Publications of the Astronomical Society of the Pacific, **119**:1349–1360, 2007 December
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In Search of Possible Associations between Planetary Nebulae and Open Clusters

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Received 2007 September 25; accepted 2007 October 15; published 2007 December 21

ABSTRACT. We consider the possibility of cluster membership for 13 planetary nebulae that are located in close proximity to open clusters lying in their lines of sight. The short lifetimes and low sample size of intermediate-mass planetary nebulae with respect to nearby open clusters conspire to reduce the probability of observing a true association. Not surprisingly, line-of-sight coincidences almost certainly exist for 7 of the 13 cases considered. Additional studies are advocated, however, for six planetary nebula/open cluster coincidences in which a physical association is not excluded by the available evidence, namely M 1-80/Berkeley 57, NGC 2438/NGC 2437, NGC 2452/NGC 2453, VBRC 2 and NGC 2899/IC 2488, and HeFa 1/NGC 6067. A number of additional potential associations between planetary nebulae and open clusters are tabulated for reference purposes. It is noteworthy that the strongest cases involve planetary nebulae lying in cluster coronae, a feature also found for short-period cluster Cepheids, which are themselves potential progenitors of planetary nebulae.

Online material: color figures

1. INTRODUCTION

For some time, our knowledge of the intrinsic properties of the Galaxy's population of individual planetary nebulae has been restricted by large uncertainties in their derived distances. Zhang (1995) suggests that the *average* uncertainty in the distances cited to Galactic planetary nebulae is in the range 35%–50%. Others are less optimistic. Such a large scatter may not be surprising, given that planetary nebulae exhibit various morphologies and span a large range in mass (Kwok 2005).

In contrast, well-studied open clusters have distances and reddenings that are established to much greater precision, with distance uncertainties as small as 2.5% (Turner & Burke 2002). Planetary nebulae established as members of open clusters are therefore a potential alternative means of calibrating their fundamental properties. With an inferred distance from cluster membership in conjunction with a planetary nebula's angular diameter and expansion velocity, its true dimensions and age can be deduced. Cluster membership has the potential for a more direct calibration of the core mass-nebular He, C, and N abundance relationship expected in planetary nebulae as a result of single star evolution with asymptotic giant branch dredge-up (Köppen & Acker 2000; Cazetta & Maciel 2000). Planetary nebulae confirmed as cluster members would enhance their importance as calibrators for the Shklovsky relation (Osterbrock & Ferland 2006) or other similar methods used to establish their distances (Bensby & Lundström 2001). On a cautionary note, significant improvement in such relationships may not be possible if the observed scatter is intrinsic.

Several factors conspire to reduce the probability of observing a planetary nebula associated with an open cluster. First, the effective sample of planetary nebulae includes a large number of objects that appear to populate the Galactic bulge (Akhundova & Seidov 1971; Ziznovsky 1975), according to catalog statistics (Kohoutek 2001)[1] on their distribution along the Galactic plane (Fig. 1), as well as their observed radial velocities (Osterbrock & Ferland 2006). Potential calibrators lying in nearby open clusters are greatly reduced in number when that population is excluded, although many spatial coincidences still exist (Ziznovsky 1975). Associated open clusters with ages of less than $\sim 28 \times 10^6$ years ($\log \tau \leq 7.5$) are likely to be excluded, since stellar evolutionary models indicate that the end products of their evolved components are Type II supernova explosions. Current knowledge of stellar evolution suggests that the immediate precursors of C/O white dwarfs were planetary nebulae central stars that did not undergo core carbon ignition.

In addition to a small sample size, the detection of an association between a planetary nebula and an open cluster is further hampered by the short lifetimes of planetary nebulae. Models indicate that their main-sequence progenitors were stars of 1–6.5 $M_\odot$ (e.g., Weidemann 2000), with an upper limit of

[1] Kohoutek's catalogs can be found in the VizieR Online Data Catalog IV/24.

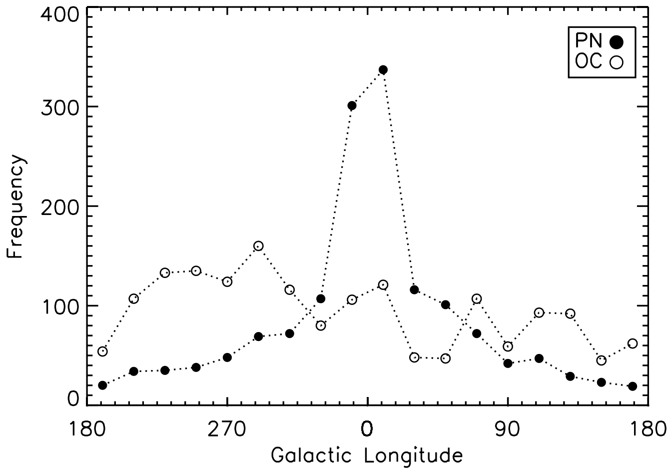

FIG. 1.—Distribution of planetary nebulae and open clusters with Galactic longitude, from data tabulated in the catalogs of Kohoutek (2001) and Dias et al. (2002). Open clusters appear to be randomly distributed along the Galactic plane, whereas planetary nebulae are concentrated toward the Galactic bulge.

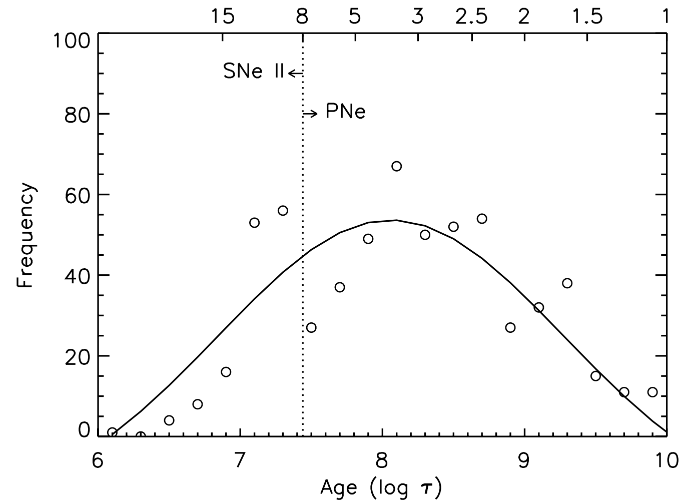

FIG. 2.—Distribution of open cluster ages compiled from the catalog of Dias et al. (2002) relative to the age–turnoff mass relation given by Iben & Renzini (1983). Open cluster ages can be described by a normal distribution with a peak near log $\tau \simeq 8$. The predicted upper turnoff mass limit, below which stars may evolve to produce planetary nebulae, is $M \simeq 8\ M_{\odot}$, above which Type II supernovae are expected.

