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Synthetic AGB evolution

III. The influence of different mass-loss laws

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Abstract. In Paper I of this series we presented a model to calculate in a synthetic way the evolution of thermal-pulsing AGB stars. The model was applied to the LMC and values were derived for the minimum core mass for third dredge-up and the dredge-up efficiency. In Paper I mass loss on the AGB was parameterized with a Reimers mass loss law with a best-fit value for the coefficient $\eta_{\rm AGB}$ of 5. In Paper II we showed that the best fitting model of Paper I could also reproduce the observed abundance patterns in planetary nebulae (PNe) in the LMC, under the assumption that there is no dredge-up after hot bottom burning (HBB) ceases.

To investigate the sensitivity of the results in Papers I and II to the adopted mass loss law we repeat in this paper the analysis of Papers I and II for two recently proposed mass loss laws, viz. that of Vassiliadis & Wood (1993, VW) and that of Blöcker & Schönberner (1993, BS).

We find that the BS-law with a scaling factor $\eta_{\rm BS} = 0.1$ fits all observational constraints equally well as the Reimers law. With a BS mass loss law there is no need to curtail dredge-up after HBB ceases. For the VW-law no combination of parameters could be found that fits all constraints simultaneously. This is probably due to the extreme luminosity dependence ($\dot{M} \sim L^{\alpha}$, $\alpha = 6$) implied by the VW-law. We conclude that synthetic AGB models with mass loss laws that are moderately luminosity dependent ($1 < \alpha \lesssim 4$) can be made to fit all presently available observational constraints.

Key words: stars: evolution of – stars: mass loss – planetary nebulae: general – Magellanic Clouds – stars: AGB and post-AGB

1. Introduction

We have developed a model to calculate the evolution of thermal-pulsing AGB stars in a synthetic way (Groenewegen & de Jong 1993a, Paper I). This model is more realistic than previous (e.g. Renzini & Voli 1981) synthetic evolution models in that more details on the evolution have been included. The variation of the luminosity during the interpulse period is taken into account as well as the fact that, initially, the first few pulses are not yet at full amplitude and that the luminosity is lower than given by the standard core mass–luminosity relation. Most of the relations used are metallicity dependent.

The model uses algorithms derived from recent evolutionary calculations for intermediate- and low-mass stars. The main free parameters are the minimum core mass for (third) dredge-up $M_{\rm c}^{\rm min}$ and the dredge-up efficiency λ as well as the parameterization of the mass loss process. In Paper I we assumed a Reimers mass loss law with coefficient $\eta_{\rm AGB}$ [defined in Eq. (2)].

In Paper I we determined the minimum core mass ($M_{\rm c}^{\rm min}$), the efficiency (λ) for third dredge-up and the scaling coefficient $\eta_{\rm AGB}$. We achieved this by fitting the carbon star luminosity function (LF), the ratio of the number of C/M stars on the AGB in the LMC, and the initial–final mass relation. We found a best-fitting model with $M_{\rm c}^{\rm min} = 0.58 M_{\odot}$, $\lambda = 0.75$ and $\eta_{\rm AGB} = 5$. We also showed that hot-bottom burning (HBB) at the level of Renzini & Voli's (1981; RV) $\alpha = 2$ case explains the observed number of high luminosity J-type carbon stars well. We furthermore showed that the best-fitting model predicts that carbon stars are formed from stars of initial masses between ~ 1.2 and $\sim 4 M_{\odot}$, in agreement with observations in LMC clusters. In addition we showed (Groenewegen & de Jong 1993b, Paper II) that the best-fitting model of Paper I also reproduces the observed abundance patterns of planetary nebulae (PNe) in the LMC, if we make the additional assumption that there is no dredge-up after HBB ceases.

One of the most uncertain aspects of the model is the parameterization of the mass loss rate. In Paper I we adopted a Reimers (1975) law which is an empirical relation derived for red giants. Since mass loss on the AGB seems to be related to pulsation, a mass loss law related to pulsations may be more physical. Recently, two such mass

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loss rate laws were presented; that of Vassiliadis & Wood (1993, VW) and that of Blöcker & Schönberner (1993, BS). In this paper we repeat the analyses of Papers I and II for these two different mass loss laws.

2. The mass-loss laws

The model is described in full detail in Paper I. Here we only discuss the aspects related to the mass loss process.

