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# HOT, FAST PLANETARY NEBULA HALOES: A NATURAL CONSEQUENCE OF CLUMPY CORES

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RESUMEN

Presentamos un modelo en el que el viento rápido de la estrella central de una nebulosa planetaria acumula masa al atravesar la región central grumosa formada por fases previas evolutivas donde los vientos son más densos y lentos. De este proceso de acumulación de masa resulta un flujo transónico que sale de la región central. El viento con masa agregada choca alrededor de las condensaciones en el halo y produce la emisión caliente, dinámicamente inerte, observada en algunos halos gigantes y tenues de nebulosas planetarias. Además, si este flujo domina la emisión del halo, podría ser una explicación del porqué se observan algunas nebulosas planetarias en las que el halo presenta una expansión más rápida que la región central.

ABSTRACT

We present a model in which the fast stellar wind from the central star of a planetary nebula picks up mass as it flows through a clumpy core region that is the result of the slower, denser "superwind" and red giant wind phases. This *mass loading* results in a transonic flow leaving the core region. The shocking of this gas around clumps and filaments in the halo would produce the hot ($T > 15\,000$ K), dynamically inert emission that has been observed in several faint, giant planetary nebula haloes. Also, if this mass loaded flow dominates the emission in the halo, it could be an explanation for the planetary nebulae in which the halo has been observed to be expanding faster than the core.

*Key words:* **PLANETARY NEBULAE: INDIVIDUAL (NGC 6543, NGC 6826, NGC 7662) — ISM: KINEMATICS AND DYNAMICS — HYDRODYNAMICS — SHOCK WAVES — STARS: MASS LOSS**

## 1. INTRODUCTION

Observations of some core-halo planetary nebulae have revealed features that cannot be explained b simple two-wind models. Firstly, the faint giant haloes of three planetary nebulae (NGC 6543, NGC 6826 an NGC 7662) have been observed to have higher electron temperatures (as measured by the line ratio method using [O III]) than their respective cores, by factors of 1.25–1.86 (Middlemass et al. 1989, 1991, see Table 1) These temperatures of around 15 000 K cannot be maintained by photoionisation alone, since in the haloe the cooling rate due to collisionally excited emission lines exceeds the photoelectric heating rate. However, th halo of NGC 6543 has an electron temperature of only 8860 K (roughly the same as in the core) when the lin

Table 1. Measured Electron Temperatures in some Core-halo Planetary Nebulae

| PN | $T_e$ (core) K | $T_e$ (halo) K |
|---|---|---|
| NGC 6543 | 7900 | 14700 |
| NGC 6826 | 10400 | 13000 |
| NGC 7662 | 13100 | 17500 |

rofile method is used, comparing profile widths on H$\alpha$ and [N II] (Meaburn et al. 1991). The hot gas in this alo has been shown to be dynamically inert, having velocity widths of the order of 7 km s$^{-1}$ (Bryce et al. 992). This is consistent with gas at around 20 km s$^{-1}$ passing through a shock, which would produce both ıe high temperatures and the small velocity widths. Secondly, some multishell planetary nebulae have haloes ıat appear to be expanding supersonically with respect to the cores (Chu 1989).

Any model of these core-halo planetary nebulae must therefore be able to account for the two different emperatures, measured in the same slit position, of the halo of NGC 6543, and the small velocity widths of ıe hot gas.

## 2. PLANETARY NEBULA MODELS

Planetary nebulae are post AGB objects, with the nebula being the photoionised remains of previous mass ›ss epochs of a progenitor red giant star. The three main periods of mass loss are:

) Red Giant Wind, having a mass loss rate of around $10^{-7}$ $M_{\odot}$ yr$^{-1}$ and a terminal wind velocity of about km s$^{-1}$.

i) "Superwind", with a mass loss rate of around $10^{-4}$ $M_{\odot}$ yr$^{-1}$ and a wind velocity of 10 km s$^{-1}$.

ii) Fast wind, with a mass loss rate of $10^{-7}$ $M_{\odot}$ yr$^{-1}$ and a terminal wind velocity greater than 1000 km s$^{-1}$.

