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DYNAMICAL EFFECTS OF WINDS AND RADIATION ON THE STRUCTURE OF THE PLANETARY NEBULAE

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RESUMEN

Se han obtenido soluciones detalladas numéricas de las ecuaciones de conservación de masa, momento y energía para modelos de nebulosas planetarias, que presentan un viento rápido ($v_f \simeq 10^8$ cm s^{-1}) de la estrella central que choca contra la envolvente previamente eyectada por la estrella. Se supone que la envolvente ha sido arrojada como viento lento ($v_s \simeq 10^6$ cm s^{-1}) durante un período de cerca de 1000 años. Se presume que la presión es constante en una región limitada en el interior por un frente de choque que separa el gas del viento rápido que fluye libremente y el gas impactado del viento rápido; y está limitado en el exterior por un frente de choque que separa el gas lento, que no ha chocado, del gas lento impactado. En esta región la presión dinámica es despreciable.

Los resultados han sido aplicados a 13 nebulosas para las que se han obtenido velocidades de viento rápido, las masas ionizadas y las velocidades de transferencia de masa. En la mayoría de los casos, la estructura exterior de la nebulosa y la dinámica total, están poco afectadas por el viento rápido. Sin embargo, la estructura interior y la radiación de alta temperatura, están ciertamente afectadas por el viento rápido.

ABSTRACT

Detailed numerical solutions of the equations of conservation of mass, momentum, and energy have been obtained for model planetary nebulae, each featuring a fast wind ($v_f \simeq 10^8$ cm s^{-1}) from the central star ploughing into the previously ejected envelope of the star. The envelope is assumed to have been ejected as a slow wind ($v_s \simeq 10^6$ cm s^{-1}) over a period of about 1000 years. The pressure is assumed to be constant in a region bounded on the inside by a shock front separating freely flowing fast-wind gas and shocked fast-wind gas and on the outside by a shock front separating undisturbed slow-wind gas and shocked slow-wind gas. In this region, dynamical pressure is negligible.

The results have been applied to 13 nebulae for which fast-wind velocities, ionized masses, and mass transfer rates have been obtained. In most cases, the outer structure of the nebula and the overall dynamics are affected little by the fast wind. However, the inner structure and high temperature radiation are definitely affected by the fast wind.

Key words: **ISM: KINEMATICS AND DYNAMICS — PLANETARY NEBULAE**

1. INTRODUCTION

Over the past twenty years the slow-wind, fast-wind model has been the preferred description of the planetary nebulae (Kwok, Purton, & Fitzgerald 1977). In this study we apply the model to the few planetary nebulae for which appropriate information exists in order to evaluate the role played by fast winds in their structure and dynamics.

2. CONSERVATION LAWS

2.1. Definitions

See Figure 1 for positions and temperatures of the regions in the planetary nebula model.

ρ_f	density in fast wind	$\dot{R}_f$	velocity of shock front
ρ_h	density in hot gas	c_h	isothermal sound speed in hot gas

v_f	velocity of fast wind	T_h	temperature of hot gas ($T_h \gg 10^4$ K)
v_h	velocity of hot gas	$K_0 T^{5/2}$	thermal conductivity ($K_0 \simeq 6 \times 10^{-7}$ cgs)

We make two assumptions, $v_f \gg \dot{R}_f$, so $v_f - \dot{R}_f \simeq v_f$; and $c_h^2 \gg (v_f - \dot{R}_f)^2$, so $P = P_h = P_w = \rho_f(R_f)\, v_f^2$.

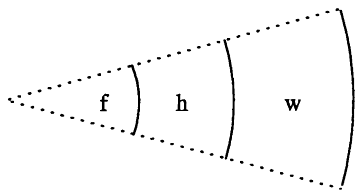


Fig. 1. Section of an idealized spherical planetary nebula, where
R_f outer radius of fast wind
R_h outer radius of hot gas ($T_h \gg 10^4$ K)
R_w outer radius of warm gas ($T_w \simeq 10^4$ K)

2.2. Boundary Conditions at R_f

$$\rho_f(R_f)\, v_f = \rho_f(R_f) \left[v_h(R_f) - \dot{R}_f\right], \tag{1}$$

$$\rho_f(R_f)\, v_f^2 \simeq P = \frac{\dot{E}_f}{2\pi R_f^2\, v_f}, \tag{2}$$

where $\dot{E}_f$ is the power carried by the fast wind.

