THE ASTROPHYSICAL JOURNAL, 360:173–183, 1990 September 1

INTERACTION OF PLANETARY NEBULAE WITH THE INTERSTELLAR MEDIUM

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Received 1989 December 14; accepted 1990 March 2

ABSTRACT

We consider the interaction of a moving planetary nebula (PN) with the interstellar medium. The PN shell is compressed first in the direction of the stellar motion. This produces a dipole asymmetry in the surface brightness of the nebula, typically at a nebular density of ~ 40 cm^{-3} if the nebula is located in the Galactic plane. In the later stages of the interaction, this part of the shell is significantly decelerated with respect to the central star, and the PN becomes strongly asymmetric in shape. This distortion and the subsequent stripping of the nebular gas away from the central star typically occurs at a low nebular density of ~ 6 cm^{-3}. We examined the morphology of PNs with central stars whose proper motions exceed 0.015 arcsec yr^{-1} and found that many of the extended nebulae are interacting with the interstellar medium (ISM). Our sample doubles the number of known PNs interacting with the ISM. We examined the morphology of nearby PNs, and found a number of strongly asymmetric nebulae. We expect that the central stars in these PNs should have large proper motions, and we predict the directions from the observed asymmetries. We suggest the use of interacting PNs to determine the filling factor of the warm neutral and ionized components of the ISM.

Subject headings: interstellar: matter — nebulae: planetary — stars: proper motion

I. INTRODUCTION

Planetary nebulae (PNs) continue to attract attention because of their importance in the stellar evolution studies and their dominant role in the mass exchange between stars and the interstellar medium (ISM). The majority of PNs arise in the evolutionary phases immediately following the asymptotic red giant branch stage in the evolution of intermediate- and low-mass stars. The strong mass loss during this phase exposes a hot stellar core which interacts with the ejected stellar envelope through the combined action of its fast stellar wind and energetic photons. The ejected stellar envelope is visible as a PN, with the stellar core detectable as its central star. Initially, the PN shell expands freely because its density exceeds the ISM density by orders of magnitude. However, once the PN density drops below a critical value because of expansion, an interaction takes place between the PN and the ISM. This interaction, constituting the final stage in the PN evolution, is the topic of our investigation.

The PN–ISM interaction depends on the ISM hydrogen number density n_0, and on the relative velocity v_* between the star and the ISM, usually dominated by the stellar motion. In a low-density environment, before an interaction can take place, the PN shell expands freely to large radii and becomes unobservable, due to its low surface brightness. Therefore, PNs distorted by the PN–ISM interaction are more likely to be found in higher density environments, particularly in the Galactic plane where the ISM densities are the highest. Another parameter which strongly influences the interaction is the relative velocity v_*. The ISM ram pressure increases quadratically with v_*, leading to a pronounced interaction for PNs with large peculiar motions. These PNs are the easiest to detect and may even be observed at large distances above the Galactic plane.

Prior to this work, only three PNs were known which were certainly interacting with the ISM. Although they are somewhat atypical, these PNs clearly show characteristic features expected from the interaction. The best studied nebula, A35, is an asymmetric and very extended object when observed in the Hα emission line (Abell 1966). Its morphology is strikingly different in the [O III] 5007 Å line, with the most intense emission concentrated in a bow-shock structure (Jacoby 1981). The central star, located in the apex of the bow-shock structure, is a close binary system consisting of a G8 III–IV star (Jacoby 1981) and a hot ($T_{\rm eff} = 1.5 \times 10^5$ K) white dwarf (Grewing and Bianchi 1988). The system is moving with a high transverse velocity of ~ 150 km s^{-1} along the symmetry axis of the nebula. Apparently, the nebular shell has been decelerated by the ISM and is now interacting either with a stellar wind originating in the close binary system (Jacoby 1981) or with the white dwarf UV radiation. It is most probably the stellar wind–nebular shell interaction which produces the distinct bow-shock structure. A similar structure is observed in the PN 623+71, a nebula surrounding a cataclysmic binary (Krautter, Klaas, and Radons 1987). The active binary systems in these two nebulae apparently produce relatively strong stellar winds; this wind directly detected in the UV spectra of the 623+71 system (Krautter, Klaas, and Radons 1987), whose collision with the surrounding PN gas reveals the PN–ISM interaction. In view of the large distances from the Galactic plane of both PNs, their high spatial velocity (amounting to ~ 150 km s^{-1} for A35) is the decisive factor in the PN–ISM interaction. The third object, the extremely large nebula S216 (with the diameter of 1°.6) is located in the Galactic plane. Originally classified as an H II region, it is now considered to be a nearby PN at a distance of ≤ 80 pc (Reynolds 1985), although its classification is still uncertain. The central star is most probably LS V + 46°21. Its proper motion indicates a low tangential velocity v_* of 10–20 km s^{-1} (Cudworth and Reynolds 1986). A high ISM density must be the primary factor governing the deceleration of the PN gas in S216.

The presence of the PN–ISM interaction in only three nebulae would seem to indicate its rarity. However, both A35 and the 623+71 nebula are in late stages of the interaction, in which they have been decelerated with respect to their central star. As will be discussed in more detail in § II, the interaction should be detectable long before the shell is visibly decelerated. The implication is that many nebulae should show signs of the PN–ISM interaction. We show that this is indeed the case in § III.

The PN–ISM interaction was discussed briefly by Gurzadyan (1969), and a refined analysis was presented by Smith (1976). Using a thin-shell approximation and Oort's snowplow model, Smith (1976) calculated the expected displacement of central stars from the PN centers. Several of the assumptions underlying this simple model are not supported by observations. For example, most PN shells are thick (Khromov and Kohoutek 1968), with gas occupying most of the PN volume. Thin-shelled PNs can be found, but they are predominantly young nebulae. These thin-shelled PNs may have thick shells of gas, but the visible nebulae may be ionization-limited, in agreement with photoionization models (Taylor, Pottash, and Zhang 1987). In a second paper (Soker, Borkowski, and Sarazin 1990), we perform hydrodynamical simulations to check the validity of the simple analytical model considered by Smith (1976).

The present paper is organized as follows. We present a crude quantitative discussion of the PN–ISM interaction in § II. The observational evidence for this interaction is presented in § III. We summarize our results in § IV.

II. QUALITATIVE DISCUSSION OF THE PN–ISM INTERACTION

Here we describe the salient features of the PN–ISM interaction and investigate under what conditions it can be detected. The ISM density n_0 is clearly an important factor, since the interaction strength is proportional to n_0. The strongest interaction is expected in the case of cold ($T \leq 100$ K) and dense "diffuse" clouds. However, their filling factor is small, resulting in a small number of interacting PNs. At the other extreme, in the hot ($T \sim 10^6$ K) ISM phase, the hydrogen number densities are low, and the interaction takes place when PNs can no longer be detected. This leaves the diffuse neutral and warm ionized media, both with $T \sim 10^4$ K, as the environment where the interaction is most likely to be observed. In the Galactic plane, the average hydrogen number density n_0 is equal to ~ 0.6 cm^{-3} in the warm neutral medium (WNM; Lockman 1984; Dickey and Lockman 1990). Note, however, that this medium is rather inhomogeneous. The WNM distribution with respect to the Galactic plane is complex, with several components present (Lockman 1984; Dickey and Lockman 1990). The scale heights range from 100 to several hundred pc, with the density decreasing to ~ 0.1 cm^{-3} at a distance of ~ 300 pc above the Galactic plane. In the plane, the space-averaged density of the warm ionized medium (WIM) is 0.04 cm^{-3}, decreasing to 0.02 cm^{-3} at a distance of 500 pc above the Galactic plane (Reynolds 1989). Local WIM densities, which PNs are likely to encounter, might be several times higher.

PNs move with respect to the surrounding ISM with relative velocities v_*. With the possible exception of the hot ISM (not considered here), whose kinetic energy might be substantial, these motions are dominated by stellar velocities. The rms radial velocity dispersion with respect to the rotating Galactic disk is equal to 40 km s^{-1} for known PNs in our Galaxy (Pottash 1984, p. 28), except for the Galactic center region (§ IV). Therefore, we take 60 km s^{-1} as the average space velocity v_*. This velocity is 5 times larger than the sound speed of ~ 12 km s^{-1} in the ISM and PN gases, implying the presence of shocks at the interface separating them.