~8 $M_{\odot}$ being possible for production of Ne white dwarfs. The lifetime of the planetary nebula stage is very sensitive to initial progenitor mass and subsequent mass loss (e.g., Schoenberner & Bloecker 1996), and varies significantly for main-sequence turnoff ages greater than ~28×10^6 yr, with estimates ranging from 10^3 to 10^5 yr (Schoenberner & Bloecker 1996; Köppen & Acker 2000). The most common age for nearby Galactic open clusters is ~100×10^6 yr ($\log(\tau) \simeq 8$), according to the catalog compilation of Dias et al. (2002) summarized in Figure 2. That corresponds to a main-sequence turnoff mass of $M_{\mathrm{TO}} \simeq 4\ M_{\odot}$. The lifetime of planetary nebulae associated with such progenitors is of order 10^3 yr, essentially instantaneous on the Galactic stage.

It is of interest to note that many planetary nebulae with massive central stars are found in the field, which is populated by the remnants of dissolved open clusters. Such clusters exceed the number of bound open clusters by a sizeable order (Lada & Lada 2003), which suggests that, despite the short lifetimes of planetary nebulae with massive central stars, increasing the statistical sampling of possible spatial coincidences between planetary nebulae and clusters may lead to successful detections. The usefulness of such surveys at extragalactic scales by Larsen & Richtler (2006) and Magrini (2006) is therefore obvious: larger statistics dominate and planetary nebulae are readily discernable, as demonstrated by their success as standard candles (Jacoby 1989). The success of the Macquarie/AAO/Strasbourg Hα (MASH) survey (Parker et al. 2006) in detecting large numbers of additional Galactic planetary nebulae has also been extremely useful in revealing additional coincidences with Galactic clusters.

The discovery of planetary nebulae within globular clusters (Jacoby et al. 1997) raises a pertinent point that must be considered. If we consider 1–1.5 $M_{\odot}$ as a strict lower mass limit for the progenitors of planetary nebulae (Kwok 2005; Osterbrock & Ferland 2006), then, for the ages assigned to globular clusters, corresponding to main-sequence turnoffs of less than 1 $M_{\odot}$, one must invoke binarity (mass transfer) to resolve the resulting discrepancy. That supports the scenario of De Marco (2006), Soker (2006), and Zijlstra (2007), who argue that a large fraction of observable planetaries may indeed stem from binary systems. Consequently, if a planetary nebula/open cluster association is established, we must be aware of the possibility that binarity might negate possible predictions for progenitor mass on the basis of the cluster's implied age from its main sequence turnoff.

In this paper we consider the possibility of cluster membership for a number of planetary nebulae that are located in close proximity to open clusters lying in their lines of sight. The often cited cases for planetary nebula/open cluster associations include the cluster and nebula designated as NGC 2818, as well as A9 in NGC 1912 (M38) and NGC 2438 in NGC 2437 (M46), but lesser known cases are also considered.

2. SUSPECTED PN/OPEN CLUSTER ASSOCIATIONS

Lubos Kohoutek has compiled an online list of suspected planetary nebula/open cluster associations, somewhat different from that given by Ziznovsky (1975), which is reproduced in Table 1. To that list we have appended a new case involving the planetary nebula M 1-80 and the open cluster Berkeley 57, and also consider two planetary nebulae that may be outlying members of IC 2488 (Pedreros 1987).

TABLE 1

POSSIBLE PLANETARY NEBULA–OPEN CLUSTER ASSOCIATIONS

Planetary Nebula (1)	PN Identifier (2)	Open Cluster (3)	Cluster r_n[a] (arcmin) (4)	Estimated R_C[b] (arcmin) (5)	Separation (arcmin) (6)
M 3-20	G002.1 − 02.2	Trumpler 31	3	24	7
M 1-80	G107.7 − 02.2	Berkeley 57	5	…	10
A9	PK172 + 00.1	NGC 1912 (M38)	10	31	13
NGC 2438	G231.8 + 04.1	NGC 2437 (M46)	10	35	5
NGC 2452	G243.3 − 01.0	NGC 2453	2	21	9
NGC 2818	G261.9 + 08.5	NGC 2818	5	24	1
NGC 2899	G277.1 − 03.8	IC 2488	17	…	54
VBRC 2	G277.7 − 03.5	IC 2488	17	…	53
ESO 177-10	G324.8 − 01.1	Lyngå 5	5	…	2
KoRe 1	G327.7 − 05.4	NGC 6087	7	31	4
HeFa 1	G329.5 − 02.2	NGC 6067	7	33	12
Sa 2-167	G347.7 + 02.0	NGC 6281	4	26	6
M 3-45	G359.7 − 01.8	Basel 5	3	…	5

[a] Estimated from the angular radius cited by Dias et al. (2002), except as noted in the text.

[b] From $R_C \simeq 35' +$ angular diameter (Barkhatova 1950).

Table 1 includes, where available, a planetary nebula identifier tied to its Galactic coordinates, along with information on the dimensions of the spatially adjacent cluster and the angular separation of the planetary from the cluster center. Open clusters are generally larger than the obvious concentrations of stars composing their core regions (Kholopov 1969; Nilakshi et al. 2002), so we list in columns (4) and (5) estimates for the nuclear radius, r_n, and coronal radius, R_C, of each cluster, where the two dimensions are tied to the definitions of Kholopov (1969) based upon linear star counts. The cluster nucleus comprises the dense central region of a star cluster that is obvious to the eye, whereas the cluster corona is the much lower density outer region. Information on both parameters is not generally available for most clusters, although estimates of cluster angular diameter given by Dias et al. (2002) closely match the diameters of cluster nuclei defined by Kholopov (1969). Coronal radii can be 2.5 to 10 times larger (Kholopov 1969), and the best means of estimating that parameter seems to be by scaling the large angular diameters for open clusters cited by Barkhatova (1950), as described in the table footnotes. The last values are crude approximations at best, but at least provide a sense of scale for establishing if a planetary nebula's angular separation from a cluster is consistent with a bona fide spatial coincidence.

Table 2 outlines the qualitative framework used to determine if the suspected associations are cospatial. The primary criteria are the differences in radial velocity and color excess between the planetary nebula and cluster $(\Delta V_R, \Delta E_{B-V})$, and the ratio of the estimated distances (D_R). The following parameters are also considered: the apparent size of the objects, their angular separation, and Galactic location. Because of the large number of planetary nebulae lying in the direction of the Galactic bulge noted earlier, there is a natural bias toward purely line-of-sight coincidences with open clusters for planetary nebulae lying in that direction (recall Fig. 1).

The interstellar reddenings of planetary nebulae cited throughout this study were usually derived from the standard constant of extinction, c, via the following generic approximation

$$E_{B-V} \simeq 0.77c$$

from Osterbrock & Ferland (2006), where c is related to the logarithmic extinction at Hβ. The resulting reddenings may be systematically higher than those for stars in the surrounding fields if there is inherent self-absorption by dust within the planetary nebulae themselves.

