METAL-RICH PLANETARY NEBULAE IN THE OUTER REACHES OF M31

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ABSTRACT

Spectroscopic data of two relatively [O iii]-luminous planetary nebulae (PNe) have been obtained with the 10.4 m Gran Telescopio Canarias. M174 and M2496 are each ∼1′′ from the center of M31 along opposite sides of its minor axis. The ensemble of these 2 distant PNe plus 16 similarly luminous outer-disk PNe published previously by Kwitter et al. forms a homogeneous group in luminosity, metal content, progenitor mass, age, and kinematics. The main factual findings of our work are (1) O/H (and other low-mass α elements and their ratios to O) is uniformly solar-like in all 18 PNe ((12 + log(O/H)) = 8.62 ± 0.14); (2) the general sky distribution and kinematics of the ensemble much more closely resemble the rotation pattern of the classical disk of M31 than its halo or bulge; (3) the O/H gradient is surprisingly flat beyond $R_g \sim 20$ kpc. The PNe are too metal-rich to be bona fide members of M31’s disk or halo, and (4) the abundance patterns of the sample are distinct from those in the spiral galaxies M33, M81, and NGC 300. Using standard PN age diagnostic methods, we suggest that all of the PNe formed ∼2 Gyr ago in a starburst of metal-rich interstellar medium that followed an M31–M33 encounter about 3 Gyr ago. We review supporting evidence from stellar studies. Other more prosaic explanations, such as dwarf galaxy assimilation, are unlikely.

Key words: galaxies: abundances – galaxies: individual (M31) – ISM: abundances – planetary nebulae: general – stars: evolution

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1. INTRODUCTION

The cumulative history of metal enrichment in disk-dominated galaxies can be gleaned from the abundances of α elements of their ionized nebulae and young stars. Ionized nebulae are particularly advantageous since their lines of the lighter α elements (notably oxygen, neon, argon, and sulfur) are luminous over a wide range of α element abundances (up to 10% of the central star’s total luminosity) and their emission-line fluxes are concentrated in narrow lines. Absorption lines of B-type stars and Cepheids can also be used to estimate α element abundances and their radial gradients in nearby spirals, though the observations are more challenging, especially when the metal abundances are small.

Until recently, most studies of the α elements and their spatial distributions have been confined to the Milky Way. See Henry et al. (2010) and Kwitter & Henry (2012, hereafter KH12) for a detailed review of the elemental abundances and their gradients measured in the Milky Way and its companion galaxies. However, the Milky Way presents several practical challenges. Interstellar absorption and extinction limit the spatial range and spectral coverage of such studies to a few kiloparsecs near the Sun (except toward the Galactic anticenter). Moreover, distances—and hence the Galactic locations—of many nebulae are poorly determined.

For these reasons, most recent studies of the distributions of the α element abundances have focused on nearby galaxies, with emphasis on those in the Local Group. Although the emission line luminosities of H ii regions are much larger than those in planetary nebulae (PNe), compact PNe offer several important strategic and tactical advantages for studies of metal enrichment in galaxies out to distances of ∼5 Mpc: (1) unlike H ii regions and early-type stars PNe can be found in all types of galaxies and stellar environments; (2) PNe can be traced to much larger radii than H ii regions in disk-dominated galaxies; (3) PNe are not constrained to spiral arms where local and foreground extinction hinder observations of important ultraviolet lines; and (4) the surface brightnesses of the most luminous PNe are far higher than those of H ii regions, which enables flux-limited observations of faint emission lines using the small entrance apertures generally needed for spectroscopy.

Most nebular emission-line studies use O/H as a proxy for the α elements in the interstellar medium (ISM) since, like other light α elements, oxygen is not altered during the evolution of the central stars of H ii regions and PNe. Thus, the observed α element abundances characterize the ISM from which the stars formed. In practice, the O/H ratio is the best determined of the light α elements owing to its prominent lines of O* and O++ as well as to the reliability of measuring the nebular temperature and correcting for unseen higher ionization states.

Observations of PNe allow the radial distribution of O/H to be traced throughout large galaxies, including their innermost and outermost regions (bulges and halos) where star formation has long ceased. Jacoby & Ciardullo (1999) used PNe to probe the abundances of M31 PNe, most of them in the bulge. Magrini et al. (2009, hereafter Mag09), Stanghellini et al. (2010, hereafter Stang10), and Stauffer et al. (2013, hereafter Stas13) studied the metal gradients of PNe in M33, M81, and NGC 300, respectively. We discuss their results later. All of these galaxies show a systematically negative slope of the radial O/H gradient. This is expected since oxygen enrichment is much stronger in the inner spiral-arm-dominated regions of disks where massive
stars have been forming and expelling light α elements at the ends of their brief lives.

Until recently, systematic studies of the O/H distribution of M31 were based on spectroscopy of its prominent H II regions. Kwitter et al. (2012, hereafter Paper I) concentrated on the O/H abundances of PNe beyond the spiral arms. They found that, unlike the other nearby spiral galaxies, the PNe of M31 show a very shallow radial O/H gradient over 18 ≤ Rg ≤ 45 kpc; that is, to distances well beyond R25⁶ and the well known warp in H I (Braun et al. 2009; Chemin et al. 2009; Corbelli et al. 2010). Their results show that O/H is within about 0.1 dex of its solar value at the outermost radius—surprisingly high since the underlying stellar population is generally characterized by [Fe/H] ≤ −0.7, but with some prominent exceptions discussed below.

Here we report the results of abundance studies of two additional bright PNe, M174 and M2496, located about a degree from the nucleus along opposite sides of M31’s minor axis. These PNe, both found in the extensive PN discovery survey of Merrett et al. (2006, hereafter M06), lie along the edge of what appears to be a faint extended disk that shares the orientation and general rotation pattern of M31’s inner disk (Ibata et al. 2005; see especially their Figure 1), but not in any of M31’s known stellar streams (Lewis et al. 2013, hereafter LB13). If the extended disk has the same inclination as the inner one, then M174 and M2496 are at deprojected distances Rg greater than 55 kpc.

Our primary goals are (1) to measure the O/H values of M174 and M2496, (2) to see whether the O/H trends found in Paper I continue to larger distances or whether PNe far beyond R25 have the metal abundances of the halo as one might normally expect (Courteau et al. 2011, hereafter Cour11), and (3) to use these results to illuminate the evolution of M31’s outermost structure and chemistry. The new observations are described in Section 2, the observational results are presented in Section 3, and we discuss these results within the context of complementary published results for the same general regions of M31 and other spirals in Section 4. In Section 5, we propose and evaluate a formation scenario for the ensemble of 16 PNe observed in Paper I and the 2 PNe reported here.

