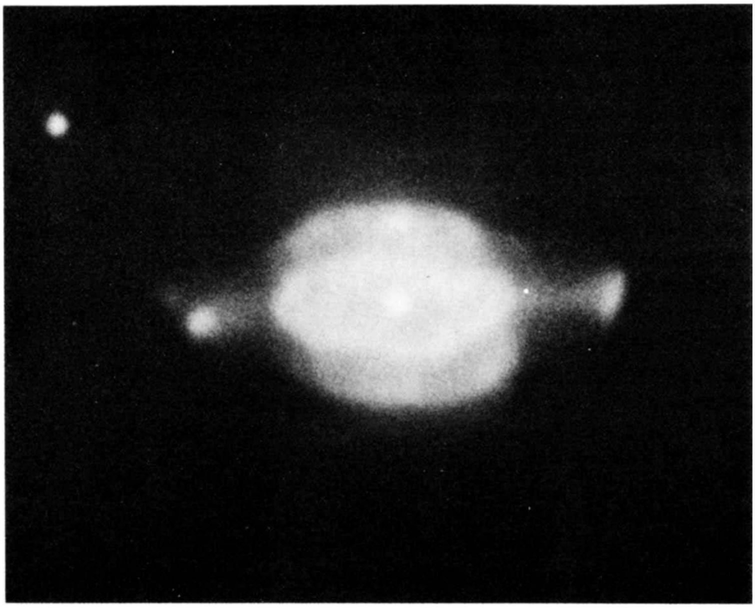

NGC 7009

SESSION VI

EVOLUTION AND MORPHOLOGY OF PLANETARY NEBULAE

EVOLUTION AND GAS DYNAMICS OF PLANETARY NEBULAE

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1. INTRODUCTION

Since the last IAU Symposium on Planetary Nebulae at Tatranska-Lomnica, a number of significant theoretical and observational advances have been made in the study of nebular dynamics. The following review emphasizes the evolution of nebulae after they have been ejected from the central star and have become optically thin to most radiation.

2. EVOLUTION OF PLANETARY NEBULAE CONSIDERED AS SINGLE GASEOUS SHELLS

When a planetary nebula shell has separated from the stellar core, its dynamic motion is described by the usual equations of gas dynamics. Continuity of matter and the equation of motion require that

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(\rho u r^2) = 0 \qquad (2\text{-}1)$$

and

$$\rho\frac{du}{dt} \equiv \rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r}\right) = -\frac{\partial P}{\partial r} - \frac{\partial P_\alpha}{\partial r} + \frac{\sigma\rho}{\mu M c}\frac{L}{4\pi r^2} \qquad (2\text{-}2)$$

Here $P = \rho kT/\mu M$ is the gas pressure, M is the proton mass, and $\mu = (1+x)^{-1}$ is the mean molecular weight corresponding to a fraction x of ionization. In the study of nebular dynamics, it is often sufficiently accurate to assume isothermality in the H II and H I regions, making a separate energy equation unnecessary.

The second term on the right in equation (2-2) represents the force produced by the gradient of the radiation pressure produced by Lyman-α photons. This term has had a long history in the subject of planetary nebulae. In the (unlikely) situation of a perfectly uniform dust-free shell moving at constant velocity, P_α and P can be, at best, of the same order (George 1973). However, the dynamical effect of radiation pressure exerted by trapped Lyman-α photons is greatly

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reduced by absorption and destruction on dust grains within the ionized nebula (Ferch and Salpeter 1975). The last term in equation (2-2) expresses the radiative force on dust grains of average cross section $\sigma = A_g \langle \pi r^2 \rangle Q_{rp}$ by the suitably attenuated stellar luminosity L within the nebula. Here A_g is the abundance of grains (of average radius r_g) by number relative to hydrogen, and $Q_{rp} \approx 0(1)$. The electric charge on the dust grains very effectively couples their motion to the surrounding gas, i.e., the terminal velocity of relative motion between dust and gas produces negligible separation on the time scale of nebular evolution.