Reddening is not necessarily a strong criterion for a spatial coincidence. The spatial distribution of interstellar extinction near the Sun (Neckel & Klare 1980) is clearly defined, and indicates that the dust is concentrated in distinct clouds rather than more or less uniformly distributed along the Galactic plane. Between the dust clouds along some lines of sight are large gaps, of a kiloparsec or more, within which all stars share similar reddenings. Small spatial variations in reddening can be attributed to density variations within the clouds themselves.

2.1. M 3-20 and Trumpler 31 ($\ell \simeq 2°$)

The open cluster Trumpler 31 was studied photographically

TABLE 2

FRAMEWORK FOR EVALUATING POSSIBLE PHYSICAL ASSOCIATIONS

Criterion	Likely Member	Potential Member	Nonmember
ΔV_R (km s^{-1})	≤5	5–10	≥10
ΔE_{B-V}	≤0.2	0.2–0.6	≥0.6
d(PN)/d(cluster)	≃1	1–2	≥ 2

on the *RGU* system by Svolopoulos (1966). Janes & Adler (1982) obtained a cluster distance of $d = 1.86$ kpc and a reddening of $E_{B-V} = 0.43$ after transforming the data to the *UBV* system. The cluster is not an obvious concentration of stars on POSS images of the field, and star counts are needed to assess its reality. A color excess of $E_{B-V} \simeq 1.10 \pm 0.08$ derived for the planetary nebula M 3-20 (Tylenda et al. 1992) places it beyond ~2 kpc according to the extinction maps of Neckel & Klare (1980). The estimated distance is $d \simeq 5000 \pm 350$ pc (Zhang 1995), which, in conjunction with the reddening, small angular size, and Galactic location toward the Galactic bulge (Fig. 2), confirm the planetary nebula as a background object to the cluster Trumpler 31, which may not exist.

2.2. M 1-80 and Berkeley 57 ($\ell \simeq 108°$)

Berkeley 57 is an older cluster recently examined by Hasegawa et al. (2004), who derived a distance of $d = 4150$ pc, a reddening of $E_{B-V} = 0.75$, and an age of 14×10^8 years ($\log \tau = 9.14$). The planetary nebula M 1-80 is located $10'$ from the cluster, and is estimated to lie at a distance of $d = 5250 \pm 500$ pc (Zhang 1995) with a reddening of $E_{B-V} \simeq 0.54 \pm 0.11$ (Tylenda et al. 1992). Reddening alone constrains the distance of both objects only to somewhere in the interval 2–6 kpc (Neckel & Klare 1980), so the case rests mainly on the similarity of the distance estimates.

Star counts compiled from Two Micron All Sky Survey (2MASS) data (Fig. 3) lead to an estimated cluster nuclear radius of $r_n = 5'$ (see Kholopov 1969), which means that the planetary lies only $2 \times r_n$ from the cluster center. It is therefore a potential member of the cluster corona, adding further interest to the study of its potential association with Berkeley 57. The next step would be to use spectroscopic observations of the many evolved cluster giants to establish the cluster's radial velocity, for comparison with the value of $V_R = -58 \pm 10$ km s^{-1} derived for M 1-80 by Durand et al. (1998).

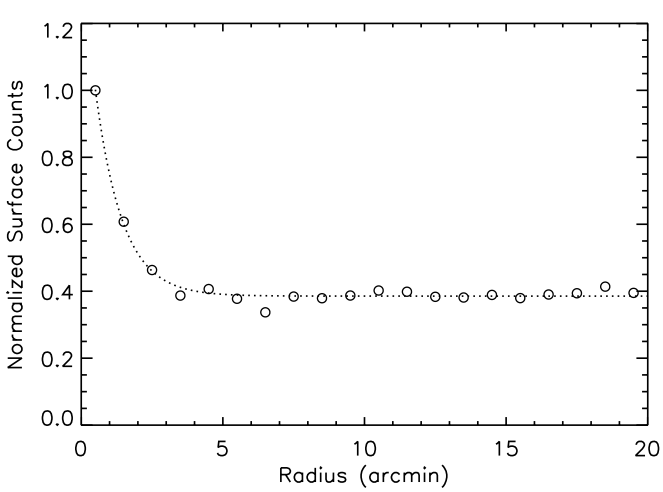

FIG. 3.—Star counts for the open cluster Berkeley 57 derived from data in the 2MASS survey.

2.3. A9 and NGC 1912 (M38) ($\ell \simeq 172°$)

Various literature studies of the parameters for NGC 1912 (M38) generated a wide range of distance estimates for the open cluster, the likely reason being the 0.4 mag spread in color excesses for member stars. The cluster distance is $d \simeq 970 \pm 40$ pc (Turner 1976) when that is taken into account. An independent distance estimate was obtained using data from 2MASS (Cutri et al. 2003) to construct a J versus $J - H$ color-magnitude diagram, shown in Figure 4. Isochrones tailored specifically to the 2MASS system were obtained from the *Padova Database of Stellar Evolutionary Tracks and Isochrones* (Bonatto et al. 2004). A subsolar metallicity solution ($Z = 0.008$) provided the best visual fit, and is supported by the work of Jennens & Helfer (1975), who determined a cluster metallicity of $[\mathrm{Fe/H}] \simeq -0.35$, which corresponds to $Z \simeq 0.009$ according to the relationship found by Bertelli et al. (1994). The following relationships were adopted between extinction and color excess in the infrared and optical regions: $A_J = 0.276 A_V$, $E_{J-H} = 0.33 E_{B-V}$ (Bica & Bonatto 2005; Dutra et al. 2002). The canonical distance modulus relation was reformulated and evaluated as

$$\log d = 0.2[J - M_J - 0.84(E_{J-H} \times R_V) + 5].$$

The results, displayed in Figure 4, yield a distance of $d = 1050 \pm 150$ pc, a reddening of $E_{B-V} = 0.27 \pm 0.03$, and an age of 18×10^7 yr ($\log \tau = 8.25 \pm 0.15$), confirming previous estimates of a low reddening and a distance near 1 kpc.