The standard model of a planetary nebula is that due to Kwok (1983) in which the fast wind compresses ıe superwind material into a thin dense shell. The core region of the planetary nebula is then the photoionised ense shocked superwind material, while the faint halo is photoionised red giant material plus any superwind ıaterial that has not yet been compressed. The halo is around $10^3 - 10^4$ times fainter than the core emission. ı this model, the fast wind is confined to the core region of the planetary nebula, trapped there by the dense ıell of swept up superwind material.

Perhaps a more realistic model for planetary nebulae takes into account both the acceleration of the fast 'ind (plus decrease in mass loss rate) and the growth of the H II region that starts around the same time. It unlikely that the fast wind will just switch on with its characteristic parameters as soon as the "superwind" ;ops (Kahn & Breitschwerdt 1990; Wentzel 1976; Breitschwerdt & Kahn 1990). The acceleration of the fast 'ind leads to the formation of low velocity shells that are subject to Rayleigh-Taylor instabilities, while the ›nisation front induces Rayleigh-Taylor instabilities in the thin neutral shell of the shocked superwind. These ıstabilities lead to fragmentation and the formation of low-ionisation knots. Thus the morphology of the lanetary nebulae resulting from these processes is that of clumpy cores and clumpy haloes, as is indeed the ase in observed nebulae. It is then reasonable to suppose that the fast wind is no longer confined to the core egion by a dense shell of swept-up superwind material but, instead, can leak out past the clumps in the core ıto the halo.

## 3. HEATING MECHANISMS FOR HALOES

Middlemass et al. (1991) suggested two mechanisms for the heating of the gas in planetary nebula haloes. 'he first of these involved the fast wind leaking out of the core and shocking around clumps in the halo. Since t the edge of the core the fast wind will still have a velocity greater than 100 km s$^{-1}$, then the shocking of this as will produce temperatures far in excess of the observed 15 000 K, and, moreover, the velocity widths will e higher than 25 km s$^{-1}$. Consequently, Middlemass et al. (1991) suggest that the high temperature emission produced by conduction fronts propagating into the clumps behind the transmitted shock waves. However, ıere are many problems with conduction (see, e.g., Hartquist & Dyson 1993), and even a weak magnetic field 'ould suppress this process.

The second mechanism involved the propagation of ~40 km s$^{-1}$ shocks through the ionised halo gas and he cooling of dense material behind them. The interaction of these shocks with filaments is proposed to be esponsible for the observed emission. However, it is unclear how these shocks would originate.

Meaburn et al. (1991) proposed a mechanism in which the fast wind *mass loads* as it flows through the