When the evolution of a planetary nebula is calculated by solving the gas dynamical equations, the result should be consistent with a number of observational features and correlations:

(1) Most, but not all, planetary nebulae have a central hole and appear to be prolate spheroids (Weedman 1968).
(2) The mean surface brightness in a recombination line (Hβ) should vary with the mean gas density roughly as $\langle n \rangle^{5/3}$ according to the Shklovsky theory for fully ionized nebulae (O'Dell 1962).
(3) The variation of (projected) outer radius with expansion velocity should be consistent with the observational data of Bohuski and Smith (1974).
(4) The flow velocity in the shell should increase (∿linearly) with radius (Wilson 1950), and the expansion velocity is proportional to the radius for prolate spheroidal nebulae (Weedman 1968).

The study by Bohuski and Smith is a particularly valuable observational approach toward understanding the basic evolution of planetaries. They find that the mean expansion velocity increases with apparent nebular radius for many planetaries, but large planetaries having small expansion velocities also exist. A number of difficulties arise, however, in comparing these results with theoretical models: (1) There is an observational bias against finding rapidly expanding planetaries of large radius, (2) the "radius" of planetaries must be systematically defined for all nebulae observed, if this is possible, and (3) the evolutionary track in the (radius, expansion velocity) - plane may depend on the mass of the nebula and other parameters. In any case, the observational approach begun by Bohuski and Smith should be developed further, perhaps also including surface brightness as a parameter.

In the early work of Mathews (1966) on evolving nebular shells, the central hole was produced by a continued stellar wind from the central star which followed the main shell ejection. Recently, Ferch and Salpeter (1975) have computed detailed models of evolving planetaries with no stellar wind but including radiation pressure on dust. Central holes can be produced by the action of starlight on the dust much as in H II regions (Mathews 1967, 1969). The thickness ΔR of the transition region of outwardly-increasing density at the edge of the central hole formed by radiation pressure on dust is governed by the scale height (from eqn. 2-2):

$$h = \frac{L}{8\pi kT\mu c} = 0.015 \; \frac{\sigma}{6\text{x}10^{-22}} \; \frac{L}{10^4 L_o} \; \frac{10^4}{T} \; \text{pc} \qquad (2\text{-}3)$$

provided the acceleration du/dt is small. This is comparable with the thickness of this transition region calculated by Ferch and Salpeter. If the acceleration of the inner shell region is positive, ΔR will be larger than h as given by equation (2-3).

Ferch and Salpeter calculated evolutionary models for planetary nebulae having a wide variety of initial conditions, allowing comparisons to be made with nebulae of different initial sizes, initial densities (masses of 0.15 and 0.5 $M_\odot$), dust content, initial expansion velocity and subject to central stars of different (but constant) ionizing photon luminosities. For each model the initial gas density and expansion velocity were assumed to be uniform over the shell. Ferch and Salpeter's models fit the observations quite well. Besides preserving the central hole, the expansion velocity was found to increase with time (as required by Gohuski and Smith). Lyman-α pressure and gas-grain separation were small or negligible. As the evolution proceeds, the inward moving rarefaction wave generates a region of (exponentially) decreasing density ρ(r) at the outer edge of the nebula which eventually contains most (∿80%) of the nebular mass. The mass observed within some outer isophote (enclosing a constant fraction of the emitted light in Hβ) decreases significantly as the nebula evolves - this may require a recalibration of the Shklovsky distance criterion which assumes a constancy of observable mass during evolution. The outer radius of a planetary does not refer to the same gas as the nebula evolves, but moves masswise inward due to the action of an inward-moving rarefaction wave (Mathews 1968). For this reason the apparent rate of increase of angular size of the nebulae cannot be directly compared with the expansion velocity to derive distances.