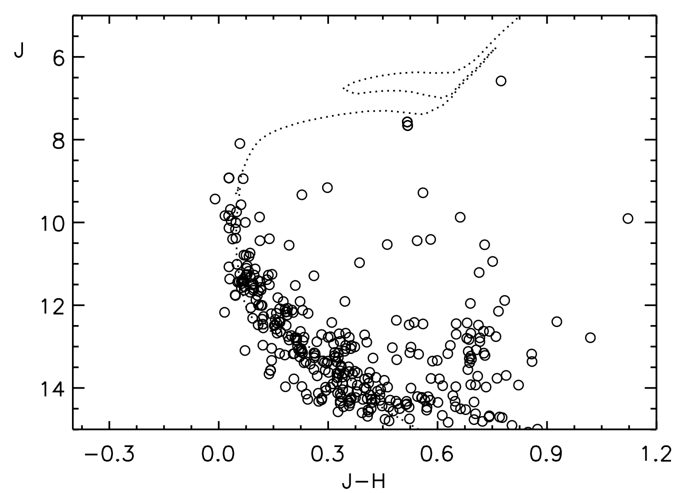

FIG. 4.—Color-magnitude diagram for M38 (NGC 1912) constructed from 2MASS data. A $\log \tau = 8.25 \pm 0.15$ ($Z = 0.008$) main sequence has been fitted to the observations, yielding a distance of $d = 1050 \pm 150$ pc and a reddening of $E_{B-V} = 0.27 \pm 0.03$.

With regard to the planetary nebula A9, a distance degeneracy has emerged, with both nearby ($d \simeq 4000$ pc, $E_{B-V} \simeq 1.05$ [Kaler et al. 1990], and $d = 5050$ pc [Phillips 2004]) and distant ($d = 8900 \pm 6100$ pc [Zhang 1995]) solutions being advocated. The planetary's large apparent diameter of 30″, measured using the Aladin environment (Bonnarel et al. 2000), would seem to favor the nearer estimates. The extreme faintness of the central star (Kwitter et al. 1988) and the large reddening of the planetary nebula, which implies a distance in excess of ~4 kpc (Neckel & Klare 1980) for A9, almost certainly place the planetary at a much greater distance than the cluster NGC 1912. A radial velocity of $V_R = -1.0 \pm 0.6$ km s^{-1} is available for a red giant member of the cluster (Glushkova & Rastorguev 1991), but the radial velocity of A9 has not yet been measured. Presumably it would merely serve to confirm that the two are unrelated.

2.4. NGC 2438 and NGC 2437 (M46) ($\ell \simeq 232°$)

The location of the planetary nebula NGC 2438 relative to the open cluster NGC 2437 (M46) is visually supportive of an association, given the planetary nebula's breadth, brightness, and proximity to the cluster core (Fig. 5). Three estimates for the distance (Zhang 1995) and reddening (Tylenda et al. 1992) to the planetary nebula yield mean values of $d \simeq 1775 \pm 630$ pc and $E_{B-V} \simeq 0.17 \pm 0.08$. Both are in general agreement with a zero-age main sequence (ZAMS) and isochrone fit to 2MASS photometry for M46 (Fig. 6), which yields values of $d = 1700 \pm 250$ pc, $E_{B-V} = 0.13 \pm 0.05$, and an age of 22×10^7 yr ($\log \tau = 8.35$). Color excesses increase along this line of sight from ~0.1 to ~0.3 at distances beyond ~1.5 kpc (Neckel & Klare 1980), which confirms the distances estimated for both the cluster and the planetary nebula. The color excesses for both are also similar enough to confirm that they share the same space reddening. The case for a physical association therefore rests on their space motions.

Early studies of the radial velocity of NGC 2438 and M46 by Cuffey (1941, citing measures by Struve) and O'Dell (1963) indicated a difference of $\Delta V_R \simeq 30$ km s^{-1} between the objects, which suggests that the pair constitutes a spatial coincidence only. A cluster red giant spectroscopic binary has a systemic velocity (Mermilliod et al. 1989) identical to that

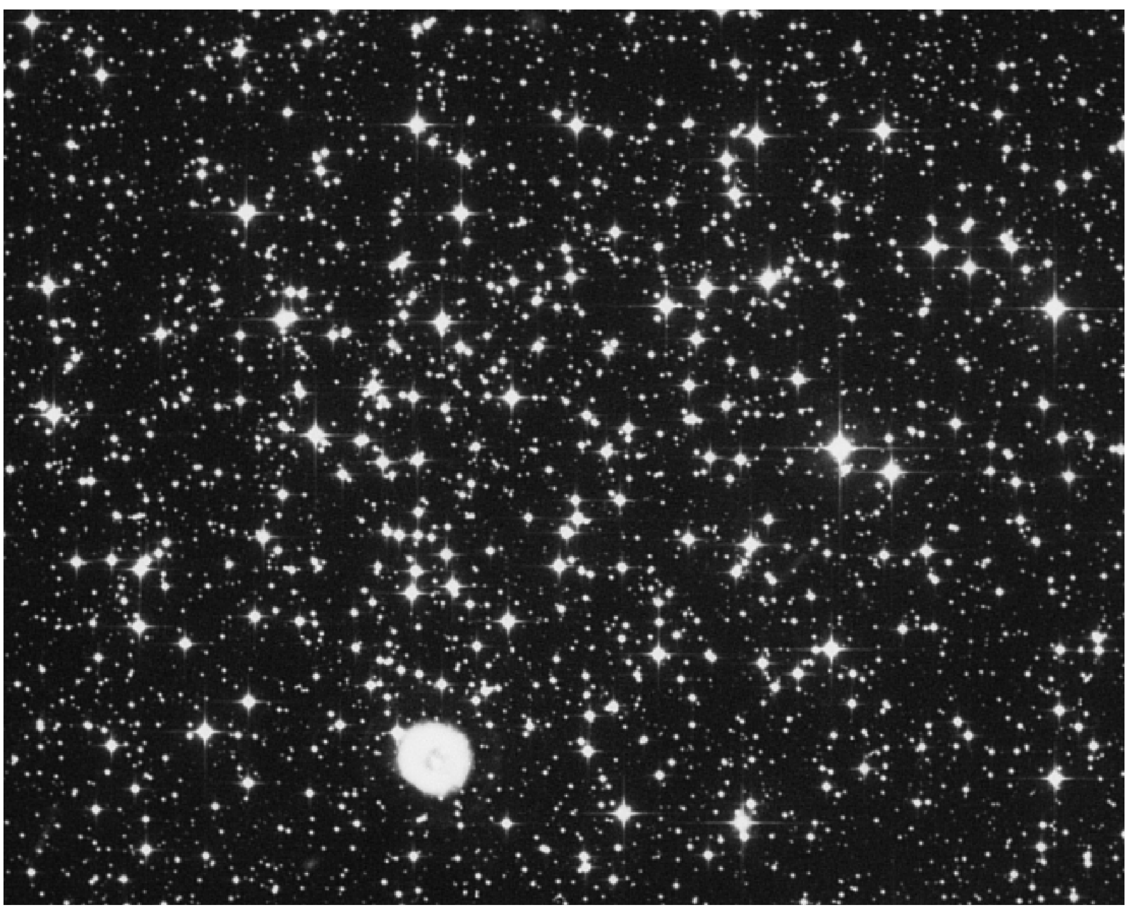

FIG. 5.—Field of view of M46 (NGC 2437), from a combination of images taken at the Abbey Ridge Observatory with POSS II. See the electronic edition of the PASP for a color version of this figure.