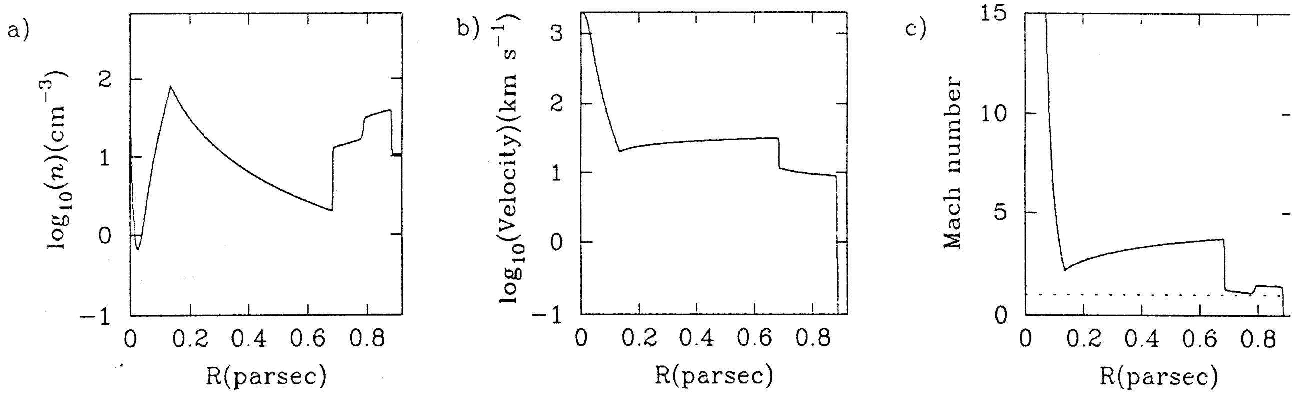


Fig. 1. Model of a mass loaded planetary nebula showing a) $\log_{10}$(density), b) $\log_{10}$(velocity) and c) Macl number.

clumpy core. The mass loaded wind then exits the core transonically (i.e., with a velocity around 20 km s$^{-1}$ and shocks around clumps in the halo. The 15 000 K emission observed in [O III] is produced in the immediat postshock region, while the lower temperature H$\alpha$ and [N II] emission comes from the postshock cooling regioi and the ionised clump respectively. Support for the idea of a transonic mass loaded wind flowing out of ε planetary nebula core comes from observations of ionised dusty globules at the edge of the core of the Heli planetary nebula (Meaburn et al. 1992). The tails of these globules have a "windswept" appearance, though th shapes suggest that the wind is barely supersonic since the tails are long and thin rather than bowshock-shaped It is this model that we develop in this paper.

## 4. A MASS LOADED MODEL FOR NGC 6543

We have developed a numerical hydrodynamic model for the mass loading of the fast wind as it flow through the core and into the halo of the planetary nebula NGC 6543. The observational parameters of thi nebula are a stellar mass loss rate of between $1.3\times10^{-8}$ $M_\odot$yr$^{-1}$ (Lucy & Perinotto 1987) and $3.2\times10^{-7}$ $M_\odot$yr$^{-1}$ (Bianchi et al. 1986) and a stellar wind terminal velocity of around 2150 km s$^{-1}$ (Lucy & Perinotto 1987). Th halo has a radius of 0.89 parsec (165 arcsec at a distance of 1.1 kpc) and the core radius is around 0.1 parsec The electron density in the halo has been measured to be about 10 cm$^{-3}$, while in the core the electron densit of ionised material is greater than 3000 cm$^{-3}$.

As parameters for the numerical model we adopt a mass loss rate of $10^{-7}$ $M_\odot$yr$^{-1}$ and a wind velocity o 2000 km s$^{-1}$. We assume an interclump density of 10 cm$^{-3}$ in both core and halo. In the core, although th density of the clumps and the ionised material being ablated from them will be large, the interclump densit is likely to be quite small. We suppose that the mass loading region extends out to 0.13 pc, which includes a clumpy region at the edge of the core, such as is observed in the high resolution pictures of the Helix nebul (Meaburn et al 1992). The characteristic mass loading rate required to produce a flow of Mach number 2 a the edge of the core can be calculated from the steady state isothermal gas dynamic equations and turns ou to be around $2.0\times10^{-33}$ g cm$^{-3}$ s$^{-1}$. Mass loading occurs by hydrodynamic ablation (Hartquist et al. 1986 and depends on the Mach number for subsonic flow, though is independent of it for supersonic flow. Further we assume that the mass loading is isothermal, and that the frictional heating caused when cold mass is adde to the flow is balanced by the strong cooling in the turbulent mixing layers around the clumps.

The results of this model are shown in Figure 1. This model was run until the outer radius of the swept u material was greater than 0.8 pc. The nebula was by then 48 100 yrs old and consisted of 0.69 $M_\odot$ of swept u "superwind" material, 0.0048 $M_\odot$ of wind material and 0.40 $M_\odot$ of ablated clump material. This is within th limits of the total mass available from a 2 $M_\odot$ progenitor red giant star. As can be seen from the Mach numbe plot, the Mach number rises gradually on leaving the core from 2 to 4 but remains barely supersonic throughou the halo. The velocity plot shows that the velocity of the mass loaded wind in the halo is maintained at aroun 20–30 km s$^{-1}$ between radii of 0.13 pc and 0.68 pc, and so the shocking of this gas around clumps anywhere i this region would produce the high temperature, low velocity emission. If the mass loaded fast wind dominate the emission in the halo, then this modest increase in velocity due to the pressure in the transonic mass loade wind could be an explanation for the "accelerating haloes" seen by Chu (1989).