Ferch and Salpeter find that the outward acceleration of nebular shells is strongly correlated with the total mass of the shell, i.e. for two initial shells differing only in their density, the shell of lower density is accelerated outward more strongly. This is at first sight a surprising result since all the important terms in equation (2-2) depend linearly on the gas density. Ferch and Salpeter attribute this effect to increases in the spatial gradients d(ln ρ)/dr as the density increases. However, it appears more likely that enhanced acceleration of low density nebulae occurs because nebulae of low density become fully ionized at an earlier time in their evolution. The rarefaction wave which accelerates the gas outward therefore begins to act sooner on shells of low density (or mass). If planetary nebulae have a range of initial masses, this effect will produce a natural spread in the velocity-radius diagram of Bohuski and Smith, as observed. Ferch and Salpeter argue that planetary nebulae of Pop II giants should on the average eject shells of lower mass than Pop I giants.

Until a good theory exists for the formation of planetary nebulae, it is not clear how much the observed velocity distribution depends on initial conditions, which may not be the same for all nebulae. In particular, the assumption of initially uniform shells may be inappropriate if the stellar envelope is ejected coherently. As an example of the possible influence of initial conditions, consider two extreme cases taken from the paper by Weedman (1968): (1) NGC 2392 with a bright inner ring having the largest known expansion velocity ($\sim$50 to $\sim$100 km/sec), and (2) IC 3568, a perfectly symmetric planetary having a gaussian brightness profile with no evidence of a central hole or shell structure (the expansion velocity is 17 km/sec). It is remarkable, therefore, that the infrared observations of Cohen and Barlow (1974) indicate that dust is unlikely to exist in NGC 2392, but that IC 3568 contains a substantial amount of dust. Although the presence of dust will cause a central hole to develop, the nature of the ejection process may also play a transient role.

If central holes can be easily produced by radiation pressure on dust, is gas near central stars also pushed away by stellar winds? A number of observations of central stars suggest the existence of high velocity winds. Spectra of many stellar nuclei show emission lines with half widths comparable to the escape velocity at the stellar surface. Some of these central stars appear to be sources of infrared emission (Cohen and Barlow 1974, MacGregor et al. 1976). If this radiation comes from dust near the central star, as these authors suggest, high velocity radiative driven winds would be expected. To the contrary, Johnson (1976) does not find unusual internal motions in planetaries having nuclei with O VI $\lambda\lambda$3811-3838 emission. Stellar winds from planetary nuclei produce surface forces on the planetary shells, while radiation pressure on optically thin shells provides a constant volume force per unit mass. For this reason, winds may be more effective than radiation pressure in extending the polar regions of prolate and bipolar nebulae if the column density is less there.

Evidence of the interaction of dynamic pressure ρu^2 of a stellar wind with the inner surface of a planetary shell is provided by instabilities and comet-like structures observed in NGC 7293 (Verontzov-Velyaminov 1968). The inner surface of this nebula shows irregularities that might be due to Rayleigh-Taylor instabilities there (Mathews 1968, Pikelner 1973) as the wind accelerates the ionized shell. The cometary structures appear to be dense (neutral) clouds which are being ablated by the erosive action of stellar ionizing flux and stellar winds, producing faint irregular tails pointing away from the central star. (The mean radial velocity of the small condensations in NGC 7293 is less than 10 km/sec (Grandi 1973).) However, it is also possible that radiation pressure on dust accounts for these tails. For this to occur, the H I clouds would have to be optically thick in dust absorption and therefore receive less outward acceleration per unit mass than the gas in the tail. Comet heads of size $R \lesssim 1''$ (Minkowski 1968) in NGC 7293 correspond to $R \lesssim 3\text{x}10^{15}$ cm at a distance of 212 pc for NGC 7293 (Cudworth 1974). The column density required for $\tau_{dust} \gtrsim 1$ is $\mathcal{N} \gtrsim 2\text{x}10 \ \text{cm}^{-2}$ using Ferch and Salpeter's standard dust abundance. Therefore, the density in the H I comet heads would have to be $3\text{x}10^4 \text{cm}^{-3}$. Such high densities in the neutral gas would be in rough pressure equilibrium with the surrounding H II gas ($n_e \lesssim 300 \ \text{cm}^{-3}$ according to Warner and Rubin 1974) only if $T_I \lesssim 90°K$. Warner and Rubin (1975) find indirect evidence for unresolved regions having electron densities $\sim 10^5 - 10^6 \ \text{cm}^{-3}$ within the central hole of NGC 7293.