The evolution of a PN moving through the ISM can be divided into at least three phases (Smith 1976; Soker, Borkowski, and Sarazin 1990). First, the PN will expand freely, and the ISM has no significant influence. Second, the ISM pressure on the upstream side of the nebula will become comparable to the pressure in the PN shell, and the gas in the shell will be compressed significantly. This occurs when the PN shell density has dropped below a critical value $n_{\rm crit}$. A reverse shock may be driven into the PN shell on the upstream side, and the compression increases the surface brightness of this region. If the Mach number of the PN expansion is large, the shell will still be nearly spherical. When the density has dropped to a lower value $n_{\rm stop}$, the upstream portion of the shell will be significantly slowed by the ISM interaction. During this phase, the shape of the PN shell will be significantly distorted. The slowing of the upstream edge of the shell will cause the central star to move close to this edge. Finally, the star will move outside of the PN shell, and the PN shell will be stripped and mixed with the ISM.

Assume the PN shell expands with a velocity of $v_{\rm exp}$ relative to the central star. The planetary nebula shell will expand freely until the dynamic pressure $\rho_0(v_* + v_{\rm exp})^2$ of the ISM is roughly equal to the PN thermal pressure $\rho_{PN} c^2$. Here, c is the isothermal sound speed in the PN gas, which is ≈ 10 km s^{-1} for a typical temperature of 10^4 K. The ISM ram pressure is largest in the direction of the PN motion, and becomes equal to the PN thermal pressure when the nebular density is comparable to the critical density

$$n_{\rm crit} \sim \left(\frac{v_* + v_{\rm exp}}{c}\right)^2 n_0 \, . \tag{1}$$

When the density of the expanding PN shell decreases to $n_{\rm crit}$, a marked asymmetry should develop due to the pressure difference between the opposite sides of the nebula. The direction of motion of the central star is then the symmetry axis of the nebula. PN expansion velocities vary from several km s^{-1} to 50 km s^{-1}, with an average value of 20 km s^{-1} (Weinberger 1989*a*). With this average value of $v_{\rm exp}$ and $v_* = 60$ km s^{-1}, the interaction takes place when the PN number density is approximately 60 times larger than the ISM density. In the Galactic plane, this implies $n_{\rm crit} \sim 40$ cm^{-3} for a PN moving through the WNM. However, note the strong dependence on $(v_* + v_{\rm exp})$. As a result, the critical density increases rapidly with increasing stellar velocity v_* or expansion velocity $v_{\rm exp}$. Note also that the interaction might be detectable in nebulae with densities several times larger than $n_{\rm crit}$.

What are hydrogen number densities in extended PNs? The PN number density $n_{\rm PN}$ (or more precisely, electron density n_e) can be estimated from Balmer emission-line fluxes and the PN angular extent, with the use of the PN distance. For the large nebulae observed by Kaler (1983) in the Hβ emission line, this gives ~ 100 cm^{-3} for the low surface brightness PNs from the NGC catalog, and ~ 10 cm^{-3} for a number of fainter PNs from the Abell (1966) catalog. These fainter nebulae were discovered on the Palomar Observatory Sky Survey plates.

Recent systematic searches of these plates revealed even fainter extended PNs. Ishida and Weinberger (1987) found two large nearby nebulae with $n_e = 6$ and 8 cm^{-3}. The very large PN S216, with a diameter of 1°.6 and $n_e = 5$ cm^{-3} (Reynolds 1985; Abramenkov, Krykmin, and Sidorchuk 1987), is an another example. Because of their low densities, many of these low surface brightness nebulae should be distorted by the interaction with the ISM.

A PN shell will expand until the dynamic pressure $\rho_0(v_* + v_{\rm exp})^2$ of the ISM is roughly equal to the PN ram pressure $\rho_{PN} v_{\rm exp}{}^2$. Assuming $v_* \gg v_{\rm exp}$, the shell expansion in the direction of PN motion is arrested when the nebular density is comparable to $n_{\rm stop} \sim (v_*/v_{\rm exp})^2 n_0$. We use a thin-shell model of Smith (1976) to estimate $n_{\rm stop}$ more accurately. By differentiating his equations (5a) and (6a), and by setting shell velocity to zero, we arrive at the following expression for the shell stopping time

$$t_{\rm stop} = \frac{(1 + 0.25 v_{\rm exp}/v_*)R_0}{[(1 + v_*/v_{\rm exp})v_*/v_{\rm exp}]^{1/3} v_{\rm exp}} , \tag{2}$$

where $R_0 = (3M_{\rm PN}/4\pi\rho_0)^{1/3}$ and $M_{\rm PN}$ is the initial PN mass. If $v_* = 0$, then R_0 is the radius at which the ISM mass swept up by a PN is equal to the initial PN mass. We obtain

$$n_{\rm stop} \simeq \frac{8(1 + v_*/v_{\rm exp})v_*}{7(1 + 0.25 v_{\rm exp}/v_*)^3 v_{\rm exp}}\, n_0 \tag{3}$$

if the PN is modeled as a uniform density thick shell with a fractional thickness of 0.5 (Khromov and Kohoutek 1968). Note that $n_{\rm stop}$ refers to the density of undecelerated nebular gas in the trailing (downstream) section of the shell. (This is valid for $v_* \geq v_{\rm exp}$; otherwise, the trailing section of the shell is also decelerated and $n_{\rm stop}$ is higher than given by eq. [3].) With $v_{\rm exp} = 20$ km s^{-1} and $v_* = 60$ km s^{-1}, $n_{\rm stop} \sim 10 n_0$ is 6 times smaller than $n_{\rm crit} \sim 60 n_0$. The nebular gas in the leading (upstream) shell section is compressed to a density of $\sim(v_*/c)^2 n_0$ ($\sim 35 n_0$ for $v_* = 60$ km s^{-1}), typically only twice as low as $n_{\rm crit}$. The nebular morphology at this advanced stage of the interaction is dominated by a crescent-shaped leading shell section which is several times brighter than the trailing PN hemisphere. Because the emissivity of the gas depends on n^2, the nebular surface brightness in the final interaction stages will be substantially lower than in the initial stage. Because low surface brightness nebulae are hard to discover, relatively few PNs in late stages of interaction are expected to be found. A35 is the best known nebula of this kind.

An upper limit to the ISM mass swept up (or displaced) by the PN can be obtained by treating the PN as a rigid sphere expanding with the constant velocity of $v_{\rm exp}$ and moving with the relative velocity v_* through the homogeneous ISM. An upper limit to the displaced mass is then

$$M_{\rm ISM} \leq \frac{4}{3}\pi R^3 \rho_0 \times \begin{cases} \dfrac{1}{4}\left(2 + \dfrac{v_*}{v_{\rm exp}} + \dfrac{v_{\rm exp}}{v_*}\right) & v_* > v_{\rm exp} \\ 1 & v_* \leq v_{\rm exp} \end{cases} , \tag{4}$$

where R is the PN radius. The term to the right of the brace, which corrects for the motion of the PN with respect to the ambient medium, may be substantial for $v_* \gg v_{\rm exp}$. For $v_* > v_{\rm exp}$, the ratio of the swept ISM mass to the PN mass is less than

$$\frac{M_{\rm ISM}}{M_{\rm PN}} \leq \left(1 + \frac{v_{\rm exp}}{v_*}\right)\left(1 + \frac{v_{\rm exp}}{4v_*}\right)^3 \frac{v_{\rm exp}}{4v_*} \tag{5}$$

at the time $t_{\rm stop}$ (eq. [2]). For typical values of v_* and $v_{\rm exp}$, this ratio is less than 0.15. Therefore, the interaction takes place before a PN sweeps up an ISM mass equal to the initial PN mass.

