The Interaction of High-velocity Planetary Nebulae with the Interstellar Medium

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Summary. Planetary nebulae may be destroyed by a snowplough effect as they accrete material during their motion through interstellar space. Smith (1976) calculated this effect for slowly-moving nebulae and a low-density interstellar medium and concluded that the time scale for significant perturbation was much greater than the observable lifetime (∼2 × 10⁴ yr) of planetary. The perturbation that he considered was the apparent offset of the exciting star from the nebula, and not the flattening of the nebula itself. That approach ignores the problem of the stability of the shell.

We analyze the problem for the case of planetary nebulae near the galactic center where a) their random velocities with respect to the interstellar medium are high, and b) the medium may be denser than the value adopted by Smith. The driving force of mass loss from a planetary's central star is taken into account and is found to increase the final radius of a nebula before expansion is halted, but not the time scale for deceleration. For most reasonable initial parameters, nebulae at the galactic center will fade from radio detectability before these effects become observable. However, observable asymmetries in the mass distribution of solar neighbourhood planetary nebulae may occur if they are formed by the mechanism recently proposed by Kwock et al. (1978).

Key words: planetary nebulae – interstellar medium

I. Introduction

Smith (1976) has considered the braking of planetary nebulae by their motion through the interstellar medium (ISM) by modifying the momentum-conserving “snowplough” model of Oort (1951). Adopting an interstellar mass density of 10⁻²³ g cm⁻³ (≤0.1 atom cm⁻³) and a nebular velocity with respect to the ISM of 60 km s⁻¹, he found that the characteristic time scale required to flatten the leading half of the shell was in general very much greater than the observable lifetime of the nebula. He did not include the effects of mass loss from the central star.

Several other authors have done numerical studies of planetary nebula expansion, including Hunter and Sofia (1971), who also neglected a possible stellar wind and Mathews (1966), who found that such a wind was required to maintain the characteristic central hole in the nebula. Neither of these works, however, took motion through the ISM into account. That such motion can have observable effects is exemplified by NGC 6543, which shows a bright “pole” in forbidden line maps as well as a radio “tail” on the opposite side of the nebula (Philips et al., 1977); these criteria have been proposed by Gurzadyan (1969) as indicative of compression and shear by the ISM. [But see Millikan (1974), who observes a symmetric low-density halo which surrounds the supposed tail of NGC 6543.] Smith measured the position offsets of several local planetary’s central stars – presumably arising from differential deceleration of the nebula by the ISM – but found a null result.

In the neighborhood of the galactic center, the velocity dispersion of the planetary nebula population is higher than in the solar neighborhood, and the ISM density throughout the galactic plane is considerably higher than Smith’s value (cf. Baker and Burton, 1975). Braking effects in the galactic center might therefore be expected to be reasonably pronounced, and could influence the statistics of radio searches for nebulae in that region. Such searches are being made at present (Wouterloot and Dekker, 1979) and are important for the determination of planetary’s radio luminosity function and the galactic mass distribution in the inner few hundred parsecs. We will therefore consider the scale time for disruption of planetary nebulae with velocities characteristic of the galactic center population, taking mass loss from the central star into account.

II. The Model

If a “snowplough” model is to obtain, we must first establish that interstellar gas, which will shock-heat the nebula, will be accreted at all. Following the treatment of Savedoff et al. (1967), we find that an impacting gas speed of 120 km s⁻¹ yields a shock temperature of ∼2 × 10⁵ K and a density enhancement of a factor of ∼5 (see Table 2 of Savedoff et al.).

Savedoff et al. computed the cooling time for shocked gas at various temperatures from radiation losses in heavy ions. For gas at 2 × 10⁵ K, the density-dependent cooling time to 2 × 10⁴ K is ∼5 × 10⁵ yr cm⁻³. Additional cooling down to typical planetary nebula temperatures of 1.2 × 10⁴ K should take no more than an additional 2000 yr cm⁻³ (see their Table 4), for a total of ∼7 × 10⁵ yr cm⁻³. For an unshocked ISM density of 1 atom cm⁻³, the cooling time is therefore ∼1400 yr. In that time, the gas travels only ∼0.06 pc along the surface of the nebula before cooling and being accreted. The small fraction of the gas that impacts far from the planetary’s leading edge will escape by blowing around the sides. Since so much of the shocked gases’ initial kinetic energy goes into ionization and radiation losses, we can conclude that substantial accretion will take place, and that the snowplough model is relevant.