Van Blerkom and Arny (1972) and Capriotti (1973) have proposed that the comet tails are shadow zones abundant in N^+ and protected from further ionization. The shadow zones will be cooler and therefore more dense when in pressure equilibrium with the surrounding regions. Such an idea is not incompatible with the notion that the tail material being shadowed is flowing away from the dense head region, as appears to be the case from the photographs. If the tails were only shadows, they would be straighter and sharper-edged than observed. In addition Mathis (1976) has shown that shadow zones in dusty H II regions are not a likely means for enhancing low-ionization radiation. Finally, there do appear to be a number of planetary nebula having transition thicknesses ΔR smaller than that predicted by dust alone (eqn. 2-3). If this is born out by detailed observations, a surface force provided by stellar winds may be required.

3. MULTIPLE SHELLS, BOWTIES AND BUTTERFLIES

In his study of ten bright planetaries having simple morphological forms, Weedman (1968) included several nebulae with apparent double ring structure. Often the two shells have separate dynamical systems strongly indicating that double ejection has occurred (NGC 7662, NGC 2392), etc.). Kaler (1974) and Millikan (1974) have made lists of planetaries with double and triple shells. Some of these faint outer shells may contain a significant fraction of the total mass. Kaler suggested that the outer shells may become visible only after the inner shell has become optically thin to ionizing radiation. Often quite inhomogeneous in brightness, these outer shells may have been subject to density enhancements following instabilities.

A variety of theoretical phenomena involving double shell ejections has been discussed by Wentzel (1976). One possible evolutionary sequence considered by Wentzel is the initial ejection of a cold neutral shell (maintaining a sharp inner boundary) followed $\sim 10^3$ years later by the ejection of a second neutral shell which then becomes ionized. After the inner shell becomes optically thin in the Lyman continuum, the outer shell is ionized by an accelerating, and therefore unstable, D-type ionization front producing inhomogeneities or globules in the outer shell (Capriotti 1973, however see below). Alternatively, if the first shell was ionized as a single shell planetary, it would tend to reveal a broader, less inhomogeneous outer shell when it is reionized for the second time. All of Wentzel's shells are initially uniform; neither radiation pressure on dust nor stellar winds were included in Wentzel's study.

Multiple shell nebulae can be produced in a single event if the dust to gas ratio increases with radius in the nebular shell. In particular, suppose that the central star becomes hot and ionizes the inner parts of an ejected shell before grain formation is complete. Eventually, when radiation pressure acts on the whole shell, the dust-rich outer parts will be preferentially accelerated and will produce a separate shell. This requires that the expansion velocities should be greater in the outer shells.

It has occasionally been proposed that the outer shells in multiple shell planetaries are due to a sustained stellar wind which preceded a more massive shell ejection. However, the gas density in isothermal or nearly isothermal winds decreases too fast with radius ($\sim r^{-2}$) to account for the faint outer shells observed. For example, an isothermal flow at T = 100°K will decrease monotonically by a factor $(\rho/\rho_0) \approx 10^{-7}$ at $r \approx 10^{17}$cm, where ρ_0 is the density just above the photosphere ($r_0 = 7 \times 10^{13}$ cm). The presence of radiation pressure on dust would cause ρ/ρ_0 to decrease even faster with radius than for the dust-free case. Such isothermal flows generally give very low densities far from the star and do not resemble the denser gas distribution in the outer shells of planetary nebulae, unless the density was enhanced by non-steady central hole production.

A most significant feature of the observations of planetary nebulae, not yet fully studied theoretically, is the common tendency for nebular shells to resemble prolate spheroids (Weedman 1968). The column density through the shell along the major axis, where the expansion velocity is greatest, appears to be less than along perpendicular axes (Weedman 1968). Prolate spheroids would develop either through the differential time scale for ionization of the shell in various directions (Ferch and Salpeter 1975), through acceleration by an isotopic stellar wind, or (perhaps less likely) by means of assuming higher initial velocities of ejection along the major axis. The enhancement of nebular gas in an equatorial region implies that stellar rotation may play a role in the ejection process. Although red giants are notoriously slow rotators, if matter is lost slowly, say by means of shocks through the stellar envelope, the slightly lower g_{eff} on the equator could have a controlling influence.

