ≤ U ≤ 200 km s^{-1}. Circled symbols denote counterrotating PNs; many of these are kinematic outliers. The two vertical lines denote the P.A. of the minor axis. The distribution of the diamonds is approximately uniform in P.A. except near P.A. = 100° − 150°, where there are 12 PNs (crossed diamonds) instead of the expected two PNs. Bottom: Radial velocity–magnitude plane. The symbols are as in the top panel. Six of eight of the brightest PNs are either kinematic outliers or are found in the overdense angular region. [See the electronic edition of the Journal for a color version of this figure.]
luminosity functions for both cases are plotted in Figure 10; they differ only slightly.

Thus, in the following we use the kinematic condition \(-100 \, \text{km s}^{-1} \leq U \leq 200 \, \text{km s}^{-1}\) together with assumption 2 above to ensure azimuthal uniformity of the bright PNs as an improved selection criterion for PNs in the main population in NGC 4697. We keep all PNs in the intermediate-luminosity bin with \(-100 \, \text{km s}^{-1} \leq U \leq 200 \, \text{km s}^{-1}\) because Figure 4 showed that their azimuthal asymmetry is not large. Also, we have checked that the mean angular velocity distribution in this magnitude bin after applying the kinematic selection follows approximately the sinusoidal variation of the faint PNs, and the velocity dispersion is approximately constant. The resulting main-population sample is identified by its brightness, distribution, and kinematic properties.

Comparing the luminosity function in Figure 10 of this main PN population with the luminosity function of all PNs in NGC 4697, we see that the bright cutoff of the main population is shifted to fainter magnitudes. We note that the bright cutoff could be shifted further to fainter magnitudes if some of the kinematically normal and azimuthally uniform bright PNs were also part of the secondary population, which we cannot tell from the present data.

We can now ask what the effect is, in practice, on the PNLF distance determination. The reduced sample for the main PN population in NGC 4697 has 214 objects. After binning these data into 0.2 mag intervals, we transform the apparent magnitudes \(m(5007)\) into absolute magnitudes, adopting the extinction correction of 0.105 mag and the distance modulus indicated in each plot. The three lines are PNLF simulations (Méndez & Soffner 1997). For a distance modulus of 30.15 the brightest PNs are a bit too weak; therefore the distance must be increased. But 30.35 is clearly excessive. The best fit is for 30.2 or 30.25.

The comparison is shown in Figure 11. We conclude that the PNLF distance modulus should be increased slightly from 30.1 (the earlier determination based on the full sample) to 30.2 or 30.25. For comparison, the \(\chi^2\) fit to the same data (Fig. 10, dotted line) gives 30.22. This correction would bring the PNLF distance modulus into better (but not perfect) agreement with the surface brightness fluctuation (SBF) distance modulus (30 ± 0.2) reported by Tonry et al. (2001).

4. DISCUSSION

4.1. Could the NGC 4697 PN Sample Be Contaminated?

Bright PNs play a significant role in the analysis of the last section. Is it possible that the brightest PNs in NGC 4697 are contaminated by compact H\(\alpha\) regions such as those observed by Gerhard et al. (2002) and Ryan-Weber et al. (2004)? The recent observations of Méndez et al. (2005) have shown that this cannot be so. These authors took spectra of 13 of 42 PNs in our bright subsample in NGC 4697 with FORS2 on the Very Large Telescope; these have no detectable continuum and the line ratios of metal-rich PNs.
The same argument also shows that these bright PNs cannot be background emission-line galaxies. Moreover, Ly$\alpha$ emission galaxies would come in at [O iii] magnitudes of $m_{5007} \approx 26.2$ (see Fig. 4 of Aguerri et al. 2005), while the bright PNs in NGC 4697 have $m_{5007} \leq 26.2$.

Furthermore, one may wonder whether the bright PNs in NGC 4697 might simply be foreground objects that could be closer to us and hence brighter than the “true” NGC 4697 PNs on which they would be superposed. Given that NGC 4697 is located in the southern extension of the Virgo Cluster, known to contain an intracluster population of PNs (Arnaboldi et al. 2002, 2004; Feldmeier et al. 2004), this possibility deserves to be considered. However, the following observational facts show that the bright PNs in NGC 4679 are not intracluster PNs (ICPNs). (1) NGC 4697 is in over 10° away from the galaxy. Depending on whether or not the azimuthally symmetric brightest PNs are part of the main population, the cutoff luminosity of the main PN population in NGC 4697 is fainter than that of the whole population by $\geq 0.15$ mag (Figs. 10 and 11). While this is consistent with the M84 result, is it also consistent with the systematic studies of PNLF distances? Ciardullo et al. (2002) have compared the PNLF and SBF distances, finding a distribution of residuals with a systematic offset by $\geq 0.3$ mag, which they suggested is due to internal extinction effects, and with a FWHM of $\approx 0.5$ mag. The offset has in the meantime been reduced to $\leq 0.15$ mag, following a revision of the SBF distance scale by Jensen et al. (2003). The width of this distribution is consistent with their determination of the observational errors in both methods. However, the offset that we have determined for NGC 4697 is also consistent with the distribution of residuals in Ciardullo et al. (2002).