III. OBSERVATIONAL EVIDENCE FOR ISM INTERACTION

a) Nebulae with Large Proper Motions

A good observational diagnostic for the PN–ISM interaction is a distortion of the nebula in the direction of the stellar motion. This distortion results in an asymmetry, clearly visible in A35 where there is strong emission enhancement ahead of the central star. Therefore, we examined the morphology of PNs whose central stars have large proper motions. The most extensive set of proper motion measurements in PNs can be found in Cudworth (1974). We used his data (Cudworth 1974, 1977), combined with measurements by Anderson (1934) and van Maanen (1933), to select nebulae with the largest proper motions. We need to know the direction of motion with respect to the ISM, which in the first approximation may be assumed to move on circular orbits around the Galaxy center. In other words, we need to determine the motion of each PN with respect to its local standard of rest (LSR). In view of the small measured motions, care is required in the transformation from relative proper motions to the LSR. This transformation involves a correction for the differing effect of solar motion on the PN and on the reference stars used in its proper motion measurement. Cudworth (1974) used preliminary results from the Lick Northern Proper Motion Survey (see Klemola, Jones, and Hanson 1987 for its description) to account for the solar motion with respect to reference stars. These results (Klemola and Vasilevskis 1971) are now known to contain large systematic errors. Therefore, we used recent results from the Lick Survey (Hanson 1987) to account for the solar motion with respect to faint ($m \sim 16$ mag) reference stars in the transformation from Cudworth's relative proper motions to the LSR. We also used standard values for the solar motion with respect to our LSR (Mihalas and Binney 1981), together with PN distances from Weinberger (1989*a*). We examined nebulae with proper motions relative to the LSR exceeding a somewhat arbitrary value of 0.015 arcsec yr^{-1}. We excluded from our sample NGC 6807 and IC 4997 because of the poor signal-to-noise ratio (less than 3 σ). We also rejected the compact nebula IC 5117 where the proper motion measurements may have been contaminated by nebular emission (Cudworth 1974). Finally, NGC 7008 was excluded on the basis of combined data from Cudworth (1974), Anderson (1934), and van Maanen (1933). In the case of A35 and S216, whose proper motions were not measured by Cudworth (1974), we used motions from the SAO catalog and from Cudworth and Reynolds (1986), respectively.

The results are presented in Table 1. Column (1) contains the nebula name, columns (2) and (3) give the nebular proper motion μ, with respect to the LSR, and its position angle Θ (measured to the east starting from north). The nebular distances d are from Weinberger (1989*a*), except for S216 where we assumed a distance of 80 pc (Reynolds 1985). These distances were used to obtain maximum radii (the semimajor axis sizes in col. [5]) and transverse velocities (col. [6]) with the aid of the angular extents of nebulae and their tabulated proper motions from column (2). Finally, we indicate in column (7) whether or not the nebular morphology can be ascribed to the PN–ISM interaction.

TABLE 1

PLANETARY NEBULAE WITH LARGE PROPER MOTIONS[a]

Nebula (1)	μ ($'' \mathrm{yr}^{-1}$) (2)	Θ (°) (3)	d (kpc) (4)	R (pc) (5)	v_T (km s^{-1}) (6)	Interaction (7)
A35	0.075	245	0.35	0.80	125	Yes
NGC 7293	0.032	70	0.30	1.7	45	Yes
S216	0.030	20	0.08	1.2	10	Yes
NGC 246	0.029	270	0.45	0.26	60	Yes
A36	0.027	85	0.6	0.70	80	Yes?
NGC 6309	0.019	25	3.0	0.40	280	No
NGC 6833	0.016	65	7.0	0.01	530	No
A33	0.015	310	0.9	0.58	65	Yes
NGC 6853	0.015	60	0.6	1.2	40	Yes

[a] Nebulae with proper motions in excess of 0.015 arcsec yr^{-1}.

As expected from our selection criteria, most nebulae in Table 1 are nearby ($d < 1$ kpc), with only two exceptions to be discussed later. The transverse velocities v_T of these nearby nebulae do not exceed ~ 100 km s^{-1}, in accord with expectations. All of them might be interacting with the ISM, with strong morphological evidence for the interaction in a majority of the cases. We now discuss several of the individual nebulae.

i) A35

The discovery by Jacoby (1981) that A35 is interacting with the ISM was the first observational evidence for the PN–ISM interaction. An asymmetric morphology of A35, with an emission enhancement present ahead of the fast-moving (~ 125 km s^{-1}) central star, is characteristic of the PN–ISM interaction. However, a bow-shock structure visible in the [O III] 5007 Å emission line (Jacoby 1981) is the most striking nebular feature. Its presence implies that the nebular expansion in the direction of the stellar motion was halted, and the nebular gas is now accelerated past the central star by the ram pressure of the ISM. A35 is in its final evolutionary stage, with the nebula being stripped away from its central star. The nebular rms electron density is ~ 10 cm^{-3} (Jacoby 1981) and should be approximately equal to $(v_*/c)^2 n_0 = 150 n_0$. We obtain $n_0 \sim 0.07$ cm^{-3}, indicating that A35 moves through the warm neutral (or ionized) medium whose average density at a distance of 230 pc above the Galactic plane is ~ 0.1 cm^{-3} (Dickey and Lockman 1990).

The bow shock forms where the ram pressure of the accelerated PN gas is balanced either by the stellar wind ram pressure (Jacoby 1981) or by the stellar radiation pressure. The ram pressure of the accelerated PN gas depends quadratically on an unknown velocity difference Δv between the central star and the PN gas. On the basis of theoretical considerations, $\Delta v \sim v_{\mathrm{exp}}$, a small velocity difference in view of the low nebular expansion velocity v_{exp} of 4 km s^{-1} (Bohuski and Smith 1974). For example, with $v_* = 125$ km s^{-1} and $v_{\mathrm{exp}} = 4$ km s^{-1}, $\Delta v = 10$ km s^{-1} in the thin-shell model of Smith (1976). Future observations of the bow shock should reveal whether the velocity of the PN gas entering the bow shock is indeed sonic or mildly supersonic with respect to the central star. The PN ram pressure is most likely balanced by the stellar wind ram pressure. With angular distance of 30″ (0.05 pc at 360 pc) between the central star and the bow-shock stagnation point, and the PN density of 10 cm^{-3}, the product of the stellar mass-loss rate $\dot{m}_{-9}$ (in 10^{-9} $M_\odot$ yr^{-1}) and the stellar wind velocity $v_{w,6}$ (in 10^6 cm s^{-1}) is $\dot{m}_{-9} v_{w,6} \sim (\Delta v/\mathrm{km\ s^{-1}})^2$. If $\Delta v \sim 10$ km s^{-1}, then the required stellar wind with $\dot{m}_{-9} v_{w,6} \sim 100$ seems to be excessive for the optical G8 III–IV companion (Jacoby 1981), while no stellar wind is expected from the hot white dwarf detected by Grewing and Bianchi (1988). There is a possibility that the interaction between the hot white dwarf and its optical companion might drive a stellar wind with the characteristics required to produce the bow shock (Jacoby 1981).

Another solution for the bow shock involves the white dwarf radiation pressure pushing the PN dust away from the central binary system. A similar model was proposed by Van Buren and McCray (1988) to explain bow shocks observed near massive B-type stars. We use their formula (7) to estimate the distance r_{pc} (in pc) between the central star and the bow-shock stagnation point. Since $r_{\mathrm{pc}} \sim 0.1 L_{36} (\Delta v)^{-2}$, where $L_{36} \sim 0.4$ is the white dwarf stellar luminosity in 10^{36} ergs s^{-1}, we obtain agreement with the observed distance r_{pc} of 0.05 pc if $\Delta v \sim 1$ km s^{-1}. (We calculated the white dwarf luminosity of $L_{36} \sim 0.4$ from its effective temperature of 1.5×10^5 K and gravity $\log g = 8$, obtained by Grewing and Bianchi [1988] from the far-UV spectra of the central star.) Therefore, the bow shock in A35 can be produced by balancing the ram pressure of the PN gas and the white dwarf radiation pressure, but the relative velocity Δv between the central star and the PN gas is then quite low, on the order of 1 km s^{-1}. Such a low-velocity difference is not expected but cannot be ruled out on the basis of scarce observational data.

