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METAL-POOR PLANETARY NEBULAE: EFFECTS OF WINDS

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Abstract. Some planetary nebulae in the galactic thick disk display extremely low abundances of heavy elements such as O, Ne, S, and Ar, compared with "normal" or type II nebulae. Their central stars are generally relatively cool and underluminous, indicating that the progenitor stars had very low masses. It is suggested that strong stellar winds have had an important role in the formation of these objects, which is supported by the large mass loss rates now observed.

1. Introduction

It is now generally accepted that planetary nebulae display radial abundance gradients in the galactic disk, as measured by their O, Ne, S, and Ar abundances (Faúndez-Abans and Maciel, 1986; Köppen *et al.*, 1991; Maciel and Köppen, 1993). According to the derived gradient, PN at larger galactocentric distances have lower abundances relative to H, corresponding to a factor larger than 2 for an interval of about 6 kpc from the centre. However, several nebulae present extremely low abundances, even when the gradient effect is accounted for. Some of these objects have been studied by Maciel *et al.* (1990), and it was then shown that their central stars are relatively cool and underluminous, so that the progenitor masses are probably very low, in comparison with accepted evolutionary tracks for the central stars of planetary nebulae (Paczyński, 1971; Schönberner, 1981, 1983; Shaw and Kaler, 1985, 1989; Wood and Faulkner, 1986). Other nebulae probably have similar characteristics, as suggested by Maciel *et al.* (1990).

In this work, we have considered several nebulae for which strong heavy element underabundances are associated with low mass central stars, comprising about 10 objects. Since all these nebulae present strong stellar winds, we investigate the connection between the fast mass ejection now observed and the formation of metal poor planetary nebulae.

2. Underabundant Planetary Nebulae

Table I lists the planetary nebulae for which strong metal underabundances are observed, including the objects studied by Maciel *et al.* (1990), plus He2-90 (Costa *et al.*, 1993) and M2-9 (Maciel and Köppen, 1993). The object He2-99 has several characteristics of the remaining nebulae in this paper, and is also included in Table I. However, the nebular chemical composition is not known, except for oxygen, which is apparently normal, and nitrogen, which is somewhat depleted relative to H (Maciel and Köppen, 1993; Freitas Pacheco *et al.*, 1993; Kaler *et al.*, 1989). We

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TABLE I
Abundances [log(X/H)+12] and reduction factors f (within parentheses)

object	O/H	Ne/H	S/H	Ar/H
IC 4593	8.32(2.9)	7.70(2.4)	6.77(1.7)	6.08(2.4)
IC 4634	8.67(1.5)	8.00(1.3)	6.75(2.0)	6.19(2.0)
BD+30 3639	8.58(1.3)	8.16(0.7)	6.86(1.1)	
Cn3-1	8.11(5.0)	7.81(1.9)	6.40(4.2)	6.18(2.0)
He2-90	7.84(7.7)	7.24(6.3)	6.51(2.7)	6.32(1.3)
He2-99	8.79(1.0)			
Hu2-1	8.60(1.3)	7.41(4.2)	6.38(3.6)	6.04(2.3)
M1-26	8.14(4.4)		6.71(1.9)	
M2-9	8.55(2.1)	7.41(5.6)	6.06(11.1)	
SwSt-1	8.54(1.6)		6.48(3.1)	

have concentrated on the elements O, Ne, S, and Ar, for which abundance gradients are better known, as discussed by Maciel and Köppen (1993). However, most of these objects also display underabundances of N, C, and Cl (Maciel *et al.*, 1990). The table gives the adopted abundances and within parentheses the *reduction factor* f, defined as

$$f = \frac{(X/H)_{\rm exp}}{(X/H)_{\rm obs}} \tag{1}$$

where X = O, Ne, S, and Ar, respectively, $(X/H)_{\rm obs}$ is the observed abundance, and $(X/H)_{\rm exp}$ is the expected abundance, assuming that the objects follow the average interstellar gradient as defined by type II planetary nebulae (Maciel and Köppen, 1993):

$$\log({\rm O/H}) + 12 = -0.069R + 9.25, \tag{2}$$

$$\log({\rm Ne/H}) + 12 = -0.056R + 8.46, \tag{3}$$

$$\log({\rm S/H}) + 12 = -0.067R + 7.46, \tag{4}$$

$$\log({\rm Ar/H}) + 12 = -0.051R + 6.81. \tag{5}$$

The adopted distances to the sun d and the calculated distances to the galactic centre R are given in Table II, where we have used $R_0 = 8.5$ kpc for the distance of the LSR (Local Standard of Rest) to the galactic centre. Recent work points to a lower value $R_0 = 7.6$ kpc (Maciel 1993), but this modification does not affect the main conclusions of the present paper.