2. OBSERVATIONS

We present new spectrophotometry of two outer PNe in M31 from the catalog of Merrett et al. (2006, hereafter M06), M174 and M2496 (Figure 1(a)). Their fundamental properties are presented in Table 1. The values of Rg were estimated using the method described in Paper I and its erratum (Kwitter et al. 2013). We also show the apparent magnitude in [O iii], m5507, listed by M06. M2496 is one of the brightest PNe in the M06 survey, and indeed, all 18 of our objects are within 0.7 mag of the bright end cutoff of the planetary nebula luminosity function (PNLF; see, e.g., Ciardullo 2010).

The spectra were obtained on different nights in 2012 August and September at the 10.4 m Gran Telescopio Canarias (GTC) at the Roque de los Muchachos Observatory on the island of La Palma, Spain. Finding charts were generated from Sloan Digital Sky Survey images (DR8). The GTC calibration plan provides, in each observing night, at least one spectrophotometric standard to be used for flux calibration. The OSIRIS instrument was used in its long-slit mode. The combination of grism R1000B and a slit width of 0′.8 provides a spectral dispersion of 2.1 Å per (binned 1 × 2) pixel, a resolution of 6.3 Å, and a spectral coverage from 3700 Å to 7850 Å. Seeing was 0′.8, and the spatial scale along the slit is 0′.254 per binned pixel. Neither of the targets was spatially resolved. The total exposure was 117 minutes for M174 and 106 minutes for M2496, each split into four sub-exposures. These data were obtained under photometric weather conditions and the slit was placed along the parallactic angle in

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⁶ We adopt R25 = 30.1 kpc, estimated from Figure 1 of Courteau et al. (2011, hereafter Cour11); see also Chapman et al. (2006, hereafter Ch06).
order to minimize the effects of atmospheric dispersion. The nebular data and results are given in Appendix A.

An additional 145 minutes of exposure of M174 were taken during a night with strong dust pollution from the Sahara desert. This, together with the observations of a poorly sampled spectrophotometric standard, prevented a precise flux calibration and therefore these data were not used for the nebular analysis. However, they were added to the best quality data for M174 to improve the signal-to-noise ratio of the faint stellar features discussed in Appendix B.

3. RESULTS

The observations and results for M174 and M2496 are compiled in Appendix A.

We used cloudy version c08.00 (Ferland et al. 1998) with the measured nebular abundances to fit the observables—the [O iii] luminosity found by M06, along with important emission line strengths and ratios—by appropriate choices of initial conditions including stellar surface gravity, luminosity, and temperature, and the nebular density structure. On a Hertzsprung–Russell (H–R) diagram the derived properties of the central stars place them near the evolutionary tracks for central stars of mass $0.6 M_\odot$ and independently confirm the initial masses of the central stars near $2 M_\odot$, as expected. In brief, the properties of the nebulae derived from the present spectroscopic observations are very similar to the 16 PNe studied earlier (Paper I). As we shall see, all 18 PNe form a homogeneous group with similar masses, ages, and metallicities. We shall see that all 18 PNe form a homogeneous group with similar masses, ages, and metallicities.

Hereafter, we refer to the “oxygen abundance” using the convention $12+\log(O/H)$, where $O/H$ is the result of the ict analysis. The average abundance for the sample of 18 PNe is $8.62 \pm 0.14$. Richer et al. (1997b) found essentially the same value, $8.64 \pm 0.32$, for 19 PNe in M31’s bulge. Using different analysis methods than ours, Jacoby & Ciardullo (1999) found $8.40 \pm 0.33$ for 12 bulge and $8.46 \pm 0.18$ for three disk PNe. The large dispersion in $O/H$ among bulge PNe appears to be real and much larger than that of disk PNe. The corresponding value for the Sun is 8.69 (Asplund et al. 2009) and for the Orion Nebula it is 8.73 (Esteban et al. 2004). Thus, the ensemble-average $O/H$ ratio is solar (within the uncertainties). Figure 1(b) displays the oxygen abundance gradient; no significant trend is obvious. The slope of a simple linear fit is $-0.005$ dex kpc$^{-1}$ with a regression coefficient, $R$, of 0.41 and a standard deviation of the residuals $\pm 0.14$ (that is, fitting a linear slope does not decrease the scatter of the points from the trend line).

In Paper I, M1074 (denoted “PN10”) was included in the data tables but omitted from the gradient fit because [O iii] $\lambda 3727$ was not detected, yielding only an upper limit for $O^+/H^+$. In reviewing the data for M1074, we found that the upper limit of $O^+/O$ is a tiny fraction of $O^+/H^+$, so the omission of $O^+$ in its $O/H$ ratio is insignificant. Accordingly, we have included it here for completeness. Had M1074 been included in Paper I, it would have decreased the slope of the gradient from $-0.011$ to $-0.007$ dex kpc$^{-1}$.

3.1. Comparison with Overlapping Spectroscopic Surveys

Recently, Sanders et al. (2012, hereafter SC12) obtained spectra using the “Hectospec” fiber spectograph of the MMT near Tucson for 713 heterogeneously selected H ii regions and PNe in M31 and cross-referenced their targets with those of M06. The way in which their sample of PNe was chosen precludes an unbiased PNLF from their measurements. SC12 derived $O/H$ values for all 68 of the 459 of the PNe for which the [O iii] $\lambda 4363$ flux was derived. We compute that their average oxygen abundance is $8.41 \pm 0.25$. This scatter is almost twice as large as we derive for our measurements. The gradient of their $O/H$ abundances is $+0.00386$ dex kpc$^{-1}$ with a regression coefficient $0.015$; that is, consistent with a scatter diagram.

Both M174 and M2496 were observed by SC12, who derived a value of $O/H$ for M174 that is larger than ours by 0.1 dex (well within the common uncertainties); they did not observe [O iii] $\lambda 3727$ in M2496 and therefore did not determine its $O/H$. A comparison between our fluxes and theirs shows general agreement except for (1) the fluxes of the relatively weak [O iii] $\lambda 4363$ line of M174, for which the disagreement is 50% (more than the sum of the errors) and (2) the fluxes of the bright H$\alpha$ and [O iii] $\lambda \lambda 4959, 5007$ lines for which we sometimes find fluxes 10% larger than theirs. We also find that the ratio of two bright lines, H$\alpha$/[N ii] is consistently different by up to 10% for five objects in common. Their H$\alpha$/[N ii] ratio is sometimes <2.8, below the limit for case-B recombination lines for conditions in PNe. As a consequence, our extinction corrections and final results do not generally agree well.