A pair of linear trails, aligned with the direction of the nebular proper motion, can be seen on the red POSS plate. These knotted trails abruptly end at the well-defined outer edge of the nebula, constituting the boundary between the shocked ISM and the nebular gases. One of them is clearly related to a protruding feature located on the upstream nebular edge, along the bow-shock symmetry axis. Both the protruding feature and linear trails of knotted emission indicate that the interaction of A35 with the ISM is more complicated than suggested by Smith's (1976) analytic models. A complex interaction is also seen in the Helix nebula which is discussed next.

ii) *Helix Nebula*

The well-known Helix nebula (NGC 7293) is one of the closest PNs. This large nebula of low surface brightness has been thoroughly studied, and a great deal of information about its complicated structure is available. The outermost feature to the east of the central star, at an angular distance of 20′ (1.7 pc at a distance of 300 pc), is quite unusual. Photographically amplified prints (Malin 1982; Malin and Murdin 1984) reveal a conical filament (feature B) pointing almost directly to the east. Two additional filaments with related morphologies are also visible: a cometary object A to the northeast, with its tail pointing to the west, and filament C to the southeast. On the opposite side of the central star, at a position angle of 240°, a looplike emission structure is visible at approximately the same angular distance from the central star as filaments A and B. This loop D was discovered by Araya, Blanco, and Smith (1972). Malin (1982) suggested that all these features constitute a common bipolar loop. A much brighter shell (the eastern filament in the nomenclature of Walsh and Meaburn 1987) has been known for a long time in the northeast quadrant at a distance of 11′ from the central star. It is located almost exactly on the opposite side of loop D, between the main (brightest) body of the nebula and filaments A and B. Spectroscopic observations in Hα and [N II] lines (Walsh and Meaburn 1987) revealed double-peaked profiles, with the violet component blueshifted from the mean nebular velocity by 50 km s^{-1}. They interpreted their observations in terms of an expanding ellipsoidal shell whose long axis is inclined toward the line of sight.

The asymmetry between the loop D in the southwest quadrant and the filaments A, B, C, and the eastern filament in the northeast quadrant can be naturally explained by the interaction between the Helix nebula and the ISM. The motion of the central star is directed at a position angle of 70°, and coincides, to within observational errors, with the direction determined by the conical filament B and the cometary object A. One possibility is that these filaments are condensations in the outer bipolar shell which interact with the ISM. These condensations would not have been substantially decelerated by the ram pressure of the ISM since they are at the same distance from the central star as the loop D. The difficulty with this interpretation lies in the lack of alignment between filaments B and A, and the outer bipolar outflow delineated by the loop D and the eastern filament. If filaments A and B were indeed moving away from the central star with velocities exceeding 50 km s^{-1}, then their relative motion with respect to the ISM would be $\sim$100 km s^{-1} at a position angle of 70° because the proper motion of the central star happens to be aligned with the outer bipolar shell. However, the conical filament B points almost directly to the east (at a position angle of 85°), and the same is true of the cometary object A. In view of the large velocities involved, neither errors in the proper motion measurements nor the peculiar motion of the surrounding ISM are likely to account for the resulting discrepancy. Because of this discrepancy, we favor an alternative explanation of filaments A, B, and C as shock-compressed red giant wind gas. This gas is visible in the east because it has been compressed by the ram pressure of the ISM. The red giant wind hypothesis leads to a natural explanation for the asymmetry of the bipolar outflow delineated by the loop D and the eastern filament. This bipolar outflow expands in the distorted red giant wind whose density is higher in the direction of nebular motion, resulting in the strong asymmetry between the eastern filament and the loop D. Spectroscopic observations of filaments A, B, and C would be most useful in securing this interpretation.

The interaction between the Helix nebula and the ISM is apparently more complex than our simple interaction model involving a uniform PN. First, the red giant wind is distorted by the ISM. In the second stage of the PN–ISM interaction, the outermost bipolar outflow becomes asymmetric in the course of its interaction with the asymmetric red giant wind. The main body of the nebula is still unaffected by the ISM.

iii) *S216*

The large PN S216 was discussed in detail by Fesen, Blair, and Gull (1981), Reynolds (1985), and Abramenkov, Krymkin, and Sidorchuk (1987). Its low spatial velocity and low expansion rate distinguish it from other nebulae in Table 1. In addition, the nebula is ionization-bounded. These characteristics make it hard to decide whether S216 is a PN or an H II region, the latter interpretation being not entirely excluded at present. The position angle Θ of its proper motion depends strongly on the assumed distance to the nebula. Furthermore, in view of the low transverse velocity of the central star LS V+46°21, the unknown motion of the surrounding ISM might be of importance.

iv) *NGC 246*

The next nebula, NGC 246, is an elliptical object, 4′ × 3′.5 in size, with its semimajor axis at a position angle of 120° (Curtis 1918). The nebula is brightest on the western edge, where an inward-pointing deformation of its elliptical shape is noticeable. Because the proper motion of the central star also points to the west, we conclude that NGC 246 is distorted by the ISM. Nebular spectrophotometry (Heap 1975) reveals that the density of the western edge is at least twice as large as the average nebular density of $n_{\rm rms} \approx 70$ cm^{-3}, estimated from the Hβ flux and nebular radius (Kaler 1983) for a uniform gas distribution. This density increase can be interpreted as a result of gas compression by the ISM ram pressure. We can then estimate the density of the surrounding ISM. Using the tangential velocity from Table 1 and the LSR radial velocity of -50 km s^{-1} from a compilation of nebular radial velocities (Schneider *et al.* 1983), the relative stellar velocity is $v_* = 80$ km s^{-1}. The nebular expansion rate is 40 km s^{-1}, from a catalog of expansion velocities by Weinberger (1989*a*), and the nebular electron temperature $T_e \sim 2 \times 10^4$ K (Kaler 1983). By assuming undecelerated expansion of the nebula, we arrive at the lower limit of $\sim$1 cm^{-3} to the surrounding ISM density. The actual ISM density might be higher because the western shell section could have been already decelerated, and the shell density might have been underestimated. A high ISM density is also suggested by applying a thin-shell approximation to model the nebular distortion (Soker, Borkowski, and Sarazin 1990). The high ($\geq$1 cm^{-3}) ISM density at the location of the high-galactic latitude nebula NGC 246 comes as a surprise. At a relatively well-known distance of 450 pc below the Galactic plane as determined spectroscopically for a visual companion to the central star (Pottash 1984, p. 101), the expected WNM density is $\sim$0.05 cm^{-3} (Lockman 1984; Dickey and Lockman 1990). The interaction of NGC 246 with the ISM reveals an unusually dense medium surrounding this planetary. An examination of an H I sky map, compiled by Dickey and Lockman (1990) from existing 21 cm H I emission-line surveys, reveals that NGC 246 is located at an edge of a bright high-latitude H I filament. This filament appears to be associated with a nonthermally emitting radio loop (the Loop II; Berkhuijsen 1971) which passes through this region of the sky. Therefore, NGC 246 might be moving through a high-density shell associated with the radio Loop II. NGC 246 clearly illustrates a potential value of PNs as probes of the ISM density.

