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ON THE ORIGIN OF PLANETARY NEBULAE*

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ABSTRACT

The stellar wind from a red giant produces an extensive circumstellar cool nebula of appreciable mass. We suggest that in some cases mass loss continues until the hot core of the star is exposed, and that the stellar wind from the remnant star collides with the circumstellar nebula, producing a relatively dense shell of gas which increases in mass and radius at a constant rate. It is shown that such a shell, when ionized by radiation from the central star, has the characteristics of a planetary nebula. V1016 Cygni is used as an example of a star which has recently undergone the transition from a red giant to a young low-mass planetary nebula.
Subject headings: nebulae: planetary — stars: mass loss

I. INTRODUCTION

It is now widely accepted that red giants are the progenitors of planetary nebulae (see, e.g., Salpeter 1971; Osterbrock 1974), but the details of the transition from one type of object to the other are not known. It is significant that appreciable mass loss occurs from a red giant (through radiation pressure on dust which condenses in the atmosphere, and which transfers its momentum to the gas through collisions [Kwok 1975]), producing an extensive circumstellar envelope; such envelopes have become "visible" with the advent of infrared and microwave techniques (Gehrz and Woolf 1971; Wilson and Barrett 1972; Morris 1975). It is also significant that planetary nebulae nuclei have stellar winds (through radiation pressure acting directly on the gas) with velocities one or two orders of magnitude greater than the velocities of the red-giant winds (Osterbrock 1964), and the two gas components must interact, regardless of the details of the process leading from red giant to planetary nebula. We propose that this transition process is nothing more dramatic than the exposure of the hot core of the red giant through continuous mass loss, and that the planetary nebula is produced by the collision of the two stellar winds, one overtaking the other.

In some planetary nebulae, observational evidence exists for the continuing high-velocity wind from the nucleus (Greenstein and Minkowski 1964; Smith and Aller 1969) and/or the remnant of the slower wind from the precursor red giant (Mufson, Lyon, and Marionni 1975). V1016 Cygni is a star which has been suggested as a very young planetary nebula, as it has been observed both in its red-giant phase and in its emission-line stage, with a very brief transition in 1964 (Boyarchuk 1968; FitzGerald and Pilavaki 1974). Radio emission is found coming from the remnant of the red-giant wind, now ionized by the hot central star, and optical observations indicate the presence of a gas shell expanding at 34 km s^{-1} and a new stellar wind from the central star (expanding at 105 km s^{-1}) (Kwok 1977; Ahern *et al.* 1977).

II. THE MODEL

Constant velocities and mass-loss rates are assumed for both stellar winds, V and $\dot{M}$ for the red giant, v and $\dot{m}$ for the central star of the planetary. The winds originate close to the surfaces of the stars, at radial distances R and r, respectively. The time at which the hydrogen envelope of the red giant is depleted and the hot core exposed is taken as $t = 0$, and it is assumed that the red-giant wind ceases and the central-star wind begins at that time. The details of the transition are ignored. The basic assumption of the model is that the detailed processes at that stage do not have an appreciable effect on the nebula produced by the interaction of the two winds. The light curve of V1016 Cygni provides evidence that the transition period is very short (Mammano and Ciatti 1975; Boyarchuk 1968).

The number density of the red-giant wind can be expressed as

$$n = \frac{\dot{M}}{4\pi\mu m_{\rm H} V r^2},$$

where μ is the mean molecular weight and $m_{\rm H}$ is the mass of a hydrogen atom. At the interface between the two winds the mean free path of an atom from the central-star wind in the red-giant wind is then

$$l = \left(\frac{4\pi\mu m_{\rm H} V}{\sigma \dot{M}}\right) r_{\rm I}^2 \tag{1}$$

σ is the collision cross section, and $r_{\rm I}$ the radius of the interface. For $\mu = 1.26$, $\sigma = 10^{-16}$ cm^2, and typical