$$\frac{1}{2}\, \rho_h(R_f)\, v_f^3 \simeq \frac{5}{2}\, \rho_f(R_f) \left[v_h(R_f) - \dot{R}_f\right] c_h^2(R_f) - \frac{2}{7} K_0 \left. \frac{\partial T_h^{7/2}}{\partial r} \right|_{R_f} . \tag{3}$$

2.3. Mass and Energy Balance in Hot Gas

$$\frac{1}{P}\frac{dP}{dt} - \frac{1}{T_h}\frac{dT_h}{dt} = -\frac{1}{r^2}\frac{\partial(r^2 v_h)}{\partial r}, \tag{4}$$

$$\frac{5}{2}\frac{1}{T_h}\frac{dT_h}{dt} - \frac{1}{P}\frac{dP}{dt} = \frac{2K_0}{7Pr^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T_h^{7/2}}{\partial r}\right) - \frac{P\Psi(T_h)}{4k^2 T_h^2}. \tag{5}$$

In equation (5), $\Psi(T_h)$ is the radiative cooling rate (erg cm^3 s^{-1}).

2.4. Boundary Conditions at R_h

We pick the temperature of the warm gas to be $T_w = 1.5 \times 10^4$ K; therefore, at $r = R_h$, we have $T_h(R_h) = 1.5 \times 10^4$ K and $\frac{dT_h}{dt}\big|_{R_h} = 0$.

2.5. Determination of Parameters

If $\dot{E}_f$, v_f, R_f, and $\dot{R}_f$ are specified, P, $T_h(r)$, $v_h(r)$, $\frac{\partial T_h(r)}{\partial r}$, and R_h can be determined from conditions specified in previous subsections.

Regarding $\dot{E}_f$, we have $\dot{E}_f = \frac{f}{2}\frac{v_f}{c}\mathcal{L}$ where $\mathcal{L}$ is the amount of ionizing luminosity absorbed by the nebula, and f is the ratio of the momentum carried by the fast wind to the momentum carried by absorbed radiation.

TABLE 1

TEMPERATURE, MACH NUMBER, AND COOLING IN HOT GAS

r/R_f	$T_h(r)$	$v_h^2(r)/c_h^2(r)$	$C_{tot}(r)/\dot{E}_f$	$C_{ff}(r)/\dot{E}_f$
1.00	4.0×10^6	0.0310	0.0000	0.00000
1.44	3.5	0.0060	0.0016	0.00023
2.05	3.0	0.0013	0.0012	0.00043
3.29	2.3	0.0034	0.0091	0.0026
4.53	1.6	0.0004	0.0450	0.0099
5.47	7.7×10^5	0.0015	0.1800	0.0260
5.58	5.5	0.0025	0.2400	0.0300
5.66	2.6	0.0066	0.3700	0.0350
5.67	1.1	0.0170	0.4800	0.0370
5.67	5.6×10^4	0.0340	0.5300	0.0370
5.67	2.1	0.0920	0.6000	0.0380
5.67	1.5	0.1700	0.6400	0.0380

3. EXAMPLE OF STRUCTURE OF HOT GAS

If we use $\dot{E}_f = \frac{f v_f}{2c}\mathcal{L}$, the input parameters become v_f, f, $\dot{R}_f$, and $\mathcal{L}/R_f$. Values used to construct Table 1 are

$$v_f = 1.5 \times 10^8 \text{ cm s}^{-1} \qquad f = 1$$
$$\dot{R}_f = 10^5 \text{ cm s}^{-1} \qquad \mathcal{L}/R_f = 2 \times 10^{20} \text{ erg cm s}^{-1}$$

We define:

$C_{tot} =$ ratio of total radiative power from hot gas to power of fast wind, and

$C_{ff} =$ ratio of free-free radiative power from hot gas to power of fast wind.

Table 1 shows that the hot gas and warm gas are separated by a very thin front. The temperature profile is similar to that obtained by Weaver et al. (1977).