We compared the $O/H$ abundances of five PNe observed by SC12 in common with our samples. The ratios of $O/H$ for individual PNe derived by SC12 and our group for individual

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Table 1

| Merrett # | R.A.2000 | Decl.2000 | $m_{5007}^a$ | $V_{helio}^b$ | Angular Offset$^c$ | $R_c^d$ (kpc) |
|----------|---------|----------|-------------|-------------|-----------------|-------------|
| M174     | 0:39:01.0 | 41:51:11.1 | 20.89       | $-209.0$    | 0:91            | 57.6        |
| M2496    | 0:44:26.0 | 40:15:45.6 | 20.42       | $-324.0$    | 1:06            | 55.5        |

Notes.

a $m_{5007} = -2.5 \log F_{5007} - 13.74$.
b Taken from Merrett et al. (2006).
c Measured from M31’s center.
d Assumep $D_{M31} = 770$ kpc (Freedman & Madore 1990) and disk inclination $= 77.7$.

7 We have accounted for extinction/reddening in terms of the observed versus expected Balmer decrement in the nebular gas; we cannot measure and have ignored circumstellar extinction/reddening in this analysis. Corrections for circumstellar dust would increase estimates of stellar temperature and luminosity, shifting them onto the evolutionary tracks of rapidly evolving higher-mass central stars, and decreasing the estimated PN ages.

8 There are Merrett numbers for 101 of their 253 H ii regions, suggesting that the M06 studies of the PNLF are contaminated by small numbers of tiny H ii regions in the inner disk.

9 We suspect that confusion of this line with the $\lambda 4358$ sky line of Hg I is to blame when observing at moderate dispersion using a fiber spectrograph. This sky line is faint at the Roque de los Muchachos Observatory.
PNe range from 0.4 to 1.8. We have not attempted to resolve the systematic differences of our abundance results.

3.2. Additional Results

The deep GTC spectra also yielded some unexpected detections of broad C\textsc{iii} and C\textsc{iv} lines in the stellar spectrum of M174 and M2496. These are lines commonly associated with the winds of WC stars; we present these results in Appendix B.

It is worth adding that in 2012 October we obtained spectra of three additional PNe in M31: M50, M2507, and M2549, which were observed between two and three hours each on the same night using the Double Imaging Spectrograph at Apache Point Observatory in generally clear weather but erratic seeing. M50 lies just inside the inner range of our previous sample of PNe (\(R_g \approx 16\) kpc). The other two lie well beyond it (\(R_g \approx 100\) kpc).

Our goal was to see whether the general spectroscopic properties of these PNe were readily distinguishable from those of M174, M2496, and the other 16 PNe of Paper I. The innermost of the three PNe, M50, is sufficiently bright that we could derive an oxygen abundance of \(8.7 \pm 0.2\) dex, in good agreement with other PNe at the same \(R_g\). The brighter lines of the other two objects, M2507 and M2549, are very similar to those of the other 18 PNe. The [O\textsc{iii}] \(\lambda 4363\) lines were detected but faint.

The measured [O\textsc{iii}] \(\lambda 4363/\lambda 5007\) ratios support only a lower limit on their O/H abundances: \(\geq 8.2\) and 8.6, respectively. In brief, the limits of O/H for M2507 and M2549 indicate no clear sign of any abrupt change of the O/H abundance ratio for PNe inside \(R_g = 16\) kpc or beyond \(\approx 60\) kpc. The results of the new Apache Point Observatory (APO) data are preliminary. We have been granted time to obtain deeper spectra of these and other PNe in M31 using the 10.4 m GTC and 3.5 m APO telescopes in the autumn of 2013.

4. DISCUSSION

Our primary goal in this section is to find a framework for interpreting the basic observables in this paper: (1) the uniformly solar-like O/H (and other low-mass \(\alpha\) elements) in 18 bright PNe; (2) the general kinematics of the sample that much more closely resemble the rotation pattern of the classical disk of M31 than its halo or bulge; and (3) the uniqueness of the high O/H and flat gradient in our M31 ensemble of PNe relative to PNe in other galaxies. Our first task is to integrate the present results into complementary information about the outer regions of M31. We focus on studies of stellar populations since no significant reservoir of cold gas, dust, or ionized gas is found (Thilker et al. 2004; Irwin et al. 2005; Montalto et al. 2009; Azimlu et al. 2011), nor is there direct evidence of ongoing star formation in the disk of M31 beyond \(R_g \approx 20\) kpc (Choi et al. 2002; Cour11).

4.1. Population Membership

As noted earlier, M174 and M2496 lie along M31’s minor axis a degree from its center. Their locations suggest that they might be members of M31’s bulge or halo (Brown et al. 2008, Figure 1) rather than an extended disk in which we have argued the other 16 PNe are found (Paper I). By way of review, note that the innermost dozen PNe in this study between \(\sim 20 < R_g < 30\) kpc lie along an elliptical arc that has the same shape and orientation as the outer isophotes of the disk itself. Indeed, as Figure 1(a) shows, all of the luminous PNe inside the 40 kpc ellipse have disk-like angular distribution. This strongly suggests a direct association of these PNe with the disk.

Moreover, taken as a group, the set of 16 PNe studied initially shares the same kinematic patterns (and statistical deviations) as nearby disk stars (Ibata et al. 2005, Figure 5; Chapman et al. 2006, Figure 1(b)) and scattered clouds of H\textsc{i} (Thilker et al. 2004). Such large scatter is characteristic of the thick disk of M31 (Collins et al. 2011) and the disks of spiral galaxies that have been disrupted by impacts with smaller galaxies (Sales et al. 2009). This all but eliminates the hypothesis that most of all of the 16 PNe are or have been members of the metal-poor and kinematically inhomogeneous halo.