The nature of the momentum coupling between the central star and the nebula is also an important question. Although
The geometry of the problem, shown in Fig. 1. Velocities are measured in the reference frame of the central star. The initial shell expansion velocity is $V_e$.

Mathews (1966) suggested that a stellar wind created planets' characteristic central holes. Calculations by Ferch and Salpeter (1975) showed that dust, radiatively accelerated by the star and electromagnetically coupled to the gas, could be responsible. They showed, however, that the effect of the dust on the gas was most pronounced when the nebula was optically thick. This will occur at an early stage in the expansion, when dynamical effects of accretion from the ISM are unimportant. Two other factors in Ferch and Salpeter's results suggest that a gaseous stellar wind is more important for present purposes than radiation-driven dust.

1. When $r < 1$, only a fraction $\sim 10^{-4}$ of the energy radiated by the star is converted via the dust into kinetic energy of the nebular gas.

2. The outward motion of the dust grains relative to the gas is small, and observational evidence in NGC 7027 (Becklin et al., 1973) suggests that the dust is well mixed with the gas. The dust probably contributes, therefore, only a small fraction of the nebula's expansion momentum at late stages. Density clumping and filamentary structure probably have more important dynamical effects.

We will therefore employ a simple dynamical model in which a thin uniform nebular shell accretes mass from a stellar wind and from the ISM.

The geometry of the problem, in the reference frame of the central star, is shown in Fig. 1. For a differential section of the leading edge of the nebula (position angle $\theta = 0$), having surface area $dA$ and subtending a solid angle $d\Omega$ at the central star, the equation of motion is

$$
\frac{d^2r}{dt^2} = \left[ q + \left( \frac{dr}{dt} + V_{ISM} \right)^2 \right] - \left( \frac{M}{4\pi V_{ISM} r^2} \right)^{-1} \left( \frac{dr}{dt} - V_{ISM} \right)^2 \left( \frac{dm}{dA} \right) \left( \frac{dA}{d\Omega} \right),
$$

where $q$ is the mass density of the ISM, $V_{ISM}$ the speed of the nebula through the medium, $M$ the mass loss rate via the stellar wind from the central star, $V_w$ the stellar wind velocity, and $dm/dA$ the mass of the differential leading section. $dm/dA$ is time due to accretion from the ISM and the stellar wind, as follows:

$$
dm(t) = \eta \pi r^2 \sqrt{1 + e^2} \frac{1}{2e} \ln \left( \frac{1 + e}{1 - e} \right),
$$

where $\eta$ is a geometrical factor ($\geq 1$) accounting for the flattening of the shell. The trailing part of the nebula ($\frac{\pi}{2} \leq \theta \leq \frac{3\pi}{2}$) with radius $r_t$ will maintain a spherical shape, insulated from accretion from the ISM as long as $V_{ISM} > dr/dt$. For high velocity nebulae this will in general be true, so that the equations of motion for $r_t$ will be Eqs. (1) and (2) with $q = 0$ and Eq. (3) with $\eta = 1$. We assume that the leading part of the shell will be flattened into an approximate oblate spheroid with minor radius $r$ and major radius $r_t$, so that the factor $\eta$ represents the ratio of surface areas of the spheroid to a sphere with the same minor radius. Thus, $\eta = 1$ when $r = r_t$.

where $e^2 = 1 - r^2/r_t^2$.

By assigning values for $q$, $V_{ISM}$, $V_w$, and $M$ and initial values for $r$, $dr/dt$, and $m$, Eqs. (1)-(4) can be easily evaluated numerically. It is clear that, initially, $r = r_t$. Mathews (1966) has proposed that $M$ may decrease with time, on the basis of Harmon and Seaton's (1964) determination that the radius of the central star shrinks from $R_0$ to $0.03 R_0$ during the lifetime of the nebula, increasing in escape velocity and thus inhibiting mass loss. We will not take this into account, assuming $M$ to be constant over the planetary's life.