A number of planetaries (NGC 6537, NGC 2346, NGC 6302, NGC 650-1, NGC 2371-2, CD-29°, 13998, etc.) resemble bowties or butterflies. Evidently these objects are more extreme cases of the typical prolate spheroidal nebulae studied by Weedman (1968), but here the ends of the prolate spheroid have been pushed out at high velocity like bursting balloons. Occasionally these nebulae with bilateral symmetry (such as NGC 650-1) are observed along the major axis. A good prospect for this is the Ring Nebula (NGC 6720), as pointed out by Minkowski and Osterbrock (1950). The brighter parts of the Ring Nebula are known to be a torus not a spherical shell. Surrounding this is a thin faint "outer shell" which has an unusually high level of ionization (Hawley and Miller 1977) and therefore is not shielded from the central star by the bright toroidal ring. Such a situation is exactly what would be expected if a bipolar object such as NGC 650-1 or NGC 6302 (Minkowski and Johnson 1967) were viewed approximately along the axis of the torus. As a further verification, it would be interesting to measure the radial velocity of the faint outer ring of NGC 6720. Finally, the question of multiple shell ejection (Kaler 1974) is further complicated by the subset of bipolar nebulae viewed pole-on which probably can be produced by a single ejection.

4. DENSITY CONDENSATIONS IN PLANETARY NEBULAE

Evidence of small high density regions in planetaries comes both from broad-band photographs, as in the famous case of NGC 7392 (Vorontsov-Velyaminov 1968), and more strikingly, from exposures in the light of [O I] $\lambda 6300$ radiation (Capriotti et al. 1971). Comparison of [O II] line ratios with surface brightness also suggest strong density fluctuations in many nebulae (Seaton and Osterbrock 1957). Theoretical attempts to understand these condensations in terms of thermal instabilities in the ionized gas have failed.

In an important paper, Capriotti (1973) has accounted for the existence of small neutral clouds within the ionized parts of the nebula in terms of a Rayleigh-Taylor instability which occurs at D-type ionization fronts (i.e. $n_I > n_{II}$) in an accelerated nebula (see also Mathews and Blumenthal 1977). In the linear theory the time scale for instability varies with the perturbation wavelength as $\lambda^{1/2}$. When the amplitudes of surface corrugations grow into the nonlinear range, the amplitude of a particular wavelength λ_c grows to equal the scale height in the neutral gas in the shortest time. This results in the production of $\sim 10^5$ neutral globules having sizes $R \sim \lambda_c \sim 10^{15}$cm and masses $\mathfrak{M} \approx 10^{27}$gm (Capriotti 1973). According to Capriotti's model, these globules persist in the ionized gas (producing small sources of [O I] radiation) and may eventually be ejected into the interstellar medium.

This last conclusion, concerning the longevity of the H I globules produced by the unstable ionization front, may not hold in every case. For example, consider a small H I globule left behind in the ionized gas by the accelerating unstable D-type ionization front. Since the globule is closer to the central star than the main part of the (corrugated) ionization front, the greater incident ionizing flux should ionize faster through the globule than at the main front on the average. In addition, the spherical shape of the globule should permit the ionized gas to flow away from its starward side more easily than the approximately plane parallel flow at the main front. Finally, the density in the neutral globule may tend to decrease. Effects produced by the Rayleigh-Taylor instability alone will not lead to significantly different densities in the globules as compared to the original H I shell. However, if the neutral gas is heated by the central star, or by ambient

Lyman-α radiation (George 1974), the globule may be hotter, and therefore less dense, than H I gas further from the star. All of these qualitative effects act in the direction of allowing the ionization front to process as fast (or faster) through the globules than it would through the H I shell if the Rayleigh-Taylor instability were suppressed. On the other hand, the recoil produced by gas flowing toward the central star, will tend to compress the globules and accelerate them outwards (Capriotti 1973, Grandi 1973). If this compression is important, it will tend to increase the lifetime of the globules. This problem should be studied in more detail.