Thus, we now explore whether M174 and M2496 are members of the same dynamical group as the other luminous PNe within the \(R_g = 40\) kpc ellipse of Figure 1(a). The heliocentric Doppler motions of M174 and M2496 are \(-209\) and \(-324\) km s\(^{-1}\), respectively. These differ somewhat from those expected of ideal disk members in circular orbits \((\sim 300\) km s\(^{-1}\))—but not by more than the deviations of the other 16 PNe. Although the spatial and kinematic evidence is inconclusive, the uniformly unusual metallicities of all 18 PNe allow us to presume that M174, M2496, and the remaining 16 PNe are a physical group that might share a common history. Thus, we place both PNe in the extended disk of M31 (Section 1) at deprojected distances \(R_g > 55\) kpc from its center (Table 1).

To further explore possible PN–stellar-population membership, we exploit the abundance studies of red giant branch (RGB) stars in the same general vicinity as the ensemble of PNe by Chapman et al. (2006, hereafter CH06). CH06 obtained deep Keck spectra of nearly 10,000 RGB stars in 54 scattered fields, most all of them located outside the 20 kpc ellipse shown in Figure 1(a). The [Fe/H] results that they found in each field are based on high-quality spectra of the Ca\textsc{ii} triplet lines in at least 10 stars per field.

CH06 divided their sample into two groups: those with distinctly disk-like kinematics and those with spheroidal kinematics. Most of their observed fields show [Fe/H] \(< -0.7\). This result is expected for the spheroidal stellar population (Kalirai et al. 2006). Of more interest here is the disk component. In Figure 9 of CH06 it can be seen that all five of their metal-rich disk fields \((0 < [\text{Fe/H}] < -0.5)\) are in the outer zone between the 20 kpc and 40 kpc ellipses of Figure 1(a). (That is, the [Fe/H] gradient has a positive slope.) Moreover, the metal-rich fields each lie to the northwest of the 20 kpc ellipse; that is, in the immediate vicinity of 13 of the PNe studied in Paper I in which the O/H abundances are nearly solar. This shows a high spatial correlation of some high-metallicity RGB stars and most of our oxygen-rich PNe.

The potentially high metallicity of disk stars at about the same \(R_g\) is confirmed by the analysis of very deep color–magnitude diagrams (CMD) obtained by Brown et al. (2006) with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope. They analyzed spheroidal and disk-dominated fields at \(R_g \approx 30\) kpc. After subtracting the spheroidal contamination in the disk field, BS06 found that the relatively metal-rich disk population is characterized by [Fe/H] \(\approx +0.3\) (and its age is estimated at 6 Gyr). The disk field is located along M31’s major axis about 28 kpc to the northeast of the nucleus where we are planning future observations of luminous PNe.

Similarly, Richardson et al. (2008, 2009) constructed CMDs from deep ACS images in several fields in M31 far beyond \(R_{25}\). Their fields lie along the edge of the extended disk. This outer stellar disk is characterized by an exponential scale length of 14 kpc, a semimajor axis of 55 kpc (similar to the deprojected
radii of M174 and M2496), and the general colors of a metal-rich stellar population (Irwin et al. 2005). The CMDs at the edge of this extended disk constructed by Richardson et al. show that the metallicity of stars at the outer edge of has an irregular distribution at that projected radius. Values of [Fe/H] derived by Richardson et al. (2009) in these and more distant fields show significant variations from ∼−0.54 to −1.03 with only a small correlation of the metallicity with the presence of faint stellar streams and related features.

Recently, Bernard et al. (2012, hereafter BFB12) published deep ACS CMD studies of the stellar populations in two fields on either side of M31’s Hα warp. They concluded that a relatively young (∼2 Gyr) stellar population is present in the warp field that is characterized by solar [Fe/H]. Interestingly, another CMD of a field located inside M31’s warp radius showed no trace of a young and high-metallicity counterpart.

4.2. α Element Abundances of PNe in Other Spiral Galaxies

Our second task is to investigate whether the O/H trends found in our M31 ensemble of PNe are typical of other galaxies. The ensemble-average value of O/H for the PNe in M31 are essentially the same as the corresponding values for PN in disk galaxies of comparable luminosity; that is, the value of (12 + log(O/H)) for the PNe in the outer disk of M31 is in agreement with or slightly higher than those of the inner disks of the Milky Way (8.61; Kwittr & Henry 2012, hereafter KH12), M81 (8.59; Stang10), and NGC 300 (8.57; Stas13). All of these O/H results are well in excess of those in less massive galaxies, including M33 (8.29; Mag09), the LMC (8.27; KH12), the SMC (8.04; KH12), and M32 (≈8.3; Richer & McCall 2008, with considerable dispersion in the data, as estimated from their Figure 4).

However, the O/H values of PNe in M31 differ from those in other systems in that M31 shows little, if any, sign of a radial gradient. Mag09 and Stang10 found that the radial gradients in M33 and M81, respectively, are clearly established and in line with those of Hα regions in the same ranges of R. These authors concluded that there is no evidence of recent oxygen enrichment in either galaxy. PNe in NGC 300 also show a somewhat negative O/H gradient (Stas13), though its slope is flatter than that of nearby Hα regions. From this, Stas13 concluded that oxygen is currently undergoing enrichment in its disk.

From their analysis of N and O gradients of the PNe, Stas13 (p. A12) conclude “oxygen is affected by nucleosynthesis in the PN progenitors, by an amount which depends at least on the stellar rotation velocity and possibly other parameters.” In other words, PNe in NGC 300 are enhancing their oxygen, in contradiction to many common models of nucleosynthesis (next section) and the studies of M31, M81, and the Milky Way cited in Section 1.

5. INTERPRETATION

The science goal of this section is to uncover—or at least to illuminate—the origins of the highly enriched PNe in this study. There are some hard constraints; the anomalously high O/H ratio and flat radial gradient of all 18 PNe in M31 suggests that a common explanation of their solar-like O/H abundances is necessary. Moreover, we seek an explanation of the abundance pattern of PNe of our M31 ensemble that is not characteristic of other spiral galaxies whose radial O/H abundance gradient is steeper. Thus, we seek a scenario that connects our results to a particular history for M31’s outer regions. In particular, we are looking for some sort of a ongoing mechanism that transports the metal-rich stars or ISM in the inner disk into the outer extended disk after nuclear burning processes had a chance to enrich the metals. This may take the form of an event that deposited stars or gas with α elements with approximately solar abundances in the other disk of M31.

5.1. Injection of Enriched Gas and Stars in M31’s Outer Disk

It is instructive to identify and eliminate some common enrichment scenarios that do not seem to apply to M31. For example, we have just seen that many nearby RGB stars in addition to the PNe share similar metallicities, so it seems unlikely that PNe in M31 have undergone self-enrichment of oxygen.