Oort (1977) has determined a velocity dispersion of 134 km s$^{-1}$ for 64 nebulae with known radial velocities and within 700 pc of the galactic center, while Baud et al. (1978) found a dispersion of $130 \pm 30$ km s$^{-1}$ for the radial velocity distribution of Type II OH masers, which probably belong to the same dynamical population as planets. We will adopt a value of 120 km s$^{-1}$ for $V_{ISM}$. An ISM gas density of 1 cm$^{-3}$ a value less than that of H I regions but greater than the intercloud medium – will also be used in all calculations. Assuming that the gas consists of 90% H I and 10% H II, by number, this represents a mass density of 2.18 $10^{-24}$ g cm$^{-3}$.

We must also define a scale time characterizing disruption of the nebula by the ISM. Smith (1976) used the criterion $r = 0$, that is, the time that the unbraked central star penetrates the decelerated leading edge of the nebula, and did not consider the change in curvature of the nebula itself. This implies a certain optimism about the durability of the shell, since both its flattening and expansion accelerate the mass accretion rate from the ISM, hastening the onset of a Rayleigh-Taylor instability. Gurzadyan (1969) has shown that the instability will set in when the nebula has accumulated an amount of material on the order of its initial mass. This time scale for mass accretion is also comparable to the time scale for deceleration in Oort's (1951) snowplough model.

There is, moreover, shear on the nebula as a consequence of the largely-undamped motion in the direction perpendicular to $V_{ISM}$ and of the unequal accretion of mass from the ISM as a function of position angle $\theta$. Equations (1)-(3) can be written in vectorial form and broken down into $x$- and $y$-components (parallel and perpendicular to $V_{ISM}$, respectively) and then solved for any value of $\theta$. Figure 2 illustrates the solutions for the $x$- and $y$-components of the shell velocity (with respect to the star) as a function of $\theta$ at two stages in the planetary's lifetime for a typical set of parameters. At $T = 5000$ yr, the nebula is still approximately spherical and the velocity components vary sinusoidally with $\theta$ as
Fig. 2. x- and y-components of the leading shell velocity as a function of position angle $\theta$ at (dotted line) 5000 and (solid line) 15,000 yr after the shell ejection. The ISM and initial shell parameters are indicated.

Fig. 3. The “stopping time”, $T_s$, necessary to bring the leading edge ($\theta=0$) to a halt with respect to the central star, as a function of the stellar mass loss rate and wind velocity, for three initial shell masses: (1) $m_0=0.01 M_\odot$, (2) $m_0=0.15 M_\odot$, (3) $m_0=0.6 M_\odot$. The assumed nebular velocity through the ISM is 120 km s$^{-1}$, and the ISM density 1 atom cm$^{-3}$. The initial shell expansion velocity $V_*$ is taken to be 10 km s$^{-1}$. Stellar wind velocities $V_\infty$ are (solid line) 75 km s$^{-1}$, (dotted line) 150 km s$^{-1}$, and (dashed line) 300 km s$^{-1}$.

Expected. At $T=15,000$ yr, however, the $y$-motion has been accelerated due to the stellar wind, while the $x$-motion has been largely damped out by the ISM. The latter no longer varies as $\cos \theta$ due to the variation of surface density with $\theta$; furthermore, the material at $\theta \approx 60^\circ$ has begun to move backwards (as seen by the central star) even though the leading edge is still moving forward at 3.6 km s$^{-1}$. The nebula is thus starting to tear apart, demonstrating that the time scale for its destruction by shearing is the same as that for its deceleration. We will therefore characterize the interaction between the shell and the ISM by the time $T_s$ necessary to bring the leading edge to a stop with respect to the central star. (Note that in Oort’s snowplough model this never occurs, since there is no motion against the ISM. $T_s$ is therefore not necessarily the scale time for a Rayleigh-Taylor instability.)

III. Results

We have calculated the stopping time $T_s$ for a large number of models, taking as free parameters the stellar mass loss rate $\dot{M}$, stellar wind velocity $V_\infty$, initial shell mass (including any neutral component) $m_0$, and initial shell expansion velocity $V_*$.

As stated earlier, we will consider planeto-terrestrial moving at 120 km s$^{-1}$ through an ISM with a mean density of 1 atom cm$^{-3}$. Virtually all observed planetary nebulae have expansion velocities within a factor of two of 25 km s$^{-1}$, so we will investigate those having initial expansion $V_*$ of 10, 25 and 50 km s$^{-1}$ (Figs. 3–5 respectively).