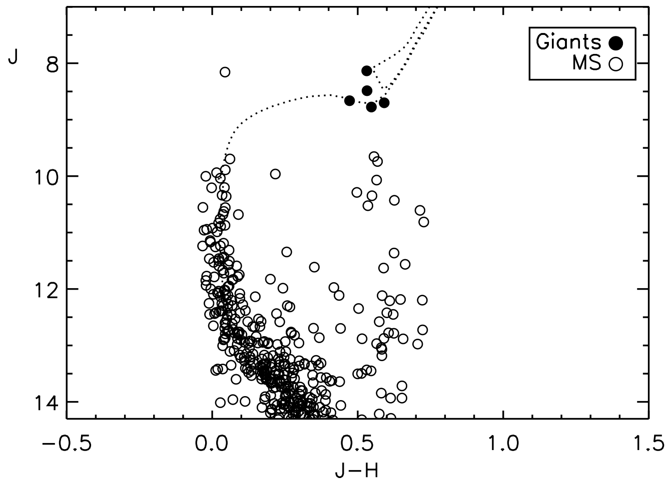

FIG. 6.—Color-magnitude diagram for M46 (NGC 2437) constructed from 2MASS data. A $\log\tau = 8.35$ isochrone has been fitted to the observations, yielding a distance of $d = 1700 \pm 250$ pc and a reddening of $E_{B-V} = 0.13 \pm 0.05$.

obtained for cluster dwarf members by Cuffey (see Table 3). However, Pauls & Kohoutek (1996) rekindled interest in a possible planetary nebula/open cluster association when they found similar radial velocities for both. While it is conceivable that the early radial velocity measures for cluster stars, which were made from spectrograms obtained from the northern hemisphere, might be affected by spectrograph flexure or by the presence of spectroscopic binaries in the sample, it is noteworthy that the radial velocity measured for the planetary nebula is similar to more recent measurements (Table 3). If the radial velocity measurements of Pauls & Kohoutek (1996) are reliable, then there is a good case for a physical association of NGC 2438 with M46. But additional velocity measurements are clearly needed to strengthen the case, given that proper motions may not provide a suitable test in this instance (O'Dell 1963).

2.5. NGC 2452 and NGC 2453 ($\ell \simeq 243°$)

The derived distances to the open cluster NGC 2453 are unsatisfactorily varied, as Table 4 summarizes. Field star contamination may be important in this case, given that the cluster main sequence is dominated by B-type stars, which also populate the Puppis OB associations, and an extension of the Perseus arm behind them (Peton-Jonas 1981), which lie along the same line of sight. The distances cited from two deep CCD studies by Mallik et al. (1995) and Moitinho (2001) are favored because the main sequence morphology is well defined. The latter study of NGC 2453 implies a distance of $d = 5250$ pc, a reddening of $E_{B-V} = 0.50$, and an age of 40×10^6 yr ($\log\tau = 7.6$). The parameters for the planetary nebula NGC 2452 generally agree with those of the cluster, although the cited distance of $d \simeq 2950 \pm 420$ pc (Zhang 1995) and reddening of $E_{B-V} \simeq 0.36 \pm 0.12$ (Tylenda et al. 1992) might suggest that the planetary nebula lies in the foreground of the cluster. The reddening along this line of sight remains unchanged at $E_{B-V} \simeq 0.6$ for distances in excess of ~2 kpc (Neckel & Klare 1980), so the small difference in color excesses is not useful for distance discrimination.

TABLE 3
RADIAL VELOCITIES FOR NGC 2438 AND NGC 2437 (M46)

Source	V_R(PN) (km s^{-1})	V_R(Cluster) (km s^{-1})	Stars
Struve (Cuffey 1941) …………	77	45.1 ± 5.5	5
O'Dell (1963) …………………	75 ± 5	48.1 ± 3.0	1
Meatheringham et al. (1988) …..	74 ± 4	…	…
Mermilliod et al. (1989) ………	…	48.1 ± 0.1	1 (orbit)
Durand et al. (1998) …………	75 ± 2.5	…	…
Pauls & Kohoutek (1996) ……..	60.3 ± 3.6	60.8 ± 4.0	4

TABLE 4
PARAMETERS FOR THE CLUSTER NGC 2453

Source	Distance (pc)	E_{B-V}
Moffat & Fitzgerald (1974) …..	2900	0.47
Glushkova et al. (1997) ………	2400	…
Mallik et al. (1995) …………	5900 ± 200	…
Dambis (1999) ………………	2400	0.48
Moitinho et al. (2006) ……….	5250	0.50

With reference to available radial velocities, Moffat & Fitzgerald (1974) obtained a value of $V_R = 67 \pm 14$ km s^{-1} for a cluster B5 star ideally positioned as an evolved main-sequence member in the cluster color-magnitude diagram. Despite the large uncertainty in the velocity and the fact that the spectrogram displayed double lines, the value is very similar to measures for the planetary nebula: $V_R = 62.0 \pm 2.8$ km s^{-1} (Meatheringham et al. 1988), and $V_R = 65 \pm 3$ km s^{-1} (Durand et al. 1998). Additional radial velocity measurements for established cluster members are needed to assess the viability of the case further, although existing data do not rule out a possible spatial coincidence.

It is of interest to note that Cazetta & Maciel (2000) concluded that NGC 2452 was among the most massive planetary nebulae in their sample of ~100. Their argument was based on the abundance ratio N/O, which is a tracer of mass for the progenitor star via the dredge-up scenario. Coincidentally, the cluster's young age also implies a massive progenitor of $M_{TO} \simeq 6.5\ M_\odot$ (see Fig. 2).

2.6. NGC 2818: Planetary Nebula and Cluster ($\ell \simeq 262°$)

The well-known spatial coincidence of the planetary nebula NGC 2818 with its surrounding cluster is an example of a case that visually supports an association (Fig. 7). Pedreros (1989) determined a distance of $d = 2300$ pc and a reddening of

FIG. 7.—Field of view of NGC 2818. See the electronic edition of the PASP for a color version of this figure.

$E_{B-V} = 0.18$ for the cluster, consistent with the parameters derived for the planetary nebula: $d = 2660 \pm 830$ pc (Zhang 1995) and $E_{B-V} \simeq 0.28 \pm 0.15$ (Tylenda et al. 1992). Equally encouraging are radial velocities from low-dispersion spectra (230 Å mm^{-1}) by Tifft et al. (1972) for two A-type stars in the cluster that yielded $V_R = 3 \pm 20$ km s^{-1}, compared with $V_R = 8 \pm 13$ km s^{-1} obtained for the planetary nebula. Such evidence, in conjunction with the general agreement in distance and reddening, has been the basis for the conclusion that the two are associated.