Prior to the AGB stars lose mass on the main-sequence, the RGB (important mainly for stars below $\sim 2.2 M_{\odot}$ which experience the helium core flash) and on the Early-AGB (E-AGB; important for massive stars). The total mass lost by stars with initial masses $\lesssim 2.2 M_{\odot}$ preceding the AGB is taken from the models of Sweigart et al. (1990) scaled in such a way to give a mass loss of $0.22 M_{\odot}$ for a $0.85 M_{\odot}$ star ($\eta_{\rm RGB} = 0.86$ in the nomenclature of Sect. 2.6.1 of Paper I). In addition all stars lose mass on the E-AGB parameterized as (cf. Paper I, M in $M_{\odot}$)

$$\Delta M_{\rm EAGB} = \eta_{\rm EAGB}\, 0.056\, (M/3)^{3.7} M_{\odot}\,. \quad (1)$$

In Paper I mass loss on the AGB is described by a Reimers (1975) law:

$$\dot{M} = \eta_{\rm AGB}\, 4.0\, 10^{-13}\, \frac{LR}{M}\, M_{\odot}\, {\rm yr}^{-1}\,, \quad (2)$$

with L and R in solar units. In Paper I we assumed $\eta_{\rm EAGB} = \eta_{\rm AGB}$ and found that $\eta_{\rm AGB} \gtrsim 3$ is needed to fit the initial–final mass relation for the low mass stars and that $\eta_{\rm AGB} = 5$ provides the best fit to the high-luminosity tail of the carbon star LF. In Paper II we showed that with $\eta_{\rm AGB} = 5$ the observed abundance patterns of PNe are also reproduced quite well.

We now consider alternative mass loss rate laws. The mass loss rate law proposed by BS is:

$$\dot{M} = \eta_{\rm BS} \left(4.8\, 10^{-9}\, \frac{L^{2.7}}{M^{2.1}}\right) \left(4.0\, 10^{-13}\, \frac{LR}{M}\right) M_{\odot}\, {\rm yr}^{-1}\,, \quad (3)$$

i.e. a Reimers law with an additional $(L^{2.7}/M^{2.1})$ dependence. We include a scaling factor $\eta_{\rm BS}$. BS derived this law by fitting the mass loss rates listed by Bowen (1988) for his standard model based on dynamical calculations for long-period variables. Direct comparison of Eqs. (2) and (3) shows that the mass loss rate adopted by BS is equivalent to high Reimers coefficients. For representative values of $L = 3000 L_{\odot}$, $M = 1 M_{\odot}$ or $L = 20\,000 L_{\odot}$, $M = 5 M_{\odot}$ the equivalent value of $\eta_{\rm AGB}$ are 12 and 67, respectively.

The mass loss law proposed by VW is

$$\dot{M} = \eta_{\rm VW}\, \min\left(\frac{L}{v_{\rm exp}\, c},\ 10^{-11.4+0.0125[P - y\, 100\, (M-2.5)]}\right) M_{\odot}\, {\rm yr}^{-1}\,, \quad (4)$$

where $y = 1$ for M larger than $2.5 M_{\odot}$ and $y = 0$ for smaller masses. The expansion velocity $v_{\rm exp}$ and the fundamental mode pulsation period (P, in days) are calculated using the relations in VW. We include a scaling factor $\eta_{\rm VW}$.

The luminosity L in Eqs. (2)–(4) is not the quiescent luminosity but includes the effect of luminosity variation during the flashcycle; the mass loss rate just after a thermal pulse (TP) is higher than during the quiescent H-burning phase or in the luminosity dip.

We implemented the BS and VW mass loss laws in our code. BS only consider stars of 3 and $5 M_{\odot}$ for which mass loss on the RGB is not important. In our calculations mass loss preceding the AGB is treated as in Paper I (see above). From BS we derive $\eta_{\rm EAGB} = 0.5$. VW neglect any mass loss prior to the AGB for stars above $1 M_{\odot}$. Using our model with the mass loss laws of BS and VW we determine $\eta_{\rm BS}$ and $\eta_{\rm VW}$ needed to reproduce the TP-AGB lifetimes reported by BS and VW for their models (with $Z = 0.021$ and $Y = 0.24$ for BS and $Z = 0.008$ and $Y = 0.25$ for VW). We find $\eta_{\rm BS} = 0.35$ and $\eta_{\rm VW} = 0.6$. That $\eta_{\rm BS}$ and $\eta_{\rm VW}$ are not unity is most likely due to differences in the effective temperature of the AGB tracks in the HR diagram between our code and the calculations of BS and VW. Additionally, small differences between the algorithms adopted in Paper I for the core mass–luminosity relation and other relations and the evolutionary calculations of BS and VW may play a role.