The masses of planetary nebulae are very poorly known, due partly to the lack of a reliable luminosity function or distance indicator. The so-called “constant mass” method developed by Shklovsky (1956) provides a distance determination based on a nebula’s $H\beta$ intensity on the assumption that all planetary nebulae have about the same ionized mass. Observations of nebulae at a known distance, in the Magellanic Clouds, have suggested an ionized component of $\sim 0.2 M_\odot$. Cahn and Kaler (1971) compiled a
Fig. 6. The radius in the forward direction at the time that point is brought to a halt ($R_f = r(\theta = 0, T = T_f)$), as a function of stellar mass loss rate and wind velocity, for $V_e = 25$ km s$^{-1}$. The ISM parameters are the same as in Figs. 3–5. The initial nebula mass for each set of curves is (1) $m_0 = 0.01 M_\odot$, (2) $0.15 M_\odot$, (3) $0.6 M_\odot$. Stellar wind velocities are (solid line) 75 km s$^{-1}$, (dotted line) 150 km s$^{-1}$, and (dashed line) 300 km s$^{-1}$.

The radius scale on this basis, which Weidemann (1977) has argued is 30% too low. From the (distance)$^{3/2}$ mass dependence of the Shklovsky method, this would increase the mean ionized mass of planetary nebulae to $0.4 M_\odot$.

Wood and Cahn (1977), however, have proposed on theoretical grounds that Mira variables engender planetary nebulae with a bimodel mass distribution peaking at 0.01 and 0.8 $M_\odot$. Zuckerman et al. (1977) have also argued that galactic-center planetary nebulae tend to be smaller and much less massive than those in the solar neighborhood, and Peimbert (1973) has suggested that K648, a planetary nebula in M 15, is only 0.018 $M_\odot$. In order to encompass a reasonable range of initial masses, Figs. 3–5 each show $T_f$ for $m_0 = 0.01, 0.15$, and $0.6 M_\odot$.

Characteristics of the mass loss from the central stars of planetary nebulae are also somewhat uncertain. Typical loss rates for M giants – possible precursors of planetary – range up to $10^{-5} M_\odot$ yr$^{-1}$ at $\sim 1000$ km s$^{-1}$, though Philips and Reay (1977) propose a short-term rate of $10^{-4} M_\odot$ yr$^{-1}$ to form the nebula itself. V 1016 Cygni is apparently a late M-type star that underwent a sudden transition into the planetary nebula stage in 1965 and is now losing mass at $10^{-6} \cdots 10^{-5} M_\odot$ yr$^{-1}$ at 105 km s$^{-1}$ (Fitzgerald and Pilavaki, 1974; Kwok, 1977; Ahern et al., 1977). We will consider $M$ up to $10^{-3} M_\odot$ yr$^{-1}$ at velocities $V_w$ of 75, 150, and 300 km s$^{-1}$.

The results of the calculations are summarized in Figs. 3–5, which display the stopping time $T_s$ for the leading point of the shell as a function of the stellar mass loss rate, for three values each of the stellar wind velocity and initial shell mass and expansion rate. Moving from Fig. 3 to 5, corresponding to increasing the initial expansion velocity $V_e$, one notices that the effect of changing $V_e$ decreases. This reflects the decreased fraction of the shell’s momentum contributed by the stellar wind if the shell is given a high initial expansion velocity.

It is also clear from the figures that mass loss from the central star only affects the stopping time significantly when $M \gtrsim 10^{-6} M_\odot$ yr$^{-1}$. For the two more massive nebulae indicated, the effect never exceeds a 25% change in $T_s$ even when $M = 10^{-3} M_\odot$ yr$^{-1}$ and $V_w = 300$ km s$^{-1}$. It is also of note that, above $\dot{M} \sim 2 \times 10^{-6} M_\odot$ yr$^{-1}$, increasing the stellar wind velocity causes $T_s$ to decrease, contrary to what might be expected. A similar effect holds for the initial expansion velocity, $V_e$; in both cases, the phenomenon arises because the nebula more quickly reaches a large radius at which the decelerating force of the ISM (which is proportional to the shell surface area) becomes important. This can be seen in Fig. 6, which shows the dependence on $M$ of $R_s$ for the distance from the central star to the leading edge at the stopping time $T_s$. $R_s$ varies much more regularly than $T_s$ with $M$, and in the “correct” manner; that is, the maximum radius in the leading direction increases with both the mass loss rate and stellar wind velocity, so that the average shell velocity (with respect to the star) over the lifetime of the nebula increases as expected. Only the case $V_e = 25$ km s$^{-1}$ is shown.