In addition, the process of radial migration (Sellwood & Binney 2002; Schönrich & Binney 2009a, 2009b; Loebman et al. 2011; Bird et al. 2012) has been suggested as a means to transport stars and gas radially outward from inner metal-rich parts of the disk. However, migration acts gradually and only where the gravitational perturbations of the arms are prominent. This mechanism is not likely to account for the flat O/H gradient or patchy groups of metal-rich stars found far beyond the inner disk. Moreover, Gogarten et al. (2010) found that the migration hypothesis was inapplicable to the PNe in the disk galaxy NGC 300. Finally, the process is incapable of producing the positive [Fe/H] gradient observed in the disk component of RGB stars studied by CH06. Further, radial migration is likely to operate similarly in all comparable spirals (especially M33 and M81, in which the spiral arms are more prominent than in M31), contrary to the differences of O/H gradients in other spirals noted in Section 4.

Local ISM enrichment by core-collapse supernovae is implausible and never observed in the outer parts of large spiral galaxies. A gaseous transport process known as the “fountain effect” can redistribute enriched disk gas using the momentum of supernova blast waves as a transport mechanism. However, Spitoni et al. (2013) concluded that fountains in the inner disk of M31 could only mix gas locally (∼1 kpc).

Metal-rich stars and gas can be transported outward by external mechanisms; to wit, galaxy–galaxy encounters. The outer regions of M31 are marbled with stellar streams and other structures that are generally assumed to be the result of numerous past encounters with dwarf galaxies. The “splashes” following their impacts can also disrupt the ambient ISM of the inner disk (Purcell et al. 2010). However, random bombardments by dwarf galaxies only eject and disperse small amounts of ISM to high galactic latitudes. Even many encounters with dwarf galaxies are not likely to account for the high metal content of all of the PNe in the ensemble or the many metal-rich stars far from the inner disk.

Thus, we seek some sort of rare, major, recognizable, and probably fairly recent event that led to a major disruption of the ambient metal-enhanced gas and the possibly the stars in the inner disk. We now review the evidence—for which there is a growing body—for an encounter between M31 and a gas-rich galaxy that triggered a starburst from which the ensemble of PNe in this paper evolved. Our aim is to find a “smoking gun”.

10 It is worth noting that the PNe in all of these galaxies as well as and those in M31 (Paper 1), the SMC and LMC (KH12), and the Milky Way (H10)—as well as the Sun and Orion—share the same Ne/O ratios. This indicates that O and Ne are universally enriched at the same rates and, presumably, by the same processes in all of these galaxies, implying that any oxygen enrichment process operating within NGC 300 (and apparently only NGC 300) also proportionally enriches Ne. See the discussion in Section 7 of Stas13 for more details.
an event identified by its age and degree of disruption of both galaxies involved in the encounter.

5.2. The Enrichment of Gas and Stars in the Outer Disk of M31

Cox & Loeb (2008) modeled the plausible consequences of a future collision of M31 and the Milky Way. They stated (p. 461): “Eventually, after the merger has completed, the Sun is most likely to be scattered to the outer halo and reside at much larger radii (>30 kpc).” By analogy, the formation of a starburst in M31 that could lead to the production of a generation of metal-rich group of PNe might have resulted from a comparable encounter with another large galaxy in the past.

The obvious candidate is the spiral galaxy M33 presently located about 14° (≈200 kpc) southeast of M31. McConnell et al. (2009, hereafter Mc09) obtained very deep tiled images of a 220 deg² in an extended field containing both M31 and M33 as well as a three-color image overlay around M31. They found a bridge of RGB stars that includes a prominent stellar stream joining the two galaxies. Mc09 ran a “soft-particle hydrodynamical” model (SPH) which demonstrated that an encounter of M31 and M33 about 2.6 Gyr ago (pericenter ≈ 53 kpc) could account for the morphologies of the warp in the inner disk of M31 and some of its stellar streams. The model of the interaction shows that stars from the disk can be disrupted to the outer regions of M31 that were discussed in Section 4. Braun & Thilker (2004) and Lockman et al. (2012) have found a corresponding bridge of H I that spatially and kinematically connects M31 and M33.

The ages of stellar populations can be untangled from high-quality CMDs. Hammer et al. (2010) interpreted existing CMDs from the literature and the morphologies of stellar streams outside of M31’s extended disk to suggest similarly, that a merger with a 3:1 mass ratio at a pericenter of 25 kpc unfolded between 5.5 and 9 Gyr ago. The predominant ages of metal-rich stars ([Fe/H] ≈ 0.3), in the outer disk found by Brown et al. (2006), 5–8 Gyr, serve as evidence of a post-encounter starburst.

More recently, BFB12 found that a high-quality CMD of a field at the outer edge of the disk in M33 (originally published by Barker et al. 2011) contains a metal-rich, ≈ 2 Gyr old stellar population—much the same as that found from their deep CMD in their warp field of M31. These unusual findings are best explained by a common origin—the ongoing M31–M33 encounter modeled by Mc09—and establish that the starburst occurred from a highly metal-enriched ISM. The recent M31–M33 encounter scenario is also corroborated indirectly. On the observational side, even though the H-band flux of M33 is 15 times fainter than that of M31 (NED), M33 has a current global rate of star formation that is 4.6 times higher (Kennicutt 1988). This supports the notion that a massive starburst in M33 has been triggered by a recent global disruption. Also, Cioni (2009) found that the stellar population of M33 shows that the [Fe/H] gradient flattens abruptly beyond the spiral arms (R_p < 9 kpc). This is an expected outcome of the numerical model of the M31–M33 encounter by Mc09.

H II regions of other disrupted disk galaxies have been found to show a pattern of flat O/H gradients. Werk et al. (2011) measured the O/H ratios of H II regions throughout 13 galaxies from the “Rogues H II Survey.” The target galaxies were selected for their unusually extended H I disks and/or peculiar H I features indicative of recent galaxy encounters (Hibbard et al. 2001). Werk et al. found that the H II regions in the Rogues sample show emission-line spectra indicating higher-than-expected O/H at large R_p. They suggested that the ionizing stars formed from metal-rich material that was transported to larger galactic radii by the encounter that disturbed the H I out to the regions where the present H II regions formed.