v) *A33 and A36*

Two nebulae from the Abell catalog, A33 and A36, are extended, low-density objects. Their rms electron densities are barely over 10 cm^{-3}, a significantly lower value than the NGC 246 rms density of 70 cm^{-3}, and they are only twice as large as critical densities calculated from equation (1). If these nebulae are moving through the WNM (or the WIM), the interaction with the surrounding medium might be detectable. An examination of their nebular morphology reveals that A33 is indeed interacting with the ISM. A33 is an almost perfect spherical nebula, but with an emission enhancement present in its northwest quadrant (Abell 1966; Perek and Kohoutek 1967; Hua and Nguyen-Trong 1983; Louise and Hua 1984), in the direction of the stellar motion. Further support for the interaction is provided by spectroscopic observations of Bohuski and Smith (1974). The nebula recedes from us with velocity exceeding 40 km s^{-1} with respect to its LSR. Therefore, the interaction region is located behind the central star. The redshifted and compressed interaction region should radiate more intensely than the freely expanding shell moving in our direction. The double-peaked line profiles are indeed asymmetric with the stronger redshifted component (Bohuski and Smith 1974). A similar asymmetry is expected in NGC 246, with the blue-shifted component being stronger, but its more complicated morphology makes it harder to distinguish between an asymmetry induced by internal motions and by the presence of the interaction region. The observed line profiles for NGC 246 are dominated by a redshifted component (Johnson 1976), but an additional expansion with velocity of 20 km s^{-1} may also be present along the major axis. More data are needed to investigate internal motions and the interaction region of NGC 246. An even more complicated helical morphology is observed in A36 (Abell 1966; Perek and Kohoutek 1967; Louise and Hua 1984). The eastern part of the helix, which is in the direction of the stellar motion, is brighter than its western counterpart. This suggests that there is a significant interaction with the ISM, but better observational data are needed to investigate this possibility in detail.

vi) *Dumbbell Nebula*

The well-known Dumbbell nebula (NGC 6853) also interacts with the ISM. The rms electron density in the main (bright) part of the nebula is comparable ($n_{\rm rms} \approx 65$ cm^{-3}) to the NGC 246 density. The critical density $n_{\rm crit}$ of ~ 25 cm^{-3} is only twice as low for this nebula located in the Galactic plane. Again, if NGC 6853 is moving through the WNM, its interaction with the ISM should be noticeable. An emission enhancement is indeed present on the northeast edge of this morphologically complex nebula, and it is most easily seen on an Hα photograph presented by Hua and Louise (1970). The bright nebular core is surrounded by a faint halo (Milikan 1974; Chu, Jacoby, and Arendt 1987), best visible in the northwest. An examination of a CCD image of NGC 6853, taken through the Hα + [N II] interference filter (John Graham and Phil Plait, unpublished), reveals that the halo is strongly asymmetric in shape. Its symmetry axis is at a position angle of 20° which is most likely the direction of the relative motion between the nebula and the surrounding ISM. However, the halo is fainter in this direction than in the northwest quadrant. The reason for such behavior may lie in the complex morphology of the Dumbbell nebula. The central star is surrounded by a thick molecular torus, which has been mapped in infrared lines of molecular hydrogen by Zuckerman and Gatley (1988). The torus is seen approximately edge on, at a position angle of 35°. The nebula is much more tenuous and transparent in the direction perpendicular to the torus, which produces the characteristic dumbbell-like shape at optical wavelengths. The halo morphology is directly linked to this dumbbell-like shape, with the halo being brightest in the northwest, within the cone delineated by the bright optical emission ridges and the torus edge. The halo brightness declines rapidly at the cone edge where stellar photons are efficiently absorbed within the molecular torus. In the absence of the interaction with the ISM, the halo should be also bright in the southeast. However, the northwest halo section is located on the torus side facing the incoming ISM gas, and the halo gas is being compressed by the ISM ram pressure. The compressed halo in the northwest is, thus, much brighter than the shielded halo on the opposite side of the torus.

The presence of the torus may indicate why the leading section of the halo (at a position angle of 20°) is relatively faint. The edge of the halo coincides here with the outer boundary of the torus, and the incoming ISM gas interacts directly with the torus gas. The compressed molecular gas in the torus cannot radiate efficiently at visible wavelengths and appears relatively faint on the Hα CCD frame. The torus compression in the direction of the nebular motion is noticeable at the boundary between neutral and ionized gases, constituting the edge of the nebula proper. As has already been mentioned, the northeast boundary seems to be brighter than its southwest counterpart.

vii) *NGC 6309 and NGC 6833*

The two distant nebulae NGC 6309 and NGC 6833 are not observed to be asymmetric. NGC 6309 has a symmetric appearance in the CCD image of Chu, Jacoby, and Arendt (1987). NGC 6833 is stellar in appearance on the photographic plate taken by Curtis (1918), and may be too small in angular size to detect any asymmetry. The apparent high transverse velocities of these two nebulae (in excess of 200 km s^{-1}) suggest that their proper motions might be overestimated. The presence of these nebulae in our sample of PNs with the largest proper motions is a reminder that proper motion determinations are susceptible to large errors.

viii) *The PN in M22*

The presence of large systematic errors in proper motion determinations is the reason why we have considered only PNs with proper motions in excess of 0.015 arcsec yr^{-1}. However, we should also mention the recently discovered PN in the globular cluster M22 (Gillett *et al.* 1989), because accurate proper motion measurements are available in this case (Cudworth 1986). The PN in M22 is strongly asymmetric, being brightest in its southeast quadrant. Because the absolute proper motion of the cluster is 0.0095 arcsec yr^{-1} at a position angle of 114°, we ascribe the observed asymmetry to the interaction with the ISM. This interpretation is consistent with available observational data. Nebular electron densities are low (Gillett *et al.* 1989), although somewhat uncertain because of an unknown chemical composition of the nebular gas. If the nebula is hydrogen-rich, then $n_e \sim 40$ cm^{-3}. However, since no H emission lines have been observed, n_e might be lower. For example, $n_e \sim 5$ cm^{-3} if the PN contains a pure oxygen gas. The nebular expansion velocity $v_{\rm exp}$ is 11 km s^{-1} (Cohen and Gillett 1989). With the cluster velocity of $v_* = 200$ km s^{-1} (Cudworth 1986) and the ISM density of 0.05 cm^{-3} (the WNM density at a distance of 400 pc below the Galactic plane where M22 is located), $n_{\rm stop} \sim n_{\rm crit} \sim 400 n_0 = 20$ cm^{-3} if the nebula is hydrogen-rich. Similarly, $n_{\rm stop} \sim 1$ cm^{-3} and $n_e \sim 2$ cm^{-3} are the oxygen number density and the electron density if the nebula is a pure oxygen gas, and all the oxygen is doubly ionized. These densities are only twice as low as electron densities derived from observations. The PN in the center of M22 is expected to interact with the ISM, and its strongly asymmetric shape reveals that it is indeed distorted by the ISM ram pressure.

b) *Large Asymmetric Nebulae*

Proper motions have been measured for a small fraction of PNs. As a result, our list of nebulae with large proper motions (Table 1) is incomplete, and more interacting PNs should be present among nearby nebulae. These nebulae are expected to be asymmetric.

We examined the morphology of large, nearby nebulae for signs of PN–ISM interaction. Because PN distances are poorly known, we decided to investigate PNs with major axes larger than a somewhat arbitrary value of 8′. This criterion favors old, nearby nebulae, the prime candidates to be interacting PNs with large proper motions. The selected nebulae are listed in Table 2 in order of decreasing angular size. Our sample encompasses a similar (but smaller) set of large nebulae listed by Weinberger *et al.* (1983). Two nebulae from their list, NGC 3242 and K 2–4, are not present in Table 2. We rejected NGC 3242 because of the weak evidence for a giant halo surrounding this planetary, while K 2–4 turned out to be a plate fault (Lutz and Kaler 1983). We also did not include PK 130−52, a large nebula (or an H II region) excited by the hot white dwarf PG 0108+101 (Reynolds 1987). The available data do not contain enough information to decide whether or not this nebula is asymmetric. Column (1) gives the catalog number for each object (according to a classification introduced by Perek and Kohoutek 1967), while other names are listed in column (2). The major and minor axes (in arcmin) are given in column (3) as taken from Weinberger *et al.* (1983) or from the references in column (8). The corresponding linear dimensions (in pc) are listed in column (5). The angular and linear sizes of NGC 7293, S200, NGC 6853, and He 2–111 refer to the halos which surround these planetaries. Nebular distances *d* are from Weinberger (1989*a*), except for A7, EGB 6, and HW 4 where we used distances from Ishida and Weinberger (1987), Liebert *et al.* (1989), and Hartl and Weinberger (1987), respectively. The distance to S216 was assumed to be 80 pc (Reynolds 1985). A confirmation in column (6) means that an asymmetry is visible on photographs presented (or referred to) in references listed in column (8).