3. The constraints

In this section we briefly discuss the constraints to the models.

The first constraint is the observed carbon star luminosity function (LF) in the LMC as derived from the survey results of Blanco et al. (1980) and Westerlund et al. (1978) (see Paper I). In Paper I we showed that the predicted low-luminosity tail of the LF is sensitive to the value of $M_{\rm c}^{\rm min}$ and that the peak of the LF is sensitive to the dredge-up efficiency λ. The high-luminosity tail is sensitive to the mass loss rates.

The second constraint is the ratio of C/M stars on the AGB in the LMC. The observed value is between 0.2 and 2 (Blanco & McCarthy 1983) depending on the spectral type of the M-stars included. For our best model we found a value of C/M = 0.85 in Paper I.

The third constraint is the initial–final mass relation based on stars in the solar neighbourhood (for detailed references see Paper I).

The fourth constraint is provided by observations of AGB stars in LMC clusters (Frogel et al. 1990; Westerlund et al. 1991) which show that stars between $\sim 1.2 M_{\odot}$ and $\sim 4 M_{\odot}$ become carbon stars and that S-stars originate from slightly more massive stars.

The fifth constraint is the birth rate of AGB stars. Based on the death rate of horizontal branch (clump) stars and cepheids in the LMC we derived in Paper I a birthrate of AGB stars between 0.05 and 0.15 yr^{-1}.

The sixth constraint is the set of abundance ratios of PNe in the LMC, discussed in Paper II. The abundances in the ejecta of the model stars are calculated by taking the average abundance in the material ejected during the final $5\,10^4$ yr on the AGB. This should be representative of the abundances observed in PNe. We emphasize again that we do not claim all our model stars to actually become PNe. We calculate the average abundances in the ejecta of the AGB star. Whether these ejecta will be recognised and classified as a PN is a different story.

4. Model results

We determined $M_c^{\min}$, λ and $\eta_{\rm BS}$ (c.q. $\eta_{\rm VW}$) in the following way. The C-star LF is largely determined by $M_c^{\min}$ and λ, the maximum C/O ratio observed in PNe is largely determined by η. Fine tuning by comparison to the other constraints yields the final choice of parameters: for the BS model $M_c^{\min} = 0.58 M_\odot$, $\lambda = 0.75$ and $\eta_{\rm BS} = 0.1$, for the VW model $M_c^{\min} = 0.58 M_\odot$, $\lambda = 0.75$ and $\eta_{\rm VW} = 3$.

We first discuss the BS-law model. The carbon star LF is shown in the middle panel of Fig. 1. It fits the observed distribution about equally well as using the Reimers law (Paper I, left panel). The ratio of C/M stars on the AGB is 0.93, compared to 0.85 for the Reimers-law model. The observed value is between 0.2 and 2. The initial–final mass relation is equally well fitted as with a Reimers law (Fig. 2). The predicted PNe abundances are shown in Fig. 3. The differences are small when compared to the model for a Reimers law (taken from Paper II)[1]. The maximum C/O ratio is in good agreement with observations. The BS-law model does not predict the high He/H ratios observed in some PNe. In the C/O–C/N diagram the sequence that is determined by HBB lies at lower C/O ratios (for a given C/N) than the Reimers model. Note that in the BS-law model we did not have to assume that λ drops to zero when HBB stops. The fact that there is no dredge-up after HBB ceases is due to the higher mass loss rate which causes the AGB to terminate before any fresh carbon can be added to the envelope.

The results for BS-law models for individual model stars are listed in Table 1, including the results for the best fitting Reimers-law model (taken from Table 5 of Paper I) for comparison. The differences are generally small. The model predicts carbon star formation for stars between ~ 1.2 and

[1] The Reimers model with the standard parameters of Paper I does not fit the observations in the C/O–C/N and N/O–N/H panel. In Paper II we showed that with the additional assumptions that $\lambda = 0$ after HBB ceases and with an oxygen-to-metallicity ratio which is higher in the past, the discrepancy can be explained. These additional assumptions are not made for the BS and the VW model.