4.3. Origin of the PN Population Difference: A Secondary, Younger Stellar Population?

We have shown that a large fraction of the bright PNs in NGC 4697 belong to a secondary, dynamically young stellar population that is not well mixed in the gravitational potential of the galaxy. Late infall of tidal structures (Zezas et al. 2003) or a merger with a smaller galaxy some time ago would be natural ways to add such an unmixled stellar component to NGC 4697. What physical population difference is correlated with this dynamical youth?

Méndez et al. (2005) show from their spectroscopic data for 13 bright PNs that these have near-solar metallicities. Of these 13 bright PNs, six are inside the incompleteness ellipse, one has no measured velocity, and six belong to our secondary population. Méndez et al. (2005) also use long-slit spectroscopy to show that the metallicity of the integrated stellar population within one effective radius has solar or higher metallicities. These observations make it unlikely that metallicity is the main factor responsible for the different magnitude distributions of the main and secondary PN populations in NGC 4697.

Thus, the more likely driver would appear to be an age difference, as suggested by Marigo et al. (2004) and as might generally be expected in an accretion event. Based on their result that the distribution of X-ray point sources in NGC 4697 does not follow the stellar light, Zezas et al. (2003) have argued that this is because these sources were formed several $10^8$ yr ago in tidal tails that are now falling back onto the galaxy. Note, however, that the integrated light in NGC 4697 shows no evidence of
young stars with mean age <7 Gyr (Méndez et al. 2005), so this younger component could not be luminous enough to contaminate the integrated light to the level measured. Also note that the observed increase of extinction in the PN envelope with PN core mass more than compensates for the increase of core luminosity with core mass for bright PNs in Local Group galaxies (Ciardullo & Jacoby 1999), so that stars with ages below 1 Gyr may not reach the [O III] luminosity at the PNLF cutoff. A secondary stellar population younger than 1 Gyr is therefore unlikely as well.

Recently, Ciardullo et al. (2005) have argued that the brightest PNs in the PNLF must have core masses of \( \geq 0.6 M_\odot \), corresponding to main-sequence masses of \( \sim 2.2 M_\odot \). They argue further that for such high-mass objects to occur in elliptical galaxies, either these early-type galaxies would have to contain a small, smoothly distributed component of young (\( \leq 1 \) Gyr age) stars, or more likely, the bright PNs in these systems would have to have evolved from blue straggler stars created through binary evolution. Their blue straggler model, due to the assumption of a fixed distribution of primary-to-secondary mass ratios for the initial binaries, predicts that older stellar populations produce fewer bright PNs per unit luminosity, as is observed, because the number of binary stars in a stellar population that can coalesce to \( \sim 2.2 M_\odot \) blue stragglers decreases with time.

If correct, this blue straggler model could also explain how the secondary population that we found in NGC 4697 can contain a large fraction of the brightest PNs in this galaxy, provided that the stellar population corresponding to this secondary PN population is appreciably younger than the main stellar population, whose age is \( \sim 9 \) Gyr from optical spectroscopy (Trager et al. 2000). At the same time, this secondary stellar population must not be so young as to violate the constraints from either the optical colors or the envelope absorption–PN core mass correlation; i.e., it must be older than \( \sim 1 \) Gyr. We can give an estimate for the effect of such an intermediate-age population on the optical colors as follows. The secondary subpopulation traced by the bright and predominantly counterrotating PNs may contain \( \sim 20% \) of all PNs in the complete sample for NGC 4697. A stellar population as blue as the bulge of M31 has a luminosity-specific PN density per unit \( L_B \) up to 5 times higher than the populations characterized for old elliptical galaxies (Hui et al. 1993; Ciardullo et al. 2005). Thus, the subpopulation corresponding to the secondary PN population in NGC 4697 would be expected to contain \( \geq 5% \) of the blue luminosity of NGC 4697, spread over a large fraction of at least the east image. To detect this we need deep and accurate photometry.