All nebulae in Table 2 are located in the solar vicinity (generally closer than 0.5 kpc), except for the unusual nebula He 2–111 which is discussed later. Assuming these distances and a tangential velocity dispersion of 40 km s^{-1}, the proper motions should exceed 0.015 arcsec yr^{-1} for many of these nebulae. This expectation is confirmed for those nebulae in Table 2 whose proper motions have been measured. All of them (S216, NGC 7293, A35, NGC 6853, and A36) are already contained in our sample of PNs with large proper motions (Table 1).

Over half of the nebulae in Table 2 are asymmetric. A typical asymmetry consists of a one-sided emission enhancement in the form of an arc, reminiscent to what is seen in S216 and NGC 7293. In several nebulae only this region of enhanced emission is visible, with any fainter nebular regions apparently lying below the detection limit. In other cases, the whole nebula can be seen, although the contrast in brightness between faint and bright hemispheres varies from one object to another. The remaining nebulae are either symmetric or exhibit a more complicated bipolar or helical structure.

The dipole asymmetry of nebulae in Table 2 can result from either an interaction with the ISM or an asymmetric PN ejection. The latter possibility seems to be less likely because young nebulae generally display a remarkable degree of dipole symmetry, although their morphology may be quite complex.

TABLE 2

LARGE PLANETARY NEBULAE[a]

PK (1)	Name (2)	Angular Size (arcmin) (3)	*d* (kpc) (4)	Linear Size (pc) (5)	Asymmetry (6)	Θ (°) (7)	Reference (8)
158+0°	S216	100 × 100	0.08	2.3 × 2.3	Yes	80	1, 2
36−57°	NGC 7293	35 × 18	0.30	3.1 × 1.6	Yes	85[b]	3, 4
138+4°	S200	24 × 24	0.60	4 × 4	Yes	165	5
158+17°	PW 1	20 × 20	0.25	1.5 × 1.5	...	...	6
219+31°	A31	17 × 16	0.30	1.5 × 1.4	Yes	140	7
197−6°	WDHS 1	17 × 14	0.30	1.5 × 1.2	Yes	330	8
107+7°	IW 2	16 × 14	0.25	1.2 × 1.0	Yes	345	9
303+40°	A35	16 × 11	0.35	1.6 × 1.1	Yes	245[c]	7, 10
136+5°	HFG 1	15 × 15	0.35	1.5 × 1.5	Yes	140	11
72−17°	A74	15 × 13	0.25	1.1 × 0.95	...	...	7
60−3°	NGC 6853	15 × 12	0.60	2.6 × 2.1	Yes	20[d]	
215−30°	A7	15 × 11	0.22	0.96 × 0.70	...	...	7
149−3°	IW 1	13 × 13	0.35	1.3 × 1.3	...	...	9
120−5°	S176	13 × 11	0.25	0.95 × 0.80	Yes	140	8
221+46°	EGB 6	13 × 11	0.46	1.7 × 1.5	...	...	12
205+14°	A21	12 × 8.5	0.35	1.2 × 0.87	Yes	115	7, 13
315−0°	He 2–111	10 × 4.7	2.05	6.0 × 2.8	...	...	14
339+88°	LT 5	9.3 × 8.2	0.40	1.1 × 0.95	...	...	15
149−9°	HW4	9.0 × 9.0	0.41	1.0 × 1.0	Yes	25	5
128−4°	S188	8.9 × 8.0	0.20	0.52 × 0.47	Yes	135	16
111+11°	DHW 5	8.8 × 8.8	0.40	1.0 × 1.0	Yes	330	17
244+12°	A29	8.0 × 5.6	0.40	1.0 × 0.65	...	...	7
318+41°	A36	8.0 × 4.7	0.60	1.4 × 0.82	...	...	7, 18

[a] Nebulae with major axes in excess of 8 arcmin.

[b] Determined from filament B.

[c] Bow shock position angle.

[d] See § III for an explanation.

REFERENCES.—(1) Fesen, Blair, and Gull 1981; (2) Reynolds 1985; (3) Malin 1982; (4) Malin and Murdin 1984; (5) Hartl and Weinberger 1987; (6) Purgathofer and Weinberger 1980; (7) Abell 1966; (8) Weinberger *et al.* 1983; (9) Ishida and Weinberger 1987; (10) Jacoby 1981; (11) Heckathorn, Fesen, and Gull 1982; (12) Ellis, Grayson, and Bond 1984; (13) Lozinskaya, Sitnik, and Toporova 1986; (14) Webster 1978; (15) Longmore and Tritton 1980; (16) Kwitter, Jacoby, and Lydon 1988; (17) Dengel, Hartl, and Weinberger 1980; (18) Louise and Hua 1984.

Proper motion measurements could clearly differentiate between these two possibilities. If the observed asymmetry is attributed to the PN–ISM interaction, then the central stars of asymmetric nebulae in Table 2 should have proper motions directed toward brightest nebular regions, along an axis joining bright and faint hemispheres. In column (7) of Table 2, we tabulate the predicted position angle Θ marking the direction of the stellar motion with respect to the ISM. At the present time, the PN–ISM interaction hypothesis is supported by substantial displacements of the central stars toward the brightest nebular regions in IW 2 (Ishida and Weinberger 1987), A21 (YM 29), and S188 (Kwitter, Jacoby, and Lydon 1988), and by smaller displacements in A31 and HFG 1. It is hard to measure displacements of central stars in the remaining asymmetric nebulae because only the brightest nebular regions can be seen. We now discuss several of the individual nebulae in Table 2.

i) *S188 and A21*

In addition to the displacements of their central stars, relatively bright and strongly asymmetric nebulae S188 and A21 have a peculiar filamentary morphology, reminiscent to what is seen in old supernova remnants. Because of the presence of filaments, they were even suspected to be supernova remnants until radio observations ruled out this interpretation (Salter *et al.* 1984). Filaments in S188 and A21 are most easily explained by shock compression. The presence of shocks requires that the nebular gas interacts either with a stellar wind (Arkhipova and Lozinskaya 1978) or with the ISM (Rosado and Kwitter 1982). The former explanation encounters serious difficulties because UV observations failed to detect a stellar wind in A21 (Arkhipova, Lozinskaya, and Moskalenko 1986). The PN–ISM interaction is thus the most likely cause of the filamentary morphologies of S188 and A21. Additional support for the existence of this interaction is found in the morphology of S188. The majority of filaments in this nebula are aligned along its crescent-shaped outer rim. Most probably, they are thin, sheetlike layers of shock-compressed nebular gas, parallel to the line of sight. However, a few of the filaments are aligned along the nebular symmetry axis, reminiscent of filaments observed in the interacting nebula A35. If they are of a common origin, then they should be roughly aligned with the direction of the stellar motion.

Spectroscopic observations in forbidden lines of [O II] and [S II] indicate filament densities of a couple hundred electrons per cm^{-3} in both S188 (Kwitter 1979; Rosado and Kwitter 1982) and A21 (Lozinskaya, Sitnik, and Toporova 1986 and references therein), varying somewhat from one filament to another. While such high densities are unexpected in old noninteracting PNs, they are consistent with our interpretation of these filaments as shocked nebular gas. Roughly, pressures in the filament should be equal to the ISM ram pressure. The nebular expansion velocity $v_{\mathrm{exp}} \sim 40$ km s^{-1} (Lozinskaya 1970, 1973; Rescillas-Cruz and Pismis 1981; Rosado and Kwitter 1982) is significantly higher than the average value. Combined with a typical stellar velocity $v_* = 60$ km s^{-1}, this gives $v_* + v_{\mathrm{exp}} \sim 100$ km s^{-1}. Assuming an electron temperature of 10^4 K, the filament pressures roughly match the ISM ram pressure if the ISM density is $n_0 \sim 2\ \mathrm{cm}^{-3}$. Such a density is reasonable since S188 and A21 are located in the Galactic plane.