4. CONDITIONS IN THE WARM GAS

With

$$r^2\, v_w(r) = R_h^2\, v_w(R_h) + \frac{2}{3}\frac{\dot{R}_f}{R_f}\left[r^3 - R_h^3\right], \tag{6}$$

we use the values

$$T_w = 1.5 \times 10^4 \text{ K} \qquad v_w(R_w) = 2 \times 10^6 \text{ cm s}^{-1}$$
$$c_w = 1.57 \times 10^6 \text{ cm s}^{-1} \qquad \alpha = 2 \times 10^{-3} \text{ cm}^3 \text{ s}^{-1}.$$

The number of ionizing quanta absorbed by the nebula each second is

$$\frac{\mathcal{L}}{\langle h\nu\rangle} = \frac{4}{3}\pi\left[R_w^3 - R_h^3\right]\frac{\alpha P^2}{m_p^2 c_w^4}. \tag{7}$$

Since $P = (\dot{E}_f/2\pi R_f^2 v_f) = (f\mathcal{L}/4\pi R_f^2 c)$, then

$$R_w = R_f\left[\left(\frac{R_h}{R_f}\right)^3 + \frac{12\pi m_p^2 c_w^4 c^2 R_f}{\alpha\langle h\nu\rangle f^2 \mathcal{L}}\right]^{1/3}, \tag{8}$$

and

$$M_w = \frac{4\pi R_f^2 m_p^2 c_w^2 c}{\alpha\langle h\nu\rangle f}. \tag{9}$$

TABLE 2

EFFECT OF STELLAR WIND ON PLANETARY NEBULAE

Object Name	v_f $10^8 \frac{cm}{s}$	$\frac{M_w}{M_\odot}$	$\mathcal{L}$ $10^{37} \frac{erg}{s}$	f	R_w	R_h $\cdots 10^{17}$cm$\cdots$	R_f	$T_h(R_f)$ $10^6 K$	p
NGC 7009	2.7	0.04	4.4	0.0035	0.58	0.10	0.013	4.6	0.998
NGC 6891	1.7	0.02	0.14	0.126	1.15	0.32	0.054	2.8	0.99
NGC 1535	2.1	0.02	0.32	0.124	0.89	0.33	0.053	3.7	0.98
NGC 6572	1.8	0.02	0.15	0.228	1.14	0.44	0.072	3.1	0.98
IC 418	1.6	0.04	0.17	0.711	1.78	0.90	0.18	3.2	0.94
NGC 6210	2.3	0.008	0.012	2.27	1.51	0.87	0.14	2.5	0.90
IC 3568	1.8	0.02	0.26	0.667	1.01	0.61	0.12	4.1	0.88
NGC 5189	3.8	0.4	0.26	1.64	8.21	6.14	0.87	3.6	0.76
HU2-1	1.8	0.006	0.30	1.02	0.50	0.39	0.084	5.3	0.72
NGC 6826	1.9	0.04	0.30	2.42	1.91	1.59	0.033	4.7	0.69
NGC 40	2.6	0.08	0.20	7.60	4.88	4.64	0.83	5.0	0.38
NGC 2149	1.4	0.01	0.62	4.38	0.90	0.86	0.22	6.6	0.34
NGC 2371	3.7	0.04	0.023	159.	17.9	17.8	2.7	4.9	0.08

The pressure in the warm gas in the absence wind is proportional to $\sqrt{\mathcal{L}/R_w^3}$. With a wind, the pressure is proportional to $\sqrt{\mathcal{L}/R_w^3}/\left[1-(R_h/R_w)^3\right]^{1/2}$. Therefore,

$$p \equiv \frac{P(\text{no wind})}{P(\text{with wind})} = \left[1-(R_h/R_w)^3\right]^{1/2} . \tag{10}$$

5. APPLICATION OF MODEL TO ACTUAL NEBULAE

Table 2 lists values of R_f, R_h, R_f, $T_h(R_f)$, and p calculated for 13 planetary nebulae. Observed and estimated quantities are v_f, M_w, $\mathcal{L}$, and f (Cerruti-Sola & Perinotto 1985; Pottasch 1984; O'Dell 1963; Seaton 1966).