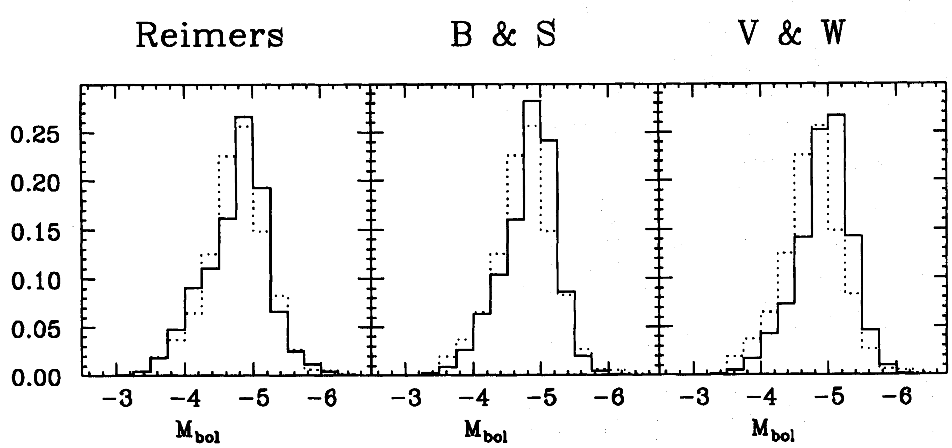

Fig. 1. The carbon star luminosity function for the Reimers law with $\eta_{\rm AGB} = 5$ (from Paper I), a BS-law with $\eta_{\rm BS} = 0.1$ and a VW-law with $\eta_{\rm VW} = 3$. The dotted curve is the observed LMC carbon star luminosity function (from Paper I)

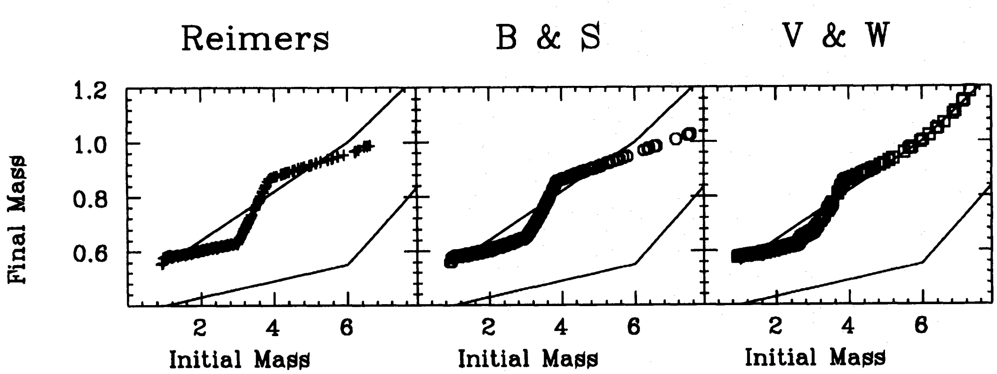

Fig. 2. The initial-final mass relation for the Reimers-law (+, from Paper I), the BS-law with $\eta_{\rm BS} = 0.1$ (○) and the VW-law with $\eta_{\rm VW} = 3$ (□). The values allowed by the observations lie between the two solid lines

Table 1. Model results for different mass-loss laws

Initial mass ($M_\odot$)	Z	Model	TM	TS	TC	TAGB
			(10^3 yr)			
1.00	0.0037	RE	160	—	—	160
1.25	0.0066	RE	134	—	136	270
1.50	0.0076	RE	124	88	157	369
2.00	0.0082	RE	272	—	339	611
3.00	0.0086	RE	302	160	603	1065
5.00	0.0087	RE	152	3.3	15	170
1.00	0.0037	BS	165	—	—	165
1.25	0.0066	BS	134	94	36	264
1.50	0.0076	BS	212	—	140	352
2.00	0.0082	BS	272	87	328	687
3.00	0.0086	BS	380	87	1260	1722
5.00	0.0087	BS	87	—	—	87
1.00	0.0037	VW	290	—	3	293
1.25	0.0066	VW	229	—	56	285
1.50	0.0076	VW	212	92	19	323
2.00	0.0082	VW	272	87	261	620
3.00	0.0086	VW	380	162	1839	2381
5.00	0.0087	VW	195	—	—	195

Notes: RE, BS and VW refer to the different mass-loss laws (see text). TM, TS, TC, TAGB refer to the lifetime of the M, S, C and the total AGB phase.

$\sim 4 M_\odot$, similar to the results of Paper I and in agreement with observations. The death rate of AGB stars is $\sim 0.05\,\mathrm{yr}^{-1}$, compared to $\sim 0.07\,\mathrm{yr}^{-1}$ with a Reimers law and an observed value between $0.05\,\mathrm{yr}^{-1}$ and $0.15\,\mathrm{yr}^{-1}$ (Paper I).