5.3. The Formation of the Ensemble of Oxygen-rich PNe in M31

The next question is whether the ages of PNe connect their progenitor stars to either of the encounter events ~2 or ~6 Gyr in the past. The method for estimating the ages of the progenitors was described in Paper I. In summary, it relies on stellar evolution models that predict the evolving ultraviolet luminosities and stellar temperatures of post-AGB stars that shed and later ionize the nebular gas. Models by Richer et al. (1997a), Marigo (2001), Marigo et al. (2004), Catalán et al. (2008), and Karakas (2010) and others predict the evolving AGB mass yields as a function of the initial mass of the progenitor star. Other models, such as those of Schaller et al. (1992), Marigo et al. (2004), Schönberner et al. (2005, 2007) and Méndez et al. (2008) predict the evolving properties and related observables of the nebula. These observables can be used to locate the central stars of PNe on an H–R diagram and, hence, to determine their initial masses and ages from evolutionary tracks.

Following this procedure, we find that the characteristic initial masses of the central stars are on the order of 1.5 M_⊙ and their corresponding evolutionary ages are ~2 Gyr. This is the same age derived by other authors who selected their targets from the PNe with highest L(0.6a), including Mag09, Stang10, and Stas13. The ages of these PNe are sufficiently short that their α element abundances must be very close to those of the current ISM. Therefore, taken at face value, associating the ensemble of PNe with the M31–M33 encounter of 2.6 Gyr ago (Mc09) and post-encounter metal-rich starburst of 2 Gyr ago (BFB12) is straightforward. Although the evidence, such as it is, is largely circumstantial, the puzzle pieces fit without mishap. If the ~2 Gyr ages of the PNe are approximately estimated, then the ensemble of PNe cannot be attributed to any earlier starburst in M31.

The veracity of this or any other PN age estimate method can be challenged owing to the universality of the bright-end cutoff of the PNLF. Specifically, the form of the PNLF has been found to be independent of the size and stellar content of the underlying galaxy, including some early-type galaxies in which star formation has been dormant for cosmic timescales. (See Ciardullo et al. 2005 and Ciardullo 2010 for a much deeper discussion of the challenges this poses to current understanding of stellar evolution.) In other words, PNe selected for their high [O III] luminosities, such as those in this study, have indeterminate ages. While their O/H enrichment might be explainable by metal-enriched gas transported to the outer disk by a past encounter, their formation cannot be directly tied to any particular event.

Despite their common abundances and kinematics, this age indeterminacy may well apply to PNe in M31. M06 found that the radial distribution of PNe follows the distribution of R-band light out to a radius of 2° along M31’s major axis (six disk scale lengths = 0.9 R_25). This and the similarity of R, I, J, and K surface brightnesses along M31’s major axis (Cour11) suggest that PNe are associated with a very old stellar population of
M31. M06 also found that the shape of the PNLF was invariant with deprojected disk radius, $R_d$, within their densely sampled zones along the entire major axis of M31. While the present sample of PNe mostly lie beyond this radius, and while their numbers are too small to check the shape of the PNLF, we have no reason to argue that the PNLF of the outer disk of M31 is anything but ordinary.

Until the enigma of the universal PNLF is resolved—that is, why otherwise successful theories of AGB and post-AGB evolution cannot be used to predict the progenitor mass—we can only conclude that all 18 O-rich PNe in M31 seem to have had a common origin, and one that is most likely the result of a past starburst event within a metal-rich environment.

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**APPENDIX A**

**TABULATIONS OF OBSERVATIONS AND RESULTS**

As stated in Section 3, these data have been analyzed using the same techniques as those in Paper I, so that the results are directly comparable to the other PNe in Figure 1(a).

Table 2 contains the emission-line measurements. The column entries are as follows: the first column lists the ion and wavelength designation of each line; $f(\lambda)$ gives the value of the reddening function, normalized to $c(H\beta) = 0$; $F(\lambda)$ is the measured flux and estimated error, relative to $H\beta = 100$; and $I(\lambda)$ gives the reddening-corrected intensity and estimated error, also relative to $H\beta = 100$. Interstellar reddening corrections are based on Savage & Mathis (1979). At the bottom of each column, for each nebula we list the logarithmic reddening parameter, $c(H\beta)$, the theoretical Hα/Hβ ratio appropriate for the

| Line | M174 | M2496 |
|------|------|-------|
|      | $f(\lambda)$ | $F(\lambda)$ | $I(\lambda)$ |
| [O ii] λ3727 | 0.292 | 47.5 | 49.4 ± 11.01 |
| H$\beta$ + H$\alpha$ λ3770 | 0.224 | 15.5 | 16.0 |
| He$\alpha$ + H$\alpha$ λ3797 | 0.460 | 9.5 | 7.5 |
| He$\beta$ + H$\alpha$ λ3835 | 0.144 | 1.1 | 0.9 |
| [Ne ii] λ3869 | 0.225 | 20.7 | 20.9 |
| He$\alpha$ + H$\beta$ λ3889 | 0.387 | 5.7 | 5.5 |
| [Ne i] λ3968 | 0.228 | 23.8 | 24.6 ± 8.15 |
| He λ3970 | 0.224 | 15.5 | 16.0 |
| He$\alpha$ + He$\alpha$ λ4026 | 0.209 | 2.7 | 2.7 |
| [S ii] λ4071 | 0.196 | 3.1 | 3.0 |
| H$\alpha$ + H$\alpha$ λ4101 | 0.188 | 2.5 | 2.5 |
| C$\alpha$ λ4267 | 0.154 | 0.1 | 0.1 |
| He$\alpha$ λ4340 | 0.124 | 4.0 | 4.0 |
| [O i] λ4363 | 0.118 | 1.5 | 1.5 |
| He$\alpha$ λ4472 | 0.090 | 1.7 | 1.7 |
| C$\alpha$ + O$\alpha$ λ4650 | 0.045 | 1.0 | 1.0 |
| [Fe ii] λ4658 | 0.043 | 0.4 | 0.4 |
| He$\alpha$ + [Ar iv] λ4711 | 0.030 | 0.39 | 0.39 |
| [Ar iv] λ4740 | 0.023 | 0.8 | 0.8 |
| H$\beta$ λ4861 | 0.000 | 0.0 | 0.0 |
| He$\alpha$ λ4922 | 0.012 | 2.1 | 2.1 |
| [O ii] λ4959 | 0.030 | 0.36 | 0.36 |
| [O iii] λ5007 | 0.042 | 0.07 | 0.1 |
| [C iv] λ5518 | 0.157 | 0.3 | 0.3 |
| [C iv] λ5800 | 0.161 | 0.7 | 0.7 |
| [N ii] λ5755 | 0.207 | 1.0 | 1.0 |
| C$\alpha$ λ5806 | 0.212 | 12.2 | 12.2 |
| He$\alpha$ λ5876 | 0.023 | 18.0 | 18.0 |
| [O i] λ6300 | 0.013 | 7.0 | 7.0 |
| [S ii] + He$\alpha$ λ6312 | 0.315 | 2.2 | 2.2 |
| [O i] λ6364 | 0.025 | 2.3 | 2.3 |
| [N ii] λ6548 | 0.058 | 13.1 | 13.1 |
| He$\alpha$ λ6563 | 0.360 | 298 | 298 |
| [N ii] λ6584 | 0.364 | 40.2 | 40.2 |
| He$\alpha$ λ6678 | 0.380 | 4.1 | 4.1 |
| [S ii] λ6716 | 0.387 | 1.4 | 1.4 |