It should be noted that all objects in Table I are classified as type III according to the Peimbert (1978) scheme, with the possible exception of BD+30 3639 and He2-99. In other words, these objects have kinematical properties characteristic of the thick disk population, as opposed to the younger type I/II objects (cf. Maciel and Dutra, 1992).

TABLE II
Physical properties of the central stars

object	d(kpc)	R(kpc)	$\log T_*$	$\log(L/L_\odot)$
IC 4593	2.4	6.90	4.49	3.43
IC 4634	2.5	6.06	4.62	3.04
BD+30 3639	0.7	8.23	4.46	2.96
Cn3-1	2.9	6.51	4.49	2.99
He2-90	1.5	7.74	4.71	3.00
He2-99	4.2	6.70	4.43	3.32
Hu2-1	1.2	7.82	4.56	2.67
M1-26	1.6	6.90	4.48	3.62
M2-9	3.3	5.45	4.55	3.08
SwSt-1	1.2	7.31	4.44	2.61

3. Low Mass Central Stars

The characteristics of the PN central stars are also given in Table II. Temperatures are generally Zanstra temperatures (cf. Maciel *et al.*, 1990), and the luminosities are calculated from the Hβ flux corrected for the interstellar extinction and for optical depth effects according to Pottasch (1984). For He2-90 the H Zanstra temperature is from Kaler and Jacoby (1991), and the Hβ flux and extinction from Shaw and Kaler (1989). For M2-9 we have used the energy balance temperature from Preite-Martinez *et al.* (1989) and the Hβ flux/extinction from Cahn *et al.* (1992) and Shaw and Kaler (1989). The data for He2-99 are from Maciel and Köppen (1993), Freitas Pacheco *et al.* (1993), and Kaler *et al.* (1989). For the remaining nebulae, the sources of temperatures and Hβ fluxes are given by Maciel *et al.* (1990).

Figure 1 shows the position of the PN central stars on the HR diagram, along with evolutionary tracks from Shaw and Kaler (1985, 1989). Although the uncertainties are large, especially in the determination of the luminosity, it is clear that IC 4634, BD+30 3639, Cn3-1, He2-90, Hu2-1, M2-9, and Swst-1 correspond to very low mass progenitor stars, and IC 4593, He2-99, and M1-26 probably do so.

4. Effects of Stellar Winds

The formation of a planetary nebula is a complex phenomenon, and may involve up to three different kinds of stellar winds (cf. Schönberner, 1990): the slow red giant wind, the so-called "superwind" and the fast wind observed in the central stars.

The analysis of the optical and UV spectra of the objects in Table I reveals that they have some interesting features in common: first, they all present the P Cyg profiles indicative of fast winds in hot stars, some of them presenting also WR spectra; second, they have strong lines of He (He I 5876, He II 4686) and C (C III 4650, C IV 4659, 5806), suggesting some exposure of burned material of the progenitor star. In fact, the C/He ratios in some of these stars (SwSt-1, He2-99,