We tried lower values for η_{BS}. This results in higher C/M star ratios and higher than observed C/O ratios in PNe. We tried to compensate this by increasing $M_{\mathrm{c}}^{\mathrm{min}}$ or decreasing λ. This results in a shift of the C-star LF to higher luminosities, in disagreement with observations.

We next discuss the VW-model. The C-star LF is presented in Fig. 1 (right panel). The C/M star ratio is 0.73. The initial–final mass relation is shown in Fig. 2. The PNe abundances are compared in Fig. 3 and the results for some models are in Table 1. Carbon stars are predicted at somewhat lower initial masses than observed. The carbon star LF peaks at higher luminosities than observed. The predicted abundances are not in good agreement with observations. The model predicts higher than observed C/O and N/O ratios. We could not find parameters that simultaneously fitted all constraints, e.g. the high C/O ratio in some PNe suggests either an increase in η_{VW}, an increase in $M_{\mathrm{c}}^{\mathrm{min}}$ or a decrease in λ. These choices would reduce the C/M star ratio close to the minimum value allowed by the observations. Such a change in $M_{\mathrm{c}}^{\mathrm{min}}$ or λ would make the C-star LF peak at even higher luminosities. A higher $M_{\mathrm{c}}^{\mathrm{min}}$ would increase the minimum mass from which carbon stars are formed.

5. Discussion

The reproduction of the BS models for Galactic stars requires $\eta_{\mathrm{BS}} = 0.35$ (Sect. 2) while the observations for the LMC require $\eta_{\mathrm{BS}} = 0.1$. This suggests that the mass loss rate in the LMC is about a factor of 3 lower than in the Galaxy. This could imply that the mass loss rate depends on metallicity like $Z^{1.5}$, compared to a $Z^{0.5}$ dependence found for O-stars (Kudritzki et al. 1987). We consider such a conclusion premature however, firstly because the adopted mass loss rate by BS for Galactic stars may be incorrect and secondly because of the uncertainty in the mass loss rates derived by Bowen (1988) [on which BS based Eq. (3)]. Uncertainties in the dust properties and other quantities (see Table 9 of Bowen 1988) make Bowen's estimates for the mass loss rate uncertain by a factor of about 5.

The main differences between the three mass loss laws considered here is in their dependence on luminosity ($\dot{M} \sim L^{\alpha}$). The Reimers-law and the BS-law have $\alpha = 1$ and 3.7, respectively. Using the period-luminosity relation for LPVs in the LMC (Hughes & Wood 1990) we derive that the $\dot{M}$–P relation of VW implies $\alpha \approx 6.1$, at least for $P \lesssim 600$.

VW use an observed $\dot{M}$–P relation (Wood 1990). Their plot contains little date below $P = 350$ d, where most of the LPVs are located (Hughes & Wood 1990). Schild (1989) and Whitelock (1990) derived $\dot{M}$–P relations containing data points at lower periods. The latter two relations agree