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TABLE 1

CALCULATED VALUES OF GAS SHELL PARAMETERS FOR VARIOUS COMBINATIONS OF $\dot{m}$, $\dot{M}$, v, AND V

$\dot{m}$ ($M_\odot$ yr^{-1})	$\dot{M}$ ($M_\odot$ yr^{-1})	v (km s^{-1})	V (km s^{-1})	V_s (km s^{-1})	M_s/t ($M_\odot/10^3$ yr)	R_s/t (pc/10^3 yr)	$\Delta R_s/R_s$	$n_e t^2$ (cm^{-3} [10^3 yr]^2)
10^{-6}	10^{-5}	500	10	31	0.022	0.032	0.22	9.3(3)
10^{-6}	10^{-5}	1000	10	40	0.031	0.041	0.12	1.2(4)
10^{-6}	3×10^{-6}	500	10	47	0.012	0.048	0.09	3.8(3)
10^{-6}	3×10^{-6}	1000	10	64	0.017	0.065	0.042	4.3(3)
10^{-6}	3×10^{-6}	500	5	32	0.017	0.033	0.17	8.7(3)
10^{-6}	3×10^{-6}	1000	5	44	0.024	0.045	0.08	9.6(3)
3×10^{-7}	10^{-5}	500	10	22	0.012	0.022	0.56	5.9(3)
3×10^{-7}	10^{-5}	1000	10	27	0.017	0.027	0.31	8.0(3)
3×10^{-7}	3×10^{-6}	500	10	31	0.007	0.032	0.22	2.8(3)
3×10^{-7}	3×10^{-6}	1000	10	40	0.009	0.041	0.12	3.4(3)
3×10^{-7}	3×10^{-6}	500	5	20	0.009	0.021	0.47	6.9(3)
3×10^{-7}	3×10^{-6}	1000	5	27	0.013	0.027	0.24	8.0(3)

values of v, V, and $\dot{M}$ (see Table 1),

$$l \approx \left(\frac{r_{\rm I}}{5\times10^{10}}\right)^2 \text{ cm}\,,$$

which is very small compared with the characteristic dimensions of the system; thus a shell of condensed gas will be produced at the interface rather than having one wind diffuse through the other. The resultant shell will be pushed outward by the central-star wind and retarded by the gas from the red-giant wind, quickly reaching a constant velocity (see below) but increasing in mass. At least part of the shell will be ionized by radiation from the central star and will have the appearance of a planetary nebula, with an emission-line spectrum and radio radiation. Depending on initial conditions and epoch, the ionizing radiation may penetrate to the remnant of the red-giant wind beyond the shell.

If $M_s(t)$ is the mass of the shell when it is at a radial distance $R_s(t)$, then

$$\begin{aligned} M_s(t) &= \int_{R+Vt}^{R_s(t)} \frac{\dot{M}}{V}\,dr + \int_{R_s(t)}^{r+vt} \frac{\dot{m}}{v}\,dr \\ &= \left(\frac{\dot{M}}{V} - \frac{\dot{m}}{v}\right) R_s(t) \\ &\quad - (\dot{M} - \dot{m})t \\ &\quad - \frac{\dot{M}}{V} R + \frac{\dot{m}}{v} r\,. \end{aligned} \tag{2}$$

If $V_s(t)$ is the velocity of the shell, then, assuming a completely inelastic collision, the equation of motion may be written

$$\frac{\dot{m}}{v}[v - V_s(t)]^2 - \frac{\dot{M}}{V}[V - V_s(t)]^2 = M_s(t)\frac{dV_s(t)}{dt}\,. \tag{3}$$

Numerical integration of equation (3), with a substitution for $M_s(t)$ from equation (2) and using typical values of $\dot{M}$, V, $\dot{m}$, and v (see Table 1), shows that $V_s(t)$ quickly reaches a constant value. This value may be obtained analytically from equation (3),

$$V_s = \frac{(\dot{M} - \dot{m}) + (v - V)(\dot{M}\dot{m}/vV)^{1/2}}{[(\dot{M}/V) - (\dot{m}/v)]}\,. \tag{4}$$

The constant velocity of the shell is an obvious result of a momentum balance between the two components with which it is colliding; recall that the density of both components decreases as r^2. After a period of a few years, the radius and mass of the shell can be written as

$$R_s = V_s t\,, \tag{5}$$

$$M_s = \left[\dot{M}\left(\frac{V_s}{V} - 1\right) + \dot{m}\left(\frac{V_s}{v}\right)\right]t - \frac{\dot{M}}{V}R + \frac{\dot{m}}{v}r\,, \tag{6}$$

where V_s is given by equation (4) and the constant term in equation (6) can generally be ignored. It is seen that both the size and the mass of the shell increase linearly with time. The thickness of the shell, ΔR_s, may be found by requiring its internal pressure to balance the pressure from the wind, giving

$$\frac{\Delta R_s}{R_s} = \frac{vkT_s}{\dot{m}\mu m_{\rm H}[(v - V_s)^2 + kT_s/\mu m_{\rm H}]} \times \left[\left(\frac{\dot{M}}{V} - \frac{\dot{m}}{v}\right) - \left(\frac{\dot{M} - \dot{m}}{V_s}\right)\right]. \tag{7}$$

For $T_s = 10^4$ K and $\mu = 0.6$, $\Delta R_s/R_s$ is found to be $\sim$0.2, justifying the thin shell approximation implicit in equations (2) and (3).