As stated in Section 3, these data have been analyzed using the same techniques as those in Paper I, so that the results are directly comparable to the other PNe in Figure 1(a).
Table 2 (Continued)

| Ion        | $f(\lambda)$ M174 | $F(\lambda)$ M174 | $I(\lambda)$ M174 | $f(\lambda)$ M2496 | $F(\lambda)$ M2496 | $I(\lambda)$ M2496 |
|------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| [S II] 6731 | $-0.389$           | 3.13               | 2.97 ± 0.44        | 2.17               | 1.92 ± 0.28        |
| He I 4713   | $-0.406$           | 9.90               | 9.33 ± 1.50        | 13.2               | 11.4 ± 1.84        |
| [Ar IV] 6713 | $-0.453$          | 14.2               | 13.4 ± 2.19        | ...                | ...                |
| He I 6728   | $-0.475$           | ...                | ...                | 2.17               | 1.86 ± 0.32        |
| [O III] 4363 | $-0.481$          | 14.8               | 13.9 ± 2.38        | 18.4               | 15.7 ± 2.70        |
| [N II] 6584  | $-0.489$           | 3.58               | 3.35 ± 0.58        | ...                | ...                |
| [Ar IV] 6775 | $-0.539$          | 2.85               | 2.65 ± 0.50        | 2.53               | 2.13 ± 0.40        |
| $c$        |                    | 0.06               | 0.14               | ...                | ...                |
| He II/He I |                    | 2.64               | 2.81               | ...                | ...                |
| log $F_{\text{He}}$ b |                    | $-14.99$           | $-15.08$           | ...                | ...                |

Notes.
- a Deblended.
- b erg cm$^{-2}$ s$^{-1}$ in our extracted spectra.

Table 3

| Ion        | $T_{\text{ion}}$ M174 | Abundance M174 | $T_{\text{ion}}$ M2496 | Abundance M2496 |
|------------|------------------------|----------------|------------------------|----------------|
| He II      | $[\text{O III}]$      | 0.116 ± 0.015 | 0.104 ± 0.014          | ...            |
| icf(He)    |                        | 1.00           | ...                    | 1.00           |
| O I (5007) | [N II]                 | $1.04 ± 0.001$ | [N II] $1.03 ± 0.001$ | ...            |
| O I (5007) | [N II]                 | $1.01 ± 0.001$ | [N II] $1.01 ± 0.001$ | ...            |
| O I (6300) | [N II]                 | $1.00 ± 0.001$ | [N II] $1.00 ± 0.001$ | ...            |
| O I (6300) |                        | 1.00           | ...                    | 1.00           |
| O I (7751) | [O III]                | $3.53 ± 0.001$ | [O III] $3.53 ± 0.001$ | ...            |
| Ar I (4102)| [O III]                | $3.53 ± 0.001$ | [O III] $3.53 ± 0.001$ | ...            |
| Ar I (4102)|                        | 1.00           | ...                    | 1.00           |
| Ar I (4740)| [O III]                | $3.53 ± 0.001$ | [O III] $3.53 ± 0.001$ | ...            |
| C I (4267)| [O III]                | $3.53 ± 0.001$ | [O III] $3.53 ± 0.001$ | ...            |
| C I (4267)|                        | 1.00           | ...                    | 1.00           |
| Cl I (3537)| [O III]                | $3.53 ± 0.001$ | [O III] $3.53 ± 0.001$ | ...            |
| Cl I (3537)|                        | 1.00           | ...                    | 1.00           |
| N I (4584)| [N II]                 | $3.53 ± 0.001$ | [N II] $3.53 ± 0.001$ | ...            |
| N I (4584)|                        | 1.00           | ...                    | 1.00           |
| Ne II (3869)| [O III]                | $3.53 ± 0.001$ | [O III] $3.53 ± 0.001$ | ...            |
| Ne II (3869)|                        | 1.00           | ...                    | 1.00           |
| S I (4077)| [S II]                 | $3.53 ± 0.001$ | [S II] $3.53 ± 0.001$ | ...            |
| S I (4077)|                        | 1.00           | ...                    | 1.00           |
| S I (4648)| [S II]                 | $3.53 ± 0.001$ | [S II] $3.53 ± 0.001$ | ...            |
| S I (4648)|                        | 1.00           | ...                    | 1.00           |

Notes.
- a Asplund et al. (2009).
- b Estimated using $T_{\text{ion}}$.
- c High-density limit.

Table 4

| Parameter | M174 | M2496 | Solar Reference$^a$ |
|-----------|------|------|---------------------|
| $T_{\text{He II}}$ | 10280 ± 573 | 12180 ± 709 | ... |
| $T_{\text{[O III]}}$ | 11140 ± 3197 | 12340 ± 364 | ... |
| $T_{\text{[N II]}}$ | 11700 ± 12430 | ... | ... |
| $T_{\text{[S II]}}$ | 10570 ± 15560 | ... | ... |
| $T_{\text{[Ne II]}}$ | 14770 ± 21540 | 15000 | ... |
| $T_{\text{[Ar II]}}$ | 16410 ± 5557 | ... | ... |
| $T_{\text{[Cl II]}}$ | 10226 ± 0037 | 0211 ± 0035 | 0174 |
| $S/H$ | 605 ± 1800(-6) | 630 ± 2111(-6) | 132(-5) |
| $O/S$ | 154 ± 0666(-2) | 237 ± 0490(-2) | 270(-2) |
| $C/H$ | 820 ± 3435(-6) | ... | 316(-2) |
| $O/C$ | 209 ± 3335(-6) | ... | 646(04) |
| $Ar/H$ | 142 ± 0415(-6) | 739 ± 1687(-6) | 251(-6) |
| $Ar/O$ | 363 ± 0745(-6) | 278 ± 0533(-6) | 513(-3) |

Notes.
- a Asplund et al. (2009).
- b Estimated using $T_{\text{He II}}$.
- c High-density limit.

nebular temperature and density, and the log of the total observed H$^\alpha$ flux through the spectograph slit.