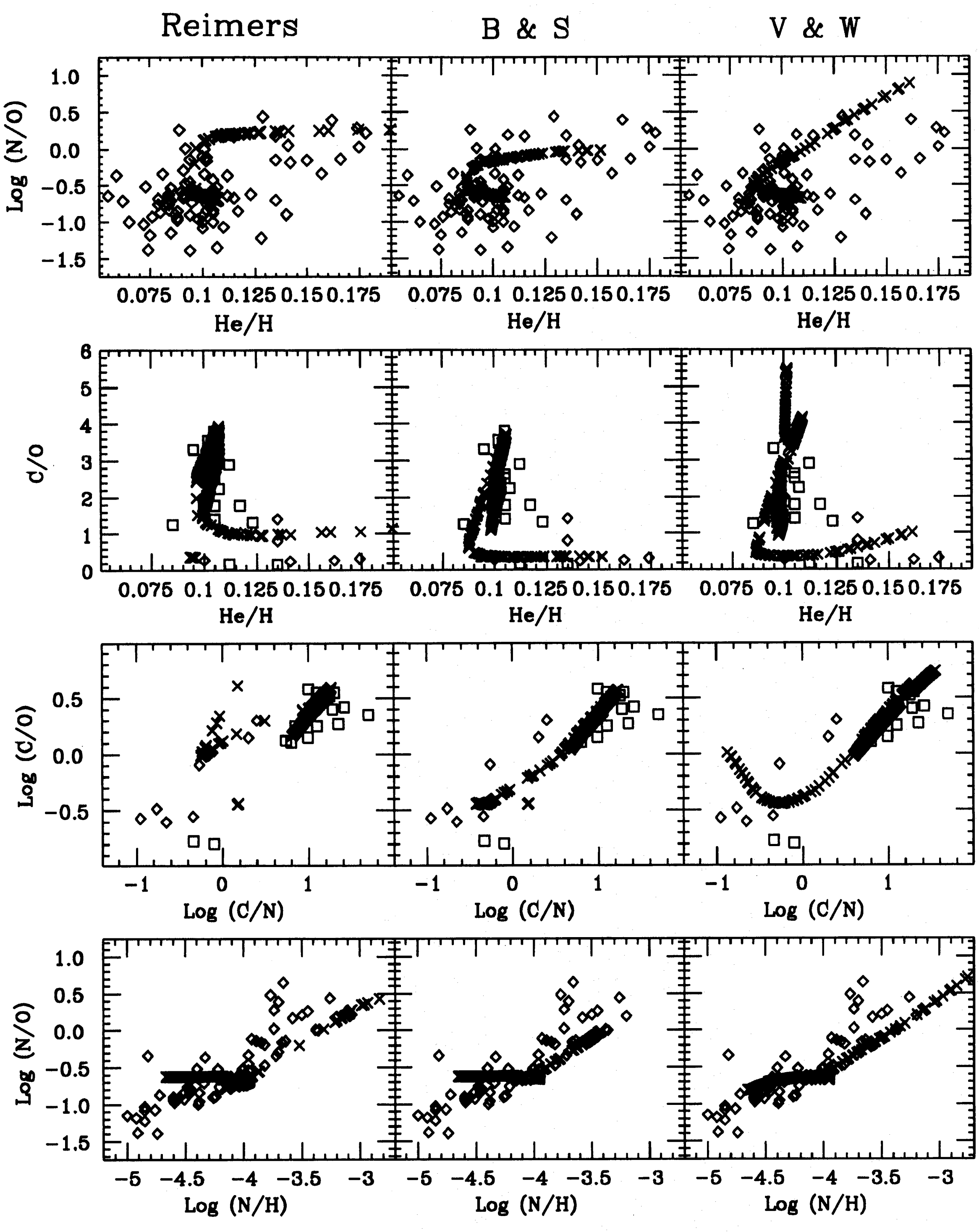

Fig. 3. Observed and predicted abundance ratios of planetary nebulae in the LMC for the Reimers model (taken from Paper II), the BS-law with $\eta_{BS} = 0.1$ and the VW-law with $\eta_{VW} = 3$. Model results are plotted as crosses. In the C/O–He/H and C/O–C/N diagram the observed type I PN (defined as having N/O> 0.5) are indicated by diamonds, the other observed PN by squares

very well with each-other and have a much shallower dependence of $\dot{M}$ on P than Wood's relation.

Since the VW-law can be excluded, while a Reimers- and BS-law fit the constraints in the LMC about equally well, we infer that probably all models with a mass loss luminosity dependence of $1 < \alpha \lesssim 4$ will fit the constraints discussed in Sect. 3. For Schild's $\dot{M}$–P relation we derive $\alpha \approx 2$ in the range $P = 200$–600 d, in between the value for the Reimers- and the BS-law.

An additional constraint on the dependence of the mass loss law on stellar parameters may come from the observation that some Galactic M-, S- and C-stars describe a loop in the IRAS color–color diagram (Willems & de Jong 1988; Zijlstra et al. 1992). Derivation of the mass loss rate in the different phases of the pulse cycle for the well studied case S Sct (Groenewegen & de Jong 1993c) shows that the ratio of the mass loss rate in the thermal pulse phase to that in the quiescent H-burning phase is about 20 and that the ratio of the mass loss rate in the thermal pulse phase to that in the luminosity dip is about 700. Since the corresponding changes in luminosity are about 1.8 and 3.5, respectively, this implies $\alpha \approx 5$. This value is somewhat larger than derived previously. Perhaps S Sct is a special case. An analysis of the mass loss rate history in other carbon stars with double-peaked CO line profiles would be interesting. Perhaps the luminosity dependence of the mass loss rate is steeper in the Galaxy than in the LMC. Perhaps the mass loss rate in AGB stars does not primarily depend on luminosity but also depends in some unknown manner on chemical composition. The carbon stars seem to describe larger loops in the IRAS color–color–diagram than the M- and S-stars, implying that the drop in the mass loss rate between the thermal-pulse phase and the luminosity-dip is larger for the carbon stars. This may be related to their particular chemical composition.

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