Numerical results are given in Table 1, using typical values of $\dot{M}$, V, $\dot{m}$, and v. It should be noted that the expansion velocity of the shell is $\sim$30 km s^{-1}, and that after 3000 years it has a mass $\sim$0.1 $M_\odot$, a radius $\sim$0.1 pc, a thickness $\sim$0.02 pc, and a density $\sim10^3$ cm^{-3}, all in good agreement with observed values for planetary nebulae. It should also be noted that we are treating the simplest possible case of interacting stellar winds—

if more than one discontinuity in velocity occurs, which is not unlikely in the red-giant phase, then more than one shell may be produced.

It is of interest to consider V1016 Cygni as a particular case. V_s, $\dot{m}$, and v are known from optical data (FitzGerald and Pilavaki 1974); $\dot{M}/V$ is known from radio data (Kwok 1977; Ahern *et al.* 1977); and equation (4) can be solved to give $\dot{M} \sim 3 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ and $V \sim 27\ \mathrm{km\ s}^{-1}$. It is noted that $\dot{m}$ is known only roughly for V1016 Cygni, but that the above results depend only weakly on that parameter. The present mass of the shell, calculated from equation (2), is $7 \times 10^{-5}\ M_\odot$, and after a further 5×10^3 yr the mass will increase to $\sim 0.04\ M_\odot$. Using this model, then, it is reasonable to consider V1016 Cygni as a very young planetary nebula.

III. DISCUSSION

The theories of planetary nebula formation have been reviewed in Osterbrock (1973), in which it is suggested that the mechanism of dynamical instability against pulsation is found to be most plausible. However, it is also pointed out that present models based on dynamical instability are incomplete, in that the means by which the instability energy is used to eject the nebular mass is far from clear. Further, one of the most attractive features of the instability model is the (assumed) association between pulsational instability and long-period variables, as this would lead naturally to the ejection of a nebula after the LPV stage, but the association between pulsational instability and LPVs has recently been brought to question (Wallerstein 1977).

The model presented in this *Letter* is based on the collision of the stellar wind from the planetary nebula nucleus with the remnant of the stellar wind from the precursor red giant. The existence of the former has been acknowledged in previous models, and invoked as a means of preventing "backfill" of the planetary nebula into the central cavity, but here we suggest that the wind is responsible for the existence of the planetary nebula itself. Apart from its simplicity, there are other features of this model which make it attractive. For example, models based on sudden ejection often lead to density profiles with a long tail outward, which would be observed as a diffuse outer edge (Mathews 1966). In our model, the outer edge is well defined by the interface of the supersonic shell and the remnant of the red-giant wind, in agreement with the sharp outer edges observed in planetary nebulae.

The mass of the system is also a problem in the models based on dynamical instability, for they predict that the combined mass of the remnant star and planetary nebula shell can be as high as $4\ M_\odot$ (Osterbrock 1974, p. 226), whereas observations indicate maximum values of not much more than $1\ M_\odot$ (Salpeter 1971; Osterbrock 1973). In the present model, mass of the progenitor red giant is not a critical factor, as mass loss occurs over an extended period of time (10^5–10^6 yr), and only a small fraction of the ejected material will be seen as a planetary nebula.

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REFERENCES

Ahern, F. J., FitzGerald, M. P., Marsh, K. A., and Purton, C. R. 1977, *Astr. Ap.*, **58**, 35.
Boyarchuk, A. A. 1968, *Astrofizika*, **4**, 289.
FitzGerald, M. P., and Pilavaki, A. 1974, *Ap. J. Suppl.*, **28**, 147.
Gehrz, R. D., and Woolf, N. J. 1971, *Ap. J.*, **165**, 285.
Greenstein, J. L., and Minkowski, R. 1964, *Ap. J.*, **140**, 1601.
Kwok, S. 1975, *Ap. J.*, **198**, 583.
———. 1977, *Ap. J.*, **214**, 437.
Mammano, A., and Ciatti, F. 1975, *Astr. Ap.*, **39**, 405.
Mathews, W. G. 1966, *Ap. J.*, **143**, 173.
Morris, M. 1975, *Ap. J.*, **197**, 603.
Mufson, S. L., Lyon, J. G., and Marionni, P. 1975, *Ap. J. (Letters)*, **201**, L85.
Osterbrock, D. E. 1964, *Ann. Rev. Astr. Ap.*, **2**, 95.
———. 1973, *Mém. Soc. Roy. Sci. Liège*, **5**, 391.
———. 1974, *Astrophysics of Gaseous Nebulae*, (San Francisco: Freeman).
Salpeter, E. E. 1971, *Ann. Rev. Astr. Ap.*, **9**, 127.
Smith, L. F., and Aller, L. H. 1969, *Ap. J.*, **157**, 1245.
Wallerstein, G. 1977, *J. Roy. Astr. Soc. Canada*, **71**, 298.
Wilson, W. J., and Barrett, A. H. 1972, *Astr. Ap.*, **17**, 385.

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