Table 3 contains the ionic abundances for each of the PNe. It also shows the temperatures adopted from Table 4 that were used to calculate them. Asterisks denote values that were used in the brightness-weighted mean values in lines below them. The derived icf, calculated as described in Kwiter & Henry (2001), is shown for each element. This shows the factor applied to the sum of the measured ionic abundances used to correct for unobserved ionization states of each atom. Table 4 lists all the available diagnostics and total derived abundances for each PN.

The physical descriptors of M174 and 2496, temperature $T_e$ and density $N_e$, as well as their abundance ratios fall into line with the other 16 PNe that were studied in Paper I. All 18 of the PNe form a homogeneous group with very similar abundance ratios.
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Figure 2. Close up view of the spectra around the WR broad emission features of the central stars.

Table 5
Derived Stellar Parameters

| Merrett # | log $T_{\text{eff}}$ | log $L/L_\odot$ | $M_f/M_\odot$ | $L_{5007}/L_*$ | $M_*/M_\odot$ | $t_{\text{ms}}$ (Gyr) |
|---------|-----------------|----------------|---------------|--------------|--------------|-----------------|
| M174    | 4.85            | 3.70           | 0.597         | 0.05         | 1.82         | 1.53            |
| M2496   | 4.86            | 4.00           | 0.677         | 0.03         | 2.51         | 0.58            |

Notes.
- Initial stellar mass, $M_*$, determined from Catalán et al. (2008).
- Main-sequence lifetime, $t_{\text{ms}}$, determined from results of Schaller et al. (1992).

The stellar temperature, luminosity, initial and final mass, and evolutionary age were estimated from Cloudy model fits to the data using procedures described by Paper I, Section 3.3.1. The results are shown in Table 5. We adopted log $g = 6.5$ and truncated the density distribution in order to match the observed flux of $\text{[O}\ ii\text{]} \lambda 3727$. The relatively large stellar mass of M2496 is consistent with its bright $\text{[O}\ ii\text{]}$ magnitude, $L_{5007}$ (Section 2). Barring errors in the fitted model, the age of this PN is surprisingly small. We find that the locations of M174 and M2496 fall slightly to the right of the other 16 PNe on an H–R diagram; see Figure 3 of Paper I.

APPENDIX B

CARBON LINES IN THE SPECTRA OF THE CENTRAL STARS

The spectra of both M174 and M2496 show broad emission features that can be attributed to central stars of Wolf–Rayet (WR) type (Figure 2). In both objects, the strongest feature is $\text{C}\ iv\ \lambda 5805$, with FWHM $\sim 35\text{Å}$. Also visible in both is $\text{C}\ iii\ \lambda 4649$ which, in M174, has a red shoulder that is likely due to $\text{He}\ ii\ \lambda 4686$. No signs of other broad emission features (in particular, $\text{C}\ iii\ \lambda 5696$ or oxygen lines) are seen in our spectra: their upper limit is estimated to be 10% of the $\text{C}\ iv\ \lambda 5805$ flux. The line ratios and FWHM, shown in Table 6, indicate that both stars are type [WC4] according to the scheme of Acker & Neiner (2003). This type corresponds to stellar temperature between 50,000 K and 90,000 K, consistent with the modeled values around 70,000 K.

M2496, only 0.2 mag from the bright cutoff of the M31 $\text{[O}\ ii\text{]}$ PNLF, is one of the brightest PNe in M31 (M06). M174 is also bright in $\text{[O}\ ii\text{]}$, 0.7 mag from the cutoff. In this respect, finding that their central stars are of WR type comes as a surprise. According to the most recent attempts to model the PNLF (Schönberner et al. 2007), PNe with He burning central stars are not expected at its bright end. This conclusion is based on the limited information available for He burners (e.g., Vassiliadis & Wood 1994), according to which these central stars are less luminous than hydrogen-burning models when they reach high temperatures, and evolve more slowly, thereby favoring the development of optically thin (i.e., less luminous) nebulae. Our detection of WR features indicates that, on the contrary, He burners also manage to have a combined stellar and nebular evolution so as to reach the large $\text{[O}\ ii\text{]}$ luminosities near the PNLF cutoff.

It is unlikely that a very late thermal pulse is at the origin of the WR nature of the central stars of M174 and M2496, as the nebulae have high density, i.e., are presumably young, and are hydrogen-rich. A final thermal pulse when the progenitor is about to leave the AGB (AFTP), or a late thermal pulse early in the post-AGB track, is favored instead.

These PNe are not the first in M31 in which WC lines have been observed. Jacoby & Cardullo (1999) found typical WC6 emission lines in their PN FJCHP 57. Although this PN is located near the edge of the M31’s disk, its discordant Doppler shift suggests it is a member of the halo. Magrini et al. (2009) also found that PN039 in M33 shows WC stellar lines.

Note that Görny et al. (2009) found that PNe with WR central stars are among the brightest ones in the Galactic bulge, and so are some WR PNe in the LMC (see, e.g., Monk et al. 1988). Together with M174 and M2496 in M31, the occurrence of PNe with WR-type central stars in the most luminous PNLF suggests that the general evolution of He burners and their nebulae are not yet adequately understood.

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Table 6
Carbon Lines from the Central Star

| Merrett # | Line Flux (10$^{-16}$ erg cm$^{-2}$ s$^{-1}$) | FWHM (Å) |
|---------|-----------------|-----------|
|        | $C\ iv\ \lambda 5805$ | $C\ iii\ \lambda 4649$ | $He\ ii\ \lambda 4686$ | $C\ iv\ \lambda 5805$ | $C\ iii\ \lambda 4649$ | $He\ ii\ \lambda 4686$ |
|---------|-----------------|-----------|-----------|-----------|-----------|-----------|
| M174    | 1.34            | 0.88      | 0.28      | 34        | 38        | 31:       |
| M2496   | 0.62            | 0.23      | ...       | 37        | 27        | ...       |