More recent results suggest otherwise. A comprehensive radial velocity study of stars in the cluster field by Mermilliod et al. (2001) yields a cluster radial velocity from 15 red giant members of $V_R = 20.7 \pm 0.3$ km s^{-1}, while the radial velocity of the planetary nebula is established to be $V_R = -0.9 \pm 2.9$ km s^{-1} (Durand et al. 1998) and $V_R = -1 \pm 3$ km s^{-1} (Meatheringham et al. 1988), consistently smaller than the velocity of the cluster. The greater precision of recent estimates results in a velocity discrepancy of $\Delta V_R = 22$ km s^{-1} (Mermilliod et al. 2001), implying a spatial coincidence rather than a physical association, as concluded by Mermilliod et al. (2001).

2.7. VBRC 2 and NGC 2899, and IC 2488 ($\ell \simeq 277°$)

Pena et al. (1997) conducted an extensive study of the planetary nebula VBRC 2 and derived a distance of $d = 1200 \pm 200$ pc and a reddening of $E_{B-V} = 0.38$. The values are consistent with the parameters found for the cluster IC 2488 by Clariá et al. (2003), who derived a distance of $d = 1250 \pm 120$ pc, a reddening of $E_{B-V} = 0.24 \pm 0.04$, and a radial velocity of $V_R = -2.63 \pm 0.06$ km s^{-1}. Those values are smaller than the estimates of $d = 1445 \pm 120$ pc and $E_{B-V} = 0.26 \pm 0.02$ obtained for IC 2488 by Pedreros (1987).

There may be a tendency to dismiss an association between the cluster and planetary nebula because of their large apparent separation ($\simeq 54'$), despite the consistent correlation among the

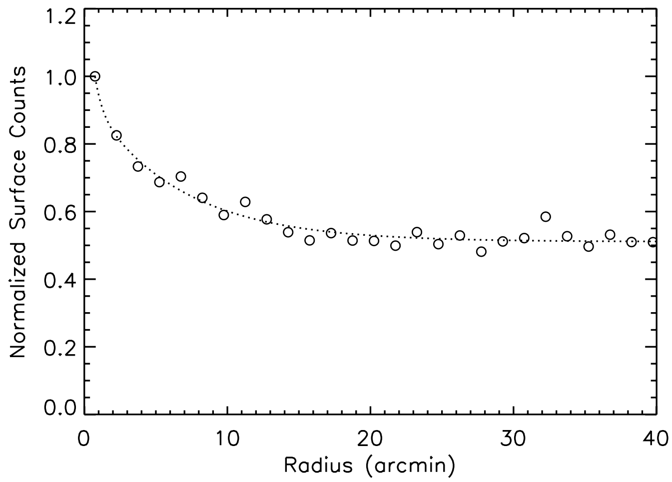

FIG. 8.—Star counts for the open cluster IC 2488 from 2MASS data.

parameters. Star counts of the field were therefore made using data available from the 2MASS survey (Fig. 8). The data highlight IC 2488's broad extent ($r_n \simeq 17'$–$18'$) and indicate that the planetary nebula VBRC 2 lies within $\simeq$3–4 cluster nuclear radii. Since cluster coronae typically extend anywhere from 2.5 to 10 times beyond their nuclear radii (Kholopov 1969), and the coronae of star clusters in the outer Galaxy are larger on average than those in the inner regions (Nilakshi et al. 2002), it may be premature to dismiss a possible association based solely on arguments of separation. It is of interest to note that a large fraction of short-period Cepheids, potential progenitors of planetary nebulae, fall within the coronae of their constituent clusters (Turner 1985). A final decision on the case must therefore await a radial velocity for the planetary nebula, to assess its potential as a cluster member properly.

Published estimates for the parameters of the planetary nebula NGC 2899 imply a distance of $d \simeq 1560 \pm 570$ pc and a reddening of $E_{B-V} \simeq 0.32 \pm 0.24$ (Zhang 1995; Tylenda et al. 1992), consistent with the parameters for IC 2488. Durand et al. (1998) measured the radial velocity of the planetary nebula to be $V_R = 3.4 \pm 2.8$ km s^{-1}, which differs slightly but only by slightly more than 2σ from the cluster value. NGC 2899 is in the same situation as VBRC 2, since it also lies nearly as far from the cluster center, yet possibly within the corona. Remeasuring the color excess and radial velocity of the planetary nebula with greater precision would help clarify the case for cluster membership. Thus, while not conclusive, both candidates offer encouraging evidence.

The reddening along this line of sight becomes larger than $E_{B-V} \simeq 0.3$ beyond ~1 kpc (Neckel & Klare 1980), so the observed color excesses for the cluster and planetary nebulae imply that they are reddened by foreground dust clouds. Reddening is therefore of little use for constraining the distances to the planetary nebulae. Presumably radial velocities would provide a stronger test for a physical association.

2.8. ESO 177-10 and Lyngå 5 ($\ell \simeq 325°$)

The open cluster Lyngå 5 has not been studied since its discovery nearly 45 years ago, so its parameters are essentially unknown. For this study we examined the field and estimated a peak in star density by eye at $15^{\mathrm{h}}41^{\mathrm{m}}55^{\mathrm{s}}$, 56°38′38″ (J2000.0), and a corresponding nuclear radius measuring about $2'$. As a means of obtaining approximate values for its distance and reddening, data from the 2MASS survey (Cutri et al. 2003) for objects in the field of the putative cluster nucleus were used to construct JHK color-color and color-magnitude diagrams for cluster stars. The color-color diagram (Fig. 9) suggests that there is a sizable group of reddened late B-type stars in the field, presumably associated with the cluster main sequence. The implied cluster reddening, $E_{J-H} = 0.33 \pm 0.03$, corresponds to $E_{B-V} = 1.18 \pm 0.11$. A simple ZAMS fit was used to estimate the distance (Fig. 10), yielding $d = 1950 \pm 350$ pc. But the values cited are only preliminary, and still uncertain. A few cluster stars may be bright enough for spectroscopic follow-up, which might confirm the derived parameters. Interestingly enough, the cluster main-sequence turnoff appears to lie roughly at B5, implying an age of ~50×10^6 yr ($\log \tau = 7.7$), corresponding to masses of ≥ $6.5\ M_\odot$ for cluster evolved components.