As the mass loss rate goes to zero, we approach the case considered by Smith (1976), who found that the time required for the central star to catch up to the decelerated leading edge is

$$T_s = K \left( \frac{m_0}{n V_e V_{\text{ISM}}^2} \right)^{1/3},$$

where $m_0$ is in $M_\odot$, $V_e$ in km s$^{-1}$, and $n$ is the number density of atoms in the ISM in cm$^{-3}$, assuming a 10% He fraction by number. In general, the stopping time $T_s$ will be roughly proportional to $T_s = 0$, so that in the limiting case of a high-velocity nebula in which $V_{\text{ISM}} \gg V_e$ we expect

$$T_s = \frac{3.03 \times 10^7 m_0^{1/3}}{n V_e V_{\text{ISM}}^{2/3}}.$$
R. Isaacman: Planetary Nebula Disruption by ISM

observable objects is thus $T_{\rm f} \geq 3 T_{\rm ion}$, which, combining (6) and (8), yields

$$m_\odot \lesssim \frac{3.4 \times 10^{12}}{n^3} \left( \frac{V_e}{V_{\rm ion}} \right)^{10} M_\odot.$$  (9)

Except when $n \gg 1$ cm$^{-3}$ (for $V_{\rm ion} \ll V_e$), such as during passage through a dense cloud, all galactic center planetary nebulae with less than $1 M_\odot$ of ionized material will therefore fade from radio visibility before being flattened and broken up by the ISM.

We now consider the consequences of the deceleration on the formation of the nebula. A recent model by Kwok et al. (1978) invokes a sudden change in the stellar wind velocity and mass loss rate as a red giant exposes its degenerate core to account for the origin of planetary nebula shells. The original, slow ($V_{\rm w} \sim 10$ km s$^{-1}$) wind from the giant fills the (assumed empty) space around the star at a rate $\sim 10^{-3} M_\odot$ yr$^{-1}$ for $10^3$ yr before a rapid ($\sim 10^6$ km s$^{-1}$) tenuous ($\sim 10^{-6}$ M$_\odot$ yr$^{-1}$) mass outflow from the exposed core takes over to form an expanding shock front. The latter accumulates mass to become the planetary nebula. An advantage over dynamical instability models is that not all of the mass shed need form part of the ionized, visible nebula, since the shock front expands at only $20-40$ km s$^{-1}$ and so will not catch up with the leading edge of the first wind within the observable lifetime of the planetary. This, however, is strictly true only if the original red giant wind can expand without opposition. If the star is moving through the ISM, then two shock fronts will be formed in the leading direction, the inner being the planetary nebula of the model and the outer arising from the collision between the original wind and the ISM. The latter can be treated as a thin, low-mass nebula which, as Fig. 3 illustrates, will be brought to a halt with respect to the star at a radius $\lesssim 0.1$ pc, since it is supported from behind only by the original low-velocity stellar wind. This will moreover occur in a time $\lesssim 10^4$ yr, fairly early in the first mass-loss stage of the giant, so that material may pile up at that radius.

The inner shock front, i.e. the leading edge of the visible planetary nebula, will reach the first (in the leading direction) after $\sim 3000$ yr at an expansion velocity of $30$ km s$^{-1}$, during which time it will accrete all of the mass shed by the progenitor in that direction, $\sim 0.5 M_\odot$. In the trailing direction, the first stellar wind expands into a vacuum (the ISM having been swept up by the shock on the leading edge), so that the nebula on that side develops as in the original model. Depending on the choice of mass-loss parameters, that part of the nebula will accrete only 0.02-0.04 M$_\odot$ by the time $r = 0.1$ pc. We therefore expect a very asymmetric nebula, though the asymmetry is probably unobservable at the distance of the galactic center.

In the solar neighbourhood, the lower peculiar velocities of planetaries ($V_{\rm ion} \approx 60$ km s$^{-1}$) and the lower mean ISM density ($n \approx 0.2$ cm$^{-3}$) combine to raise the stopping time $T_{\rm f}$ for the low-mass shock front from the first stellar wind to $\sim 210^4$ yr. This is near the upper limit of the visible lifetimes of almost all planetary nebulae, so for local objects the pronounced shell asymmetry just described would not arise much before the nebula faded from view.

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