The unmixed spatial and velocity distributions of the secondary PN population in NGC 4697 show that this population is dynamically young, i.e., has not had time to phase-mix and come to dynamical equilibrium in the gravitational potential of NGC 4697. It may well be associated with tidal structures that were formed in a merger or accretion event \( \sim 1–2 \) Gyr ago and that have now fallen back onto the galaxy, or be associated with a more recent merger/accretion with a red galaxy such as described in van Dokkum (2005). In a universe in which structures form hierarchically, such secondary stellar populations might be quite common in elliptical galaxies, but they would be difficult to see. The present work shows that studying their PN populations is one promising approach to looking for such secondary populations. However, large PN samples are required; most existing PN studies of early-type galaxies do not have the statistics for such an investigation. Moreover, in only a fraction of the cases may there be enough of an asymmetry signal to detect with a few hundred PNs.

5. CONCLUSIONS AND IMPLICATIONS

We have analyzed the magnitudes, kinematics, and positions of a complete sample of 320 PNs in the elliptical galaxy NGC 4697 from Méndez et al. (2001). This data set is large enough for drawing statistically significant conclusions, and it does not suffer from detection incompletenesses in either magnitudes or radial velocities. We know of no systematic effects in the data that could explain our results. Our main conclusions are as follows:

1. Bright and faint PNs in NGC 4697 have significantly different radial velocity distributions. The mean velocities of the faint and bright subsamples (corotating and \( \sim 0 \), respectively) and their velocity dispersions are different, with 94% and 99.3% confidence. Thus, the PNs in NGC 4697 do not constitute a single population that is a fair tracer of the distribution of all stars.

2. The luminosity functions of the extreme counterrotating subsample \(( U < \sim -100 \) km s\(^{-1}\) and of the main population (defined by \( -100 \) km s\(^{-1}\) \( \leq U \leq 200 \) km s\(^{-1}\)) are different with 99.7% confidence. The PNLF is therefore not universal.

3. Based on this, we suggest that there exist (at least) two PN populations in this galaxy. The secondary PN population in NGC 4697 is prominent in a subsample of counterrotating PNs brighter than 26.2. The luminosity function of the entire extreme counterrotating sample may be a first approximation to the luminosity function of the secondary population.

4. The spatial distribution of bright PNs with \( m(5007) < 26.2 \) is different from that of the faint PNs. The bright PNs do not follow the azimuthal distribution of the optical light, they show a left-right asymmetry, and they have a positive mean radial velocity on both sides of the galaxy major axis but zero velocity and larger dispersion on the minor axis. They are not in dynamical equilibrium in the potential of the galaxy. The fainter population has rotation properties more similar to the absorption-line velocities, with azimuthally constant dispersion.

5. Using both their kinematics and angular distribution, we can estimate a lower limit to the statistical fraction of bright PNs in the secondary population. Based on this we estimate that the bright cutoff of the main population is uncertain by \( \sim 0.15 \) mag.

Our results have two main implications for the use of PNs in extragalactic astronomy. First, for distance determinations with the PNLF, it may be important to understand how uniform the PN populations in the target galaxies are. From our analysis in NGC 4697 we estimate that unrecognized subpopulations of PNs in samples smaller than that in NGC 4697 may lead to variations of \( \sim 0.15 \) mag in the bright cutoff. This would correspond to distance errors of some 10%, which, although a minor effect, could be significant in some cases. It will be necessary to verify how frequently such subpopulations occur in elliptical galaxies. We recall that also in the halo of M84 there exists a small population of overluminous PNs whose cutoff is 0.3 mag brighter than that of the main M84 population but which appear nonetheless bound to the halo (Arnaboldi et al. 2004; Aguerri et al. 2005).

The second implication concerns the use of PNs as tracers for the angular momentum and gravitational potentials of elliptical galaxies. Our analysis has shown that in NGC 4697 the bright PNs do not trace the distribution and kinematics of stars and are not in dynamical equilibrium in the gravitational potential of the galaxy. The fainter PNs look more regularly distributed but may also contain a fraction of PNs that belong to this out-of-equilibrium population. Clearly, therefore, mass determinations based on PN kinematics will in the future require careful study of the PN samples being used, not only to verify that these PNs are in dynamical equilibrium but also to test for different
dynamical components. Even if in equilibrium, a younger population of stars may be more flattened or have a steeper falloff than the main body of the elliptical galaxy. If the PNs from this population are indeed somewhat brighter than the main population, one can recognize such differences from their lower velocity dispersion or different radial density profile. However, deep observations and large PN samples will be required.