The cited distance of 2550 ± 670 pc (Zhang 1995) to the planetary nebula ESO 177-10 is marginally consistent with the value obtained for the cluster, but the color excess of $E_{B-V} \simeq 2.46 \pm 0.07$ for the planetary nebula derived from several radio measurements (Tylenda et al. 1992; Cahn et al. 1992) indicates that it suffers from much heavier extinction. Such a large reddening implies a distance in excess of ~2

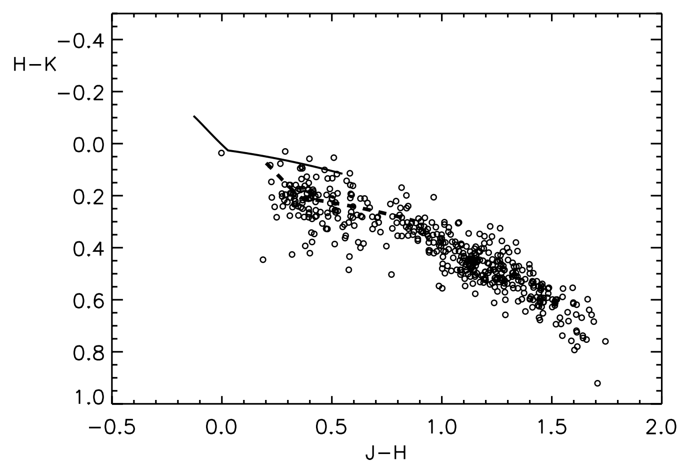

FIG. 9.—JHK color-color diagram for Lyngå 5 constructed from 2MASS data. Likely cluster stars are reddened by $E_{J-H} = 0.33 \pm 0.03$, which is equivalent to $E_{B-V} = 1.18 \pm 0.11$. A reddening relation of slope $E_{J-H} = 1.72E_{H-K}$ was adopted from Dutra et al. (2002); Bonatto et al. (2006).

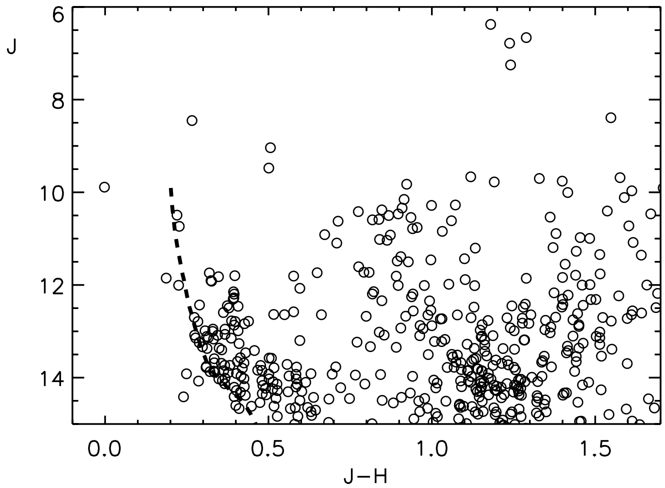

FIG. 10.—JH color-magnitude diagram for the open cluster Lyngå 5 constructed from 2MASS data for stars within a $5'$ field centered on the J2000 coordinates for the cluster cited here. A ZAMS fit yields a distance of $d = 1950 \pm 350$ pc for the reddening indicated in Fig. 9.

kpc along this line of sight (Neckel & Klare 1980), lending support to the argument that the planetary nebula lies in the cluster background. Radial velocities would likely confirm that this pair represents a spatial coincidence only.

2.9. KoRe 1 and NGC 6087 ($\ell \simeq 328°$)

Koester & Reimers (1989) conclude that the planetary nebula KoRe 1 is in a highly excited state on the basis of nearly equal spectral intensities for He II $\lambda4686$ and Hβ. According to the work of Gurzadian (1988), who formulated a relationship between the temperature of the central star and the various emission line ratios, KoRe 1 is among a small percentile of planetaries with *superhigh* temperature central stars ($\simeq 300,000$ K). A correspondingly high intrinsic luminosity, faint apparent magnitude for the nebula and central star (near the Sky Survey limits), and a small apparent diameter (14″) for the associated planetary nebula suggest that it is probably much more distant than the cluster, which is nearby ($d = 902 \pm 10$ pc; Turner 1986). The pair appears to represent another case of a spatial coincidence rather than a physical association.

2.10. HeFa 1 and NGC 6067 ($\ell \simeq 330°$)

Henize & Fairall (1983) concluded that the planetary nebula HeFa 1 is probably not associated with the open cluster NGC 6067, on the basis of an inferred reddening of $E_{B-V} = 0.66 \pm 0.04$ (Henize & Fairall 1983; Tylenda et al. 1992), which is larger than that of the cluster. The large color excess implies a distance not much greater than ~1–2 kpc, according to the run of reddening with distance along this line of sight (Neckel & Klare 1980). The cluster reddening is $E_{B-V} = 0.35 \pm 0.01$ according to Walker (1985), and $E_{B-V} = 0.32$ from Meynet et al. (1993), which places a similar constraint on its distance. Meynet et al. (1993) find a distance of $d = 1665$ pc and an age of 17×10^7 yr ($\log \tau = 8.22$) for the cluster, so the only difference in parameters between the cluster and planetary nebula is the reddening, which is not an ideal test of membership in this instance.

NGC 6067 is also statistically unique in that it hosts two Cepheid members (Eggen 1983). There is consequently an

TABLE 5

ADDITIONAL PLANETARY NEBULA/OPEN CLUSTER COINCIDENCES ($r < 15'$)

Planetary Nebula	PN Identifier	Open Cluster	Cluster r_n[a] (arcmin)	Estimated R_C[b] (arcmin)	Separation (arcmin)
NGC 6741	G033.8 − 02.6	Berkeley 81	3	…	13
K4 4-41	G068.7 + 01.9	NGC 6846	1	…	1
KLW 6	G070.9 + 02.4	Berkeley 49	2	…	11
K 3-57	G072.1 + 00.1	Berkeley 51	1	…	12
A 69	G076.3 + 01.1	Anon (Turner)	3	…	4
Bl 2-1	G104.1 + 01.0	NGC 7261	3	22	7
FP0739-2709	G242.3 − 02.4	ESO 493-03	4	…	8
PHR 0840−3801	G258.4 + 02.3	Ruprecht 66	1	…	2
PHR 0905−5548	G274.8 − 05.7	ESO 165-09	8	…	9
Pe 2-4	G275.5 − 01.3	van den Bergh-Hagen 72	1	…	9
		NGC 2910	2	24	14
NeVe 3-1	G275.9 − 01.0	NGC 2925	5	26	12
Hf 4	G283.9 − 01.8	van den Bergh-Hagen 91	3	…	14
He 2-86	G300.7 − 02.0	NGC 4463	2	22	3
PHR 1315−6555	G305.3 − 03.1	AL 67-01	2	…	1
PHR 1429−6043	G314.6 − 00.1	NGC 5617	5	25	1
vBe 3	G326.1 − 01.9	NGC 5999	2	25	5

[a] Estimated from the angular radius cited by Dias et al. (2002), except as noted in the text.
[b] From $R_C \simeq 35' +$ Angular Diameter (Barkhatova 1950).

a priori probability of detecting a planetary nebula associated with the cluster, since short-period Cepheids are potential progenitors of stars that produce planetary nebulae. A radial velocity estimate for the planetary nebula would help resolve the question of its possible cluster membership, since a cluster velocity of $V_R = -39.3 \pm 1.6\ \mathrm{km\,s^{-1}}$ has been measured (Mermilliod et al. 1987). The case for a potential physical association remains open.