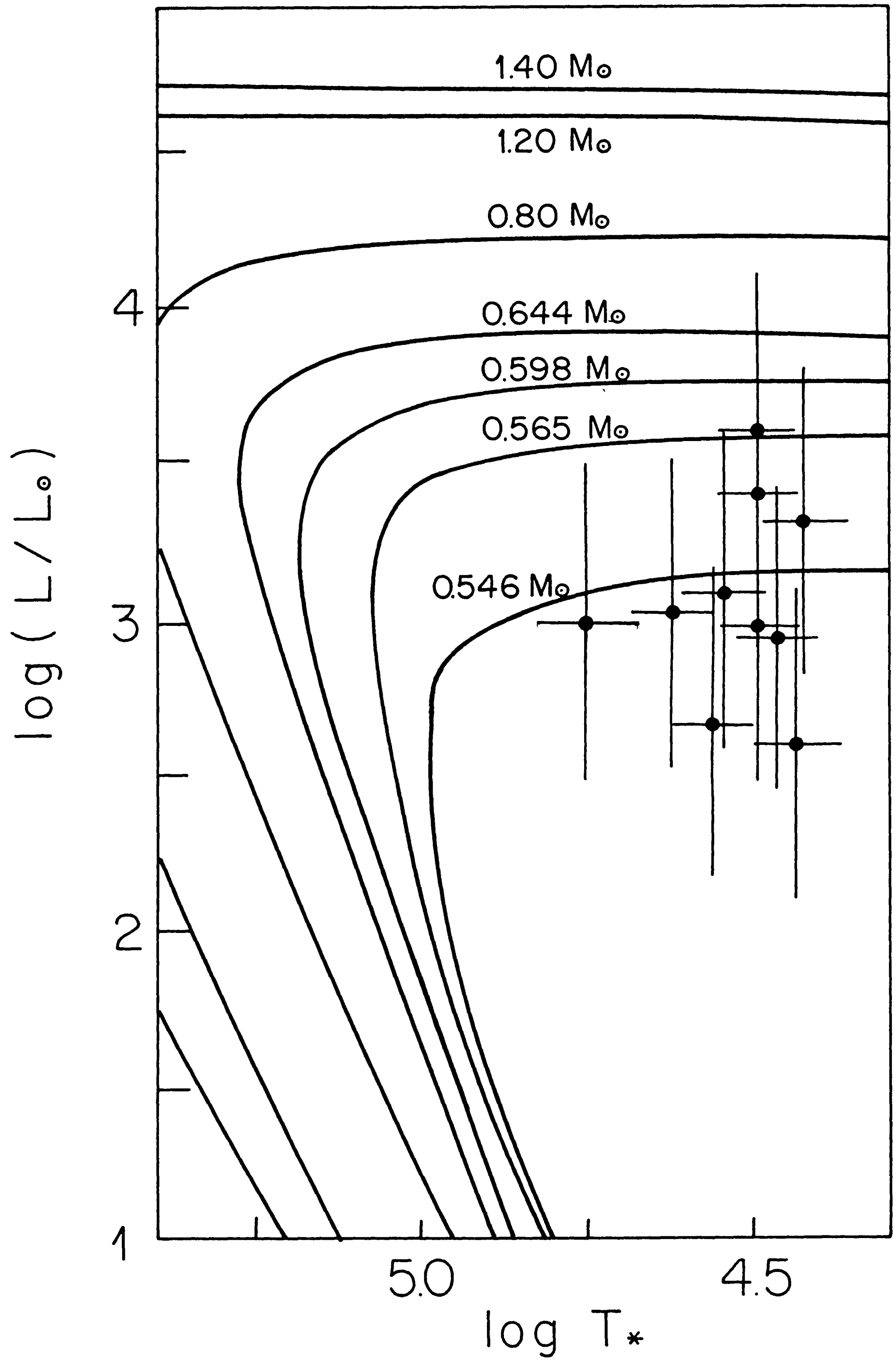

Fig. 1. Position on the HR diagram of central stars of metal-poor planetary nebulae. The evolutionary tracks are from Shaw and Kaler (1985, 1989).

BD+30 3639, ...) are generally larger than 0.4, comparable with the abundance in winds of population I WC stars (Freitas Pacheco and Machado, 1988). This can be interpreted as an evidence of hydrogen deficiency and exposure of He-burned material. The stellar winds have mass loss rates often exceeding 10^{-8} $M_\odot$ yr^{-1} (cf. Cerruti-Sola and Perinotto, 1985, 1989; Hutsemekers and Surdej, 1989; Freitas Pacheco and Costa, 1992; Costa *et al.*, 1993; Freitas Pacheco *et al.*, 1993).

The existence of strong stellar winds during earlier stages of a given planetary nebulae can probably be made evident by remnant fast winds with velocities up to 2000 km s^{-1} and rates in excess of 10^{-8} $M_\odot$ yr^{-1}. As an order-of-magnitude calculation, a one solar mass star with a mass loss rate of 10^{-6} $M_\odot$ yr^{-1} during 3×10^5 yr would produce a progenitor of mass 0.7 $M_\odot$; the PN ejection would remove 0.2–0.3 $M_\odot$, in a superwind process of rate 10^{-4} $M_\odot$ yr^{-1} for 2×10^3 yr; the result would be a central star with masses under 0.55 $M_\odot$, as observed. In fact, massive stellar winds with mass loss rates up to 10^{-4} $M_\odot$ yr^{-1} are observed for very luminous AGB stars (cf. Knapp, 1985; Schönberner, 1990). Proposed mechanisms to drive such winds include radiation pressure on dust, radial pulsations, Alfvén and sound waves (cf. Hearn, 1990). On the other hand, theoretical calculations predict evolutionary lifetimes of several thousand years for the transition region between the AGB and PN regions on the HR diagram. As an example, for core masses in the range 0.6–0.7 $M_\odot$, transition times from the tip of the AGB to an effective temperature of about 25000 K may reach 3000 yr, depending on the mass loss, according to calculations assembled by Schönberner (1990).