The dense (several atoms cm^{-3}) ISM surrounding S188 and A21 might be directly observable if a substantial fraction of ionizing photons emitted by their central stars have escaped from the nebulae. A lower limit on the total flux of Lyman continuum photons emitted by central stars can be derived from the nebular Hβ flux of A21 (Kaler 1983) and from the 5 GHz radio continuum flux of S188 (Salter *et al.* 1984; Kwitter and Jacoby 1989). The number is comparable in both nebulae, and is equal to $\sim 10^{46} d_{\mathrm{kpc}}^{2}$ photons s^{-1}, where d_{kpc} denotes the nebular distance in kpc. With distances from Table 2, we obtain 5×10^{44} and 10^{45} photons s^{-1} for S188 and A21, respectively. Because these flux measurements refer only to the bright leading section of the nebular shells, the number of ionizing photons emitted by their central stars might be somewhat higher than estimated above. Assume for a moment that all ionizing photons escape into the surrounding ISM. They will ionize it within a radius r_i whose value is uncertain; under ionization equilibrium r_i is equal to the radius of the Strömgren sphere $r_s = 2.9 L_{45}^{1/3} n_0^{-2/3}$ pc $= 21 d_{\mathrm{kpc}}^{-1/3} n_0^{-2/3}$ arcmin (L_{45} is the photon luminosity in units of 10^{45} photons s^{-1}) if the temperature of the ionized gas is 8000 K. However, the nebular lifetimes $t_{\mathrm{PN}} \sim 10^4$ yr are smaller than the recombination time $t_{\mathrm{rec}} = (n_e \alpha_{\mathrm{B}})^{-1} = 10^5 n_0^{-1}$ yr (α_{B} denotes the recombination coefficient to excited H states) in the surrounding H II regions for reasonable ($n_0 < 10\ \mathrm{cm}^{-3}$) ISM densities. This disparity in time scales implies that the H II regions cannot be in the ionization equilibrium, and must evolve in time. Their evolution depends on central star temperatures and luminosities during the nebular lifetime, and on the evolution of nebulae themselves. Because we do not have enough information to calculate their evolution, we consider steady-state H II regions with the radius r_s, bearing in mind that results obtained thereby should be treated as crude estimates. The emission measure EM in centers of such H II regions is $5.8 L_{45}^{1/3} n_0^{4/3} = 12 d_{\mathrm{kpc}}^{2/3} n_0^{4/3}\ \mathrm{cm}^{-6}$ pc. Such miniature H II regions, a few pc across and several times larger than the nebulae themselves, could be detectable in the Hα emission.

The hypothetical H II regions surrounding S188 and A21 are likely to be asymmetric for two reasons. First, the optical depth of dense filaments in the leading section of the nebular shells might be substantial, while ionizing photons could escape more easily through the tenuous trailing hemispheres. The observed spatial stratification of various ionization species in both S188 (Lozinskaya *et al.* 1984) and A21 (Lozinskaya, Sitnik, and Toporova 1986) suggests substantial optical depths in the leading nebular sections. Therefore, the H II regions surrounding these nebulae are expected to be strongly asymmetric, with brightest regions located behind the moving central stars. Second, the crossing time r_s/v_* ($5 \times 10^4 n_0^{-2/3}$ yr if $v_* = 60$ km s^{-1}) might be comparable to the nebular lifetime, and less than the recombination time $t_{\mathrm{rec}} = 10^5 n_0^{-1}$ yr in the surrounding H II region. A distorted H II region could again arise, displaced with respect to the central star in the direction opposite to the stellar motion. The structure of such distorted H II regions (in steady state) was discussed by Raymond (1984), Suchkov (1985), and by Mauche, Raymond, and Córdova (1988). Both these effects combine to create asymmetric H II regions located behind the moving PNs.

Weinberger (1989*b*) recently reported a discovery of a faint extension to A21 on a red Palomar Observatory Sky Survey (POSS) plate, located approximately one nebular diameter behind the nebula and one and a half times as large as the nebula itself. We interpret this extension as an asymmetric H II region created by ionizing photons which have escaped from the nebula. The H II region faintness suggests that its emission measure EM is close to the POSS sensitivity limit of ~ 50 cm^{-6} pc. Since $EM = 12 d_{kpc}^{2/3} n_0^{4/3}$ cm^{-6} pc, we obtain $n_0 \sim 5$ cm^{-3} at the A21 distance of 0.35 pc (Table 2). This is in good agreement with an approximate value of 2 cm^{-3}, estimated from bright filament densities and assuming $v_* = 60$ km s^{-1}. Further studies of the H II region behind A21 would be useful in refining the density of the surrounding ISM and in unraveling the PN evolution.

An inspection of a red POSS plate containing S188 did not reveal any H II region associated with the nebula. Because emission measure EM depends strongly on n_0, the ISM surrounding S188 is probably less dense than in the case of A21. With $n_0 = 2$ cm^{-3} and $d_{kpc} = 0.2$ taken from Table 2, we estimate EM = 10 cm^{-6} pc, consistent with the absence of an H II region on the POSS plates. Nevertheless, even low-brightness H II regions with such low emission measures might be detectable, and the hypothetical H II region behind S188 should be searched for in an Hα emission-line survey of the Milky Way (McCullough, Reach, and Treffers 1990), whose limiting sensitivity is $\simeq 10$ cm^{-6} pc.

ii) *A31*

We would also like to draw attention to the large asymmetric nebula A31, one of the brighter nebulae in Table 2. Its morphology is quite peculiar, with filaments superposed on an asymmetric disk (Abell 1966). These filaments are aligned with a nebular axis connecting bright and faint regions, reminiscent of filaments observed in the interacting nebulae A35 and S188. The filaments in A31 may have also resulted from an interaction with the ISM.

iii) *He 2–111*

The only distant nebula in Table 2 is He 2–111, an extreme bipolar nebula with an enormous range in radial velocities from -380 to $+350$ km s^{-1} (Meaburn and Walsh 1989). This objects differs greatly from other nebulae in our sample. An asymmetry is not expected in view of the large nebular expansion velocity, which far exceeds the typical stellar velocities. It may be noted, however, that Meaburn and Walsh (1989) presented spectroscopic evidence for an interaction between He 2–111 and the ISM.

The large number of asymmetric nebulae in Table 2 may indicate that the PN–ISM interaction is a common phenomenon. Note that Table 2 does not contain the interacting nebulae NGC 246 and A33 from Table 1 because of their small angular size (below our limiting size of 8′). Therefore, the asymmetric nebulae in Table 2 do not constitute a complete list of candidates for the interacting nebulae. Other possible examples of PN–ISM interaction include PNs with displaced stars such as LT 1 (Bond and Livio 1990), A59 and K 2–2 (Kwitter, Jacoby, and Lydon 1988), and S181 (Rosado 1986). The largest of these PNs, the strongly asymmetric nebula K 2–2, is 7′ in diameter (slightly below of our threshold of 8′).

Further support for the ubiquitous PN–ISM interaction is provided by the expansion velocity measurements of low-surface brightness nebulae (Gieseking, Hippelein, and Weinberger 1986). Nebular expansion velocities are anticorrelated with PN radii, and they appear to be lower in the Galactic plane. Gieseking, Hippelein, and Weinberger (1986) interpreted these trends in terms of the PN–ISM interaction. This may be the case in view of our results.

IV. DISCUSSION

We find that nearby PNs, with central stars whose proper motions exceed 0.015 arcsec yr^{-1}, are interacting with the ISM. These include the Helix nebula (NGC 7293), NGC 246, A33, and the Dumbbell nebula (NGC 6853), in addition to the previously known nebulae A35, S216, and 623+71. This discovery doubles the number of known PNs interacting with the ISM. They must constitute only a small fraction of interacting PNs because proper motions have not been measured for the majority of nearby nebulae. We compiled a list of PNs with major axes exceeding 8′ in order to examine their morphology for signs of the PN–ISM interaction. Over half of these old, nearby nebulae show a strong dipole asymmetry, a characteristic signature of the interaction. Further support for the interaction is provided by displacements of central stars toward brightest nebular regions, observed in IW 2, S188, and A21 (YM 29). These results suggest that the interaction between large PNs and the ISM is quite common.