2.11. Sa 2-167 and NGC 6281 ($\ell \simeq 348°$)

Feinstein & Forte (1974) established that the cluster NGC 6281 is nearby with a distance of $d = 560 \pm 30$ pc and a reddening of $E_{B-V} = 0.15 \pm 0.02$. The planetary nebula Sa 2-167, however, has a much larger color excess of $E_{B-V} \simeq 2.2$, according to Tylenda et al. (1992), which implies a distance in excess of ~2 kpc (Neckel & Klare 1980). One can also note the location of the planetary toward the Galactic bulge. The reddening discrepancy alone indicates that the planetary nebula lies in the background of the open cluster NGC 6281.

2.12. M 3-45 and Basel 5 ($\ell \simeq 360°$)

A reanalysis by Janes & Adler (1982) of photographic *RGU* photometry for the cluster Basel 5 by Svolopoulos (1966) indicates that Basel 5 is relatively nearby with a distance of $d = 1360$ pc and a reddening of $E_{B-V} = 0.39$. Conversely, the planetary nebula M 3-45 may be a member of the Galactic bulge population (Mal'kov 1998), given its Galactic longitude and large reddening of $E_{B-V} \simeq 1.86 \pm 0.01$ (Tylenda et al. 1992; Cuisinier et al. 2000). As in the previous case, the large reddening discrepancy is sufficient to indicate that the planetary nebula cannot be associated with the cluster.

3. OTHER POSSIBLE COINCIDENCES

The list of potential spatial coincidences between planetary nebulae and open clusters presented in Table 1 is only a partial listing of the spatial coincidences that exist (e.g., Ziznovsky 1975). A more exhaustive listing of potentially good cases is presented in Table 5, derived with the aid of online lists of planetary nebulae (and possible planetary nebulae) and open clusters, the latter including some rather sparse spatial groupings not yet confirmed as true clusters (such as the anonymous group lying near the planetary nebula A69). The interesting case of AL 67-01 (Andrews & Lindsay 1967) and PHR 1315−6555 was highlighted by Parker et al. (2006), but there are a few other equally interesting coincidences, such as K4 4-41 near NGC 6846. Several dozen other spatial coincidences exist, but they consist mainly of planetary nebulae lying toward the region of the Galactic center (Jacoby & van de Steene 2004) or bulge in purely spatial coincidence with foreground clusters. Most are extremely faint planetary nebulae of small angular diameter that are almost certainly background to the relatively nearby clusters. Many of the objects in Table 5 are, however, deserving of further study.

A noteworthy feature of both Tables 1 and 5 is that there are very few planetary nebulae coincident with cluster nuclei, and even those cases may represent cluster coronal objects seen in projection against cluster nuclei. A sometimes overlooked property of Milky Way open clusters is that their dimensions and stellar content are invariably underestimated when gauged on the basis of stars populating their dense nuclear regions, which are oversampled in CCD studies. As noted in § 2, Kholopov (1969) and Nilakshi et al. (2002) find that open clusters are surrounded by low-density coronae that contain the bulk of their member stars. By inference, that should include the bulk of cluster members that evolve into planetary nebulae. Cluster coronae also contain a large proportion of each cluster's massive stars (Burki 1978) and account for the majority of Cepheids that are associated with open clusters (Turner 1985). Cluster Cepheids in the Large Magellanic Cloud exhibit an identical characteristic (Efremov 2003).

There is no obvious explanation for the preference of massive stars and Cepheids, and presumably planetary nebulae progenitors, to cluster coronae. A dynamical origin for coronal Cepheids was proposed by Turner (1985), in which the greater frequency of stellar encounters in dense cluster nuclei (see Turner 1996a) results in a higher frequency of close binaries and merger products there, the former being less likely to produce post-main-sequence stars capable of reaching supergiant dimensions because of Roche lobe overflow. The same mechanism might explain the apparent shortage of planetary nebulae in cluster nuclei. An alternate explanation in terms of a radial dependence of Jeans mass M_{J} in proto-clusters was suggested by Burki (1978) to account for the discrepancy with respect to massive stars.

It is of interest to speculate on the future fate of cluster members with masses of $M \lesssim 8\ M_{\odot}$. Such objects eventually become Cepheids with pulsation periods $P \lesssim 10$ days (Turner 1996b) or planetary nebulae once they pass through intermediate stages as red supergiants and asymptotic giant branch stars. The duration of the Cepheid phase varies widely from 10^4–10^5 yr for first crossings of the instability strip to 10^6–10^7 yr for higher crossings, an order of magnitude (or more) longer than the planetary nebula stage. There are ~30 known cluster Cepheids with $P \lesssim 10$ days (e.g., Turner & Burke 2002), so statistically one might expect only a few planetary nebulae to be members of open clusters, and a preference for cluster coronae would seem logical. The survey presented here appears to confirm such expectations.

4. DISCUSSION

We have yet to establish a single physical association between a planetary nebula and an open cluster based on a correlation between their radial velocities, reddenings, and distances. However, further follow-up is indicated for a number of cases where the evidence is suggestive, namely M 1-80/Berkeley 57, NGC 2438/NGC 2437, NGC 2452/NGC 2453, VBRC 2 and NGC 2899/IC 2488, and HeFa 1/NGC 6067, 6 of the 13 coincidences considered. Additional good cases may arise from closer examination of some of the other coincidences noted in Table 5, but most of the associated clusters are as yet unstudied, limiting further progress.

Almost all potential cluster planetary nebulae lie in cluster coronal regions, typically surrounding open clusters for which limited or no photometric data exist. The fact that very few Galactic open clusters have been studied to the extent that both their nuclear and coronal regions are examined (Turner 1996a) only compounds the situation. Further progress requires not only new studies of our Galaxy's many unstudied clusters, but studies of their coronal regions as well. Spectroscopic observations of potentially associated planetary nebulae would also be of value.

We are indebted to the following groups for facilitating the research described here: the staff at Vizier, WebDA, and the NASA ADS service. We are particularly grateful to Andre Moitinho for sending us a copy of his CMD for NGC 2453, Charles Bonatto for useful discussions on taking advantage of data from the 2MASS survey, George Jacoby for suggestions on preparing the text, Gunter Cibis for drawing our attention to the possibility that some planetary nebulae might be cluster members, and Lubos Kohoutek for compiling the list of suspected PNe/OC associations that was the foundation for this research.

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