Core masses and main sequence masses are probably correlated, as expected from stellar evolution theory (cf. Osterbrock, 1989). Therefore, strong mass loss processes in the AGB would imply less massive central stars of planetary nebulae. Taking for example the central star luminosity as a function of core mass from Wood and Faulkner (1986), most objects shown in Figure 1 would have masses under 0.5 $M_\odot$, the lowest value expected from theoretical models. On the other hand, assuming that the evolution from the AGB to the PN phase occurs essentially at a constant luminosity, it becomes difficult to explain the mass loss on the basis of a purely radiative wind. Other processes, such as the effect of Alfvén waves, may play a role in these stars.

It remains to be explained why the objects considered in this paper present strong heavy element underabundances. This is not clear, but the progenitor stars are probably older, and have been formed out of an interstellar gas poorer in heavy elements, which is reflected by the low abundances presently observed. Some contribution may also come from the delay in the evolution from the presence of strong winds in an earlier phase, which would leave a less massive star, increasing thus its evolutionary time.

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References

Cahn, J.H., Kaler, J.B. and Stanghellini, L.: 1992, *Astron. Astrophys. Suppl.* **94**, 399.
Cerruti-Sola, M. and Perinotto, M.: 1985, *Astrophys. J.* **291**, 237.
Cerruti-Sola, M. and Perinotto, M.: 1989, *Astrophys. J.* **345**, 339.
Costa, R.D.D., Freitas Pacheco, J.A. and Maciel, W.J.: 1993, *Astron. Astrophys.* (in press).
Faúndez-Abans, M. and Maciel, W.J.: 1986, *Astron. Astrophys.* **158**, 228.
Freitas Pacheco, J.A. and Costa, R.D.D.: 1992, in: B. Barbuy and A. Renzini (eds.), *IAU Symposium 149*, Kluwer, p. 419.
Freitas Pacheco, J.A., Costa, R.D.D., Araújo, F.X.A. and Petrini, D.: 1993, *Monthly Notices Roy. Astron. Soc.* **260**, 401.
Freitas Pacheco, J.A. and Machado, M.A.D.: 1988, *Astron. J.* **96**, 365.
Hearn, A.G.: 1990, in: M. O. Menessier and A. Omont (eds.), *From Miras to Planetary Nebulae*, Frontières, p. 121.
Hutsemekers, D. and Surdej, J.: 1989, *Astron. Astrophys.* **219**, 237.
Kaler, J.B. and Jacoby, G.: 1991, *Astrophys. J.* **372**, 215.
Kaler, J.B., Shaw, R.A. and Feibelman, W.A., Lutz, J.H.: 1989, *Astrophys. J. Suppl.* **70**, 213.
Knapp, G.: 1985, *Astrophys. J.* **293**, 273.
Köppen, J., Acker, A. and Stenholm, B.: 1991, *Astron. Astrophys.* **248**, 197.
Maciel, W.J.: 1993, *Astrophys. Space Sci.* (in press).
Maciel, W.J. and Dutra, C.M.: 1992, *Astron. Astrophys.* **262**, 271.
Maciel, W.J. and Köppen, J.: 1993, *Astron Astrophys.* (in press).
Maciel, W.J., Freitas Pacheco, J.A. and Codina, S.J.: 1990, *Astron. Astrophys.* **239**, 301.
Osterbrock, D.E.: 1989, *Astrophysics of gaseous nebulae and active galactic nuclei*, University Science Books.
Paczynski, B.: 1971, *Acta Astron.* **21**, 417.
Peimbert, M. 1978, in: Y. Terzian (ed.), *IAU Symposium 76*, Reidel, p. 215.
Pottasch, S.R.: 1984, *Planetary nebulae*, Reidel.
Preite-Martinez, A., Acker, A., Köppen, J. and Stenholm, B.: 1989, *Astron. Astrophys. Suppl.* **81**, 309.
Schönberner, D.: 1981, *Astron. Astrophys.* **103**, 119.
Schönberner, D.: 1983, *Astrophys. J.* **272**, 708.
Schönberner, D.: 1990, in: M. O. Menessier and A. Omont (eds.), *From Miras to Planetary Nebulae*, Frontières, p. 355.
Shaw, R.A. and Kaler, J.B.: 1985, *Astrophys. J.***295**, 537.
Shaw, R.A. and Kaler, J.B.: 1989, *Astrophys. J. Suppl.* **69**, 495.
Wood, P.R. and Faulkner, D.J.: 1986, *Astrophys. J.* **307**, 659.