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REFERENCES

Aguerri, J. A. L., et al. 2005, AJ, 129, 2585
Arnaboldi, M., et al. 1998, ApJ, 507, 759
———. 2002, AJ, 123, 760
———. 2004, ApJ, 614, L33
Binney, J., Davies, R. L., & Illingworth, G. D. 1990, ApJ, 361, 78
Carter, D. 1987, ApJ, 312, 514
Ciardullo, R. 2003, in Stellar Candles for the Extragalactic Distance Scale, ed. D. Alloin & W. Gieren (Berlin: Springer), 243
Ciardullo, R., & Jacoby, G. H. 1999, ApJ, 515, 191
Ciardullo, R., Jacoby, G. H., Ford, H. C., & Neill, J. D. 1989, ApJ, 339, 53
Ciardullo, R., Sigurdsson, S., Feldmeier, J. J., & Jacoby, G. H. 2005, ApJ, 629, 499
Ciardullo, R., et al. 2002, ApJ, 577, 31
Dejonghe, H., et al. 1996, A&A, 306, 363
Dekel, A., Stoehr, F., Mamon, G. A., Cox, T. J., Novak, G. S., & Primack, J. R. 2005, Nature, 437, 707
Dopita, M. A., Jacoby, G. H., & Vassiliadis, E. 1992, ApJ, 389, 27
Douglas, N., et al. 2002, PASP, 114, 1234
Feldmeier, J. J., Ciardullo, R., & Jacoby, G. H. 1998, ApJ, 503, 109
Feldmeier, J. J., Ciardullo, R., Jacoby, G. H., & Durrell, P. R. 2004, ApJ, 615, 196
Ferrarese, L., et al. 2000, ApJ, 529, 745
Gerhard, O., Arnaboldi, M., Freeman, K. C., Kashikawa, N., Okamura, S., & Yasuda, N. 2005, ApJ, 621, L93
Gerhard, O., et al. 2002, ApJ, 580, L121
Goudfrooij, P., et al. 1994, A&AS, 104, 179
Hui, X., Ford, H. C., Ciardullo, R., & Jacoby, G. H. 1993, ApJ, 414, 463
Hui, X., Ford, H. C., Freeman, K. C., & Dopita, M. A. 1995, ApJ, 449, 592
Jacoby, G. H. 1989, ApJ, 339, 39
———. 1997, in The Extragalactic Distance Scale, ed. M. Livio (Cambridge: Cambridge Univ. Press), 197
Jacoby, G. H., Ciardullo, R., & Ford, H. C. 1990, ApJ, 356, 332
Jensen, J. B., et al. 2003, ApJ, 583, 712
Marigo, P., Girardi, L., Weiss, A., Groenewegen, M. A. T., & Chiosi, C. 2004, A&A, 423, 995
Méndez, R. H. 1999, in Post-Hipparcos Cosmic Candles, ed. A. Heck & F. Caputo (Dordrecht: Kluwer), 161
Méndez, R. H., Kudritzki, R. P., Ciardullo, R., & Jacoby, G. H. 1993, A&A, 275, 534
Méndez, R. H., & Sofiller, T. 1997, A&A, 321, 898
Méndez, R. H., et al. 2001, ApJ, 563, 135
———. 2005, ApJ, 627, 767
Merritt, D., & Saha, P. 1993, ApJ, 409, 75
Peng, E., Ford, H. C., & Freeman, K. C. 2004, ApJ, 602, 685
Romanowsky, A. J., et al. 2003, Science, 301, 1696
Ryan-Weber, E. V., et al. 2004, AJ, 127, 1431
Saglia, R. P., Kronawitter, A., Gerhard, O. E., & Bender, R. 2000, AJ, 119, 153
Sansom, A. E., Hibbard, J. E., & Schweizer, F. 2000, AJ, 120, 1946
Sarazin, C. L., Irwin, J. A., & Bregman, J. N. 2000, ApJ, 544, L101
Scozzi, C., & Bender, R. 1995, A&A, 293, 20
Tonry, J. L., et al. 2001, ApJ, 546, 681
Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 119, 1645
van Dokkum, P. G. 2005, AJ, 130, 2647
Zezas, A., Hernquist, L., Fabbiano, G., & Miller, J. 2003, ApJ, 599, L73