The effect of varying the characteristic mass loading rate was investigated and it was found that althoug igher mass loading rates cause the mass loaded fast wind to go subsonic in the core, on leaving the core the ressure in the wind causes it to accelerate slightly, attaining Mach numbers and velocities similar to the first iodel. Of course, increasing the mass loading rate means that the amount of ablated mass in the flow increases, hile the amount of mass available in the clumps is restricted by the amount of mass the progenitor lost during ie "superwind" phase. Also, the mass loading process cannot be expected to continue indefinitely since each ump contains a finite amount of mass. It was found that increasing the interclump density had no effect on ie characteristic mass loading rate required to give a transonic flow on leaving the core, though it did have an fect on the velocity of expansion of the halo.

## 5. CONCLUSIONS

Mass loading of the fast wind as it flows through a clumpy nebula core can easily give rise to a transonic ow in the halo. The shocking of this $\sim$20 km $s^{-1}$ mass loaded wind around clumps and filaments in the alo would give rise to the observed high temperature, low velocity emission. Further, if the mass loaded wind ominates the emission in the halo, then one might expect to observe a so-called "accelerating halo". Finally, it emains to point out that planetary nebulae are clumpy and this should be taken into account when considering ieir kinematics.

## REFERENCES

ianchi, L., Cerrato, S., & Grewing, M. 1986, A&A, 169, 227
reitschwerdt, D. & Kahn, F.D. 1990, MNRAS, 244, 521
ryce, M., Meaburn, J., Walsh, J.R., & Clegg, R.E.S. 1992, MNRAS, 254, 477
hu, Y.-H., 1989, in Planetary Nebulae, IAU Symposium 131, ed. S. Torres-Peimbert (Dordrecht: Kluwer), 105
artquist, T.W., & Dyson, J.E. 1993, QJRAS, 34, 57
artquist, T.W., Dyson, J.E., Pettini, M., & Smith, L.J. 1986, MNRAS, 221, 715
ahn, F.D., & Breitschwerdt, D. 1990, MNRAS, 242, 505
wok, S., 1983, in Planetary Nebulae, IAU Symposium 103, ed. D.R. Flower (Dordrecht: Reidel), 293
ucy, L.B., & Perinotto, M. 1987, A&A, 188, 125
Ieaburn, J., Nicholson, R., Bryce, M., Dyson, J.E., & Walsh, J.R. 1991, MNRAS, 252, 535
Ieaburn, J., Walsh, J.R., Clegg, R.E.S., Walton, N.A., Taylor, D., & Berry, D.S. 1992, MNRAS, 255, 177
Iiddlemass, D., Clegg, R.E.S., & Walsh, J.R. 1989, MNRAS, 239, 1
Iiddlemass, D., Clegg, R.E.S., Walsh, J.R., & Harrington, J.P. 1991, MNRAS, 251, 284
Ventzel, D.G. 1976, ApJ, 204, 452

## DISCUSSION

**odríguez**: Do you need to fine-tune the core parameters to lower the velocity from 2000 to 20 km $s^{-1}$ or is ie situation pretty robust?

**rthur**: The situation is pretty robust. As long as the mass loading rate in the core is greater than a critical alue (that which gives Mach 2 flow on exiting the core), then it doesn't really matter how high it is. Larger iass loading rates cause the mass loaded wind to go subsonic in the core, but once it leaves the mass loading one it gently speeds up to around the 20-40 km $s^{-1}$ mark in the halo. Also, varying the interclump density as no effect on the critical mass loading rate.

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