Condensations of neutral gas observed in [O I] radiation from planetaries may be relics of inhomogeneities which existed in the H I shell before it became ionized. Thermal instabilities would be expected to occur in the initial stages of shell ejection. Hunter (1973) and Hunter and Nightingale (1974) have found that O I and dust radiation will produce significant isobaric thermal instabilities as the expanding shells cool. Condensations can form very rapidly by this process as soon as the neutral shell becomes transparent to the dominant cooling radiation, but the optical depth of the shell depends on the detailed nature of the ejection process, the epoch and rate of dust formation, and the shell geometry. After the neutral condensations have cooled to some low equilibrium temperature (∿5-10°K), the lower density neutral medium which surrounds them may be heated by starlight to keep the condensations from reexpanding. The diverging nature of the overall flow will also tend to preserve the condensations. Finally, Hunter and Nightingale (1974) have suggested that the neutral condensations may be bound by self-gravity.

Whatever origin of condensations is most likely - Rayleigh-Taylor instabilities, thermal instabilities or both - the collective effects of many neutral clouds on the overall dynamics of the nebula could be considerable. Each neutral cloud will be a source of outflowing gas which may influence the bulk motion of the inter-condensation medium. In addition, the outward velocity of the globules may be increased by a rocket effect as ionized gas is ejected on the starward side. Such complications, which have been studied by Capriotti (1973), may be observable as small scale differences in radial velocities near centers of [O I] emission.

5. CONCLUDING REMARKS

A number of observational and theoretical problems remain for further study:

Observational:

(1) Are central holes correlated with evidence for dust in the nebulae?

(2) Are central holes (or expansion velocities) correlated with

evidence for dust near the central stars, or emission line nuclei?

(3) More radial velocities of outer shells should be measured. Are double or triple ejection models always required?

(4) What is the density of ionized gas near small condensations?

Theoretical:

(1) What is the temperature of neutral gas in planetaries? Can high density neutral condensations coexist in pressure equilibrium with neutral gas of lower density?

(2) Do stars which produce planetary nebulae tend to eject more gas in the equatorial regions? If so, why?

(3) If (2), will this initial situation evolve into prolate spheroids or bipolar nebulae similar to those observed?

(4) Can dust be formed near the central stars and, if so, what is the nature of the resulting winds and their effect on the nebula?

(5) How is the nebular evolution affected if ejected shells have large initial density gradients?

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DISCUSSION

Cohen: What can you tell us about the bipolar nebulae?

Mathews: They appear to be prolate spheroids that have blown their bubbles out at each end. One way to do that is with a wind.

Peimbert, S.T.: Have you made an estimate of the fraction of the mass of the shell due to stellar wind as a function of time?

Mathews: It seems apparent that the outer shells could have a significant mass.

Pequignot: Do you think that a strong stellar wind could significantly enhance the gas density in the high excitation parts of the nebula?

Mathews: Yes, I think so. If there is a wind, you would have an interaction region where you might expect to find highly excited ions. The density would go up by a factor of four in a strong shock, but then there would be a cooling region behind that.

Webster: He 2-111 is one of the class of He and N rich planetaries with strong filamentary structure. It has a faint outer shell shaped roughly like a figure eight and also with sharp filaments. I have measured the radial velocities in the central object and in the faint envelope on either side of the center and near the edge. The difference in projected velocity is nearly 500 kms^{-1}. This suggests that the outer region may have been ejected at the same time as the inner nebula. Could you comment on these high velocities?

Mathews: I think it would be fun to do some models of these objects. If there is less gas around two opposite parts of the nebula, then you can blow out these regions. They can move very fast. The fact that these velocities are 100 or 300 kms^{-1} doesn't mean that they are not planetary nebulae.

Melnick: Many of the planetaries displayed exhibit non-spherical profiles. Several years ago we examined the orientation of planetary nebulae in the galaxy and found that the major axes of these nebulae are, to a large degree, preferentially aligned along the galactic equator. It seems to me that any discussion of the morphology of planetary nebulae must address itself to this observational result.