Simple order-of-magnitude estimates show that the interaction should occur if a low-density PN is moving through the WNM or the WIM. The PN shell is first compressed where the ram pressure of the ISM is the highest, in the direction of the stellar motion. This compression increases the surface brightness of the nebula on its forward side. In the later stages of the interaction, this part of the shell is significantly decelerated with respect to the central star, and the PN becomes strongly asymmetric in shape. Typically, the first signs of the interaction can be observed long before the shell deceleration occurs, at nebular densities an order of magnitude larger. A33 is an example of such interacting nebulae. PNs in this early stage of the interaction are easiest to detect because of their relatively high densities, typically in excess of 10 cm^{-3}. Therefore, the majority of observed interacting nebulae are expected to be in the early stages of the interaction, with at most a modest asymmetry in shape. As a nebula expands, it fades rapidly and only its brightest regions, which are compressed by the ISM ram pressure, will be detectable. A number of such nebulae, frequently crescent-shaped, are found in our sample of large PNs (Table 2). Finally, the nebular shell is significantly decelerated with respect to the central star at nebular densities a few times larger than the ISM density. It is hard to detect such low surface brightness nebulae. Under favorable circumstances, such as a high spatial velocity v_* of the central star and a low nebular expansion velocity v_{exp}, these strongly decelerated nebulae can be found. The presence of a bow-shock structure in A35 proves that the nebular shell has been decelerated with respect to the central star. Therefore, A35 is in its final evolutionary stage, with the nebular gas being stripped by the ram pressure of the ISM.

PN catalogs are clearly incomplete for large nebulae (Philips 1989), and Table 2 must also be incomplete. The basic problem is the difficulty in detecting these low surface brightness nebulae, particularly in the Galactic plane where the interstellar absorption is high. Some progress is being made, as evidenced by the recent discoveries of several large nebulae, including a number of PNs in Table 2. A promising way to detect old, low surface brightness PNs is to search for extended emission around hot, low-mass stars, which are believed to be the descendants of PN nuclei. Reynolds (1987) and Kwitter *et al.* (1989) carried out sensitive searches for PNs or H II regions around such hot subdwarfs. Only one new PN (or an H II region) was detected; it had a very low density of $n_e \sim 0.4$ cm^{-3}. The upper limits for the ISM density derived by Reynolds (1987) are ~ 0.4 cm^{-3}, approximately equal to the expected average WNM density in the Galactic plane. Typically, the stripping of nebular gas by the ISM ram pressure takes place when the PN density is equal to $n_{stop} \sim 10 n_0$. In the

Galactic plane $n_0 = 0.6$ cm^{-3}, and the stripping occurs at nebular densities of 6 cm^{-3}. If present, such interacting PNs would have been detected in the Reynolds's sample of hot, low-mass stars. Apparently, the stars in his sample are sufficiently old that either the PN gas was stripped in the course of the PN–ISM interaction, or the PN had an undetectably low surface brightness due to expansion in a low-density ($n_0 \leq 0.1$ cm^{-3}) environment. More sensitive studies are required to choose between these two alternatives. In spite of the initial failure, systematic searches for PNs around hot, low-mass stars promise to reveal faint PNs interacting with the ISM.

Another class of PNs where the PN–ISM interaction may be detected are young PNs with extended halos. These halos are generally believed to be the red giant winds from the PNs progenitors located on the asymptotic red giant branch. Hot, luminous stars in centers of PNs illuminate these winds, allowing us to observe them to large (0.5–1 pc) distances from the PN centers. These red giant winds should also interact with the ISM. Again, we can use equation (1), where $v_{\rm exp}$ now denotes the wind velocity v_w. A typical wind velocity v_w is ~ 10 km s^{-1}, although it varies from subsonic values of less than 5 km s^{-1} to mildly supersonic values of ~ 20 km s^{-1} (Chu and Jacoby 1989). The interaction is now expected at wind densities 50 times larger than the ISM density. The wind density can be estimated from the observed surface brightness: values as low as a few electrons per cm^{-3} have been reported (Bässgen and Grewing 1989). Therefore, the halo–ISM interaction might even be detectable at large distances above the Galactic plane. The old nebulae NGC 6853 and NGC 7293 are examples of such an interaction. As PN halos are the subject of intensive current study, we expect that they will be traced to even larger distances from PN nuclei.

The PN–ISM interaction is expected to be stronger near the Galactic center, because of large ISM density and the high PN velocity dispersion in this region (Isaacman 1983). Pottash (1984, p. 28) obtained a velocity dispersion of 140 km s^{-1} for the known PNs in the Galactic bulge. The electron densities for these nebulae can be estimated from their radio fluxes, using the formula $n_e = 1.7 \times 10^3 S_6{}^{1/2}\ \theta^{-3/2}$ cm^{-3}, where S_6 is the radio flux at 6 cm (in mJy) and θ is the angular radius in seconds of arc. We assumed the volume filling factor of 1, and used the new Galactic center distance of 8 kpc in deriving this formula. For the known PNs in the Galactic bulge with measured radio fluxes (Pottash and Acker 1989), electron densities are generally $\sim 10^3$ cm^{-3} or higher ($S_{6\,\rm cm} \geq 5$ mJy and $\theta \sim$ a few arcsec). In a few cases, they are as low as several hundred electrons per cm^{-3}. With a stellar velocity of $v_* \sim 250$ km s^{-1} and a PN expansion velocity of $v_{\rm exp} = 20$ km s^{-1}, we obtain $n_{\rm crit} \sim 700 n_0$ cm^{-3} (eq. [1]). Therefore, the PN–ISM interaction should be detectable at ISM densities exceeding ~ 1 cm^{-3}. While the known PNs in the Galactic bulge are not located in such dense ISM, a number of PN candidates were found in the Galactic center region (Pottash *et al.* 1988), based on their radio and infrared emission. These PNs may be interacting with the ISM, as first suggested by Isaacman (1983). Note that if the hydrogen number density n_0 exceeds several atoms per cm^{-3}, the interaction takes place early in the PN evolution. It may then be neccessary to include in the analysis a fast stellar wind ejected from the hot central star. Isaacman (1979) extended Smith's (1976) model to account for the fast wind presence, and his analysis may be useful in the context of the Galactic center PNs.

In order to provide a theoretical framework for observations of interacting PNs, we have also performed hydrodynamical simulations of the PN–ISM interaction (Soker, Borkowski, and Sarazin 1990). Our results validate the thin-shell approximation used by Smith (1976) to calculate the expected displacement of the central stars from PN centers, for a typical nebula in which the shocked ISM gas cools down to a characteristic nebular temperature of $\sim 10^4$ K.

The successful identification of interacting PNs depends on the knowledge of the proper motions of the exciting stars. Unfortunately, little has been done in recent times to measure proper motions of PNs. The only systematic program has been carried at the Lick Observatory (Cudworth 1974). Clearly, more work is needed in this area; in particular, proper motion determinations of the PNs in Table 2 would be helpful.

We want to stress the potential value of PNs as probes of the ISM density. The PN–ISM interaction cannot be observed in the hot ISM phase because of its low density. All detected interacting nebulae must be located either in the WNM or in the WIM. If a large number of interacting nebulae were known, the filling factors for these ISM phases could be determined. PNs are more promising in this respect than are supernova remnants because of their much higher spatial density. Also, PNs should fairly sample the volume of the ISM, as they are the final stages of evolution of low-mass stars. Supernova remnants of Types Ib and II apparently involve high-mass stars, which may be located in the same ISM environment in which they formed. An accurate determination of the ISM density is not possible at present because of the poorly known PN distances. For nearby nebulae, such as NGC 7293, the situation should improve in the near future as the *Hubble Space Telescope* becomes operational.

We would like to thank Larry Fredrick, Ted Gull, Jay Lockman, and Dick McCray for useful discussions. We thank John Graham and Phil Plait for their unpublished data which played a crucial role in unraveling the complex interaction of the Dumbbell nebula with the ISM. This work was supported in part by NASA Astrophysical Theory Program grant NAGW-764.

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