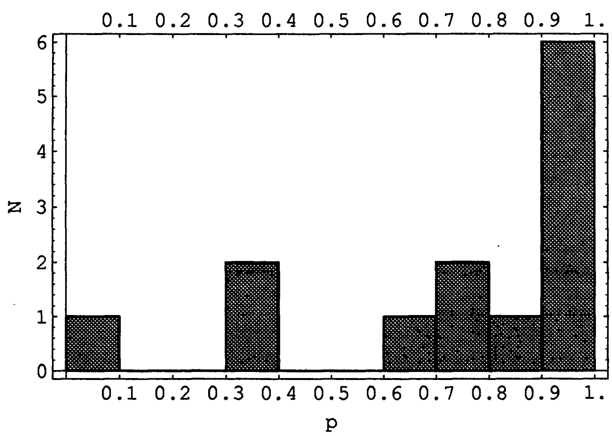


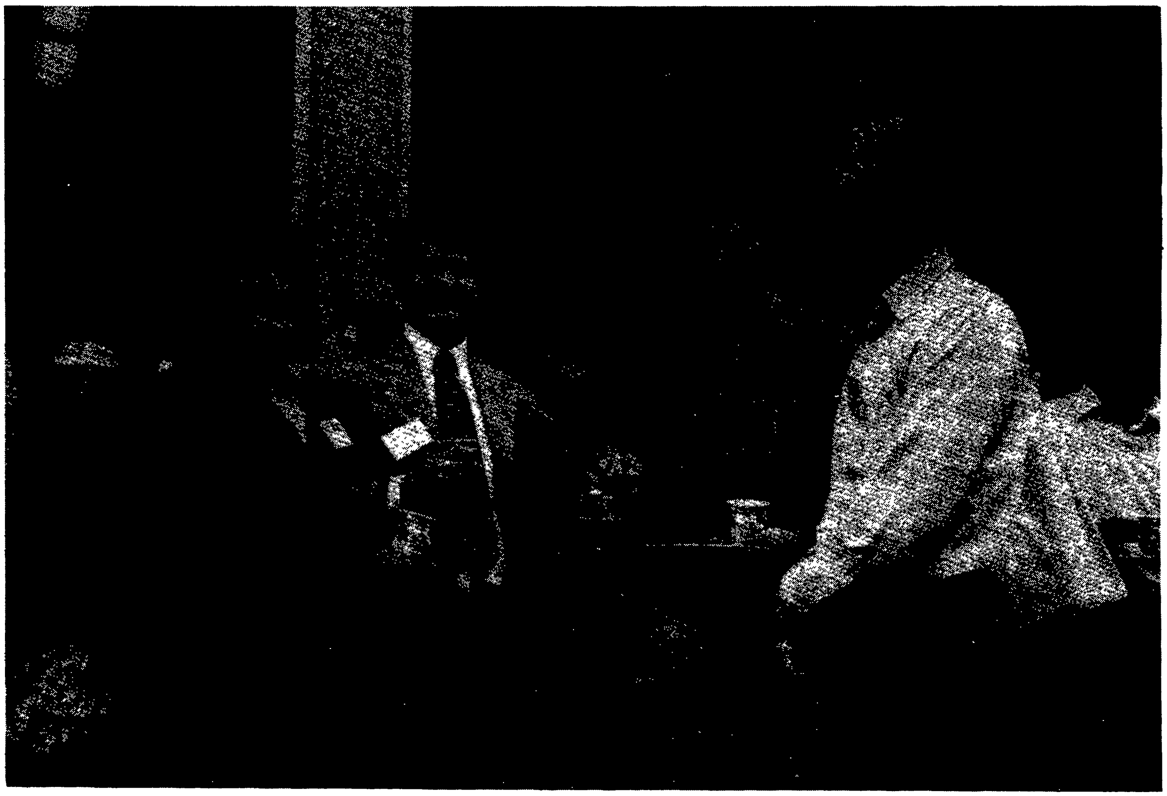
Fig. 2. Distribution of nebulae with effect of stellar wind.

6. CONCLUSIONS

Conclusions are summarized in Figure 2. The effects of fast winds on the bulk of the nebular mass are slightly noticeable for 7 of the 13 objects, weaker than the effects of photo-ionizing radiation for 10 of the 13 objects, and dominant for the remaining 3.

REFERENCES

Cerruti-Sola, M., & Perinotto, M. 1985, ApJ, 291, 237
Kwok, S., Purton, C. R., & Fitzgerald, P. M. 1977, ApJ, 219, L125
O'Dell, C. R. 1963, ApJ, 138, 67
Pottasch, S. R. 1984, Planetary Nebulae, (Dordrecht: Reidel)
Seaton, M. J. 1966, MNRAS, 132, 113
Weaver, R., McRay, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377



Pat Reiff, Jon Morse, Jeff Hester, and John Raymond.