Astron. Astrophys. 290, 936–940 (1994)

ASTRONOMY
AND
ASTROPHYSICS

Location of PN central stars on the HR diagram

J.O. Cazetta and W.J. Maciel

Instituto Astronômico e Geofísico da USP, Av. Miguel Stefano 4200, CEP 04301-904 São Paulo SP, Brazil

Received 16 February 1994 / Accepted 4 June 1994

Abstract. Galactic planetary nebulae (PN) form a complex system, which includes objects with different characteristics and evolutionary stage. The location of a sample of galactic PN central stars on the HR diagram is attempted, in order to investigate the correspondence of the PN properties such as chemical composition, space distribution and kinematics, with the main sequence masses of their progenitor stars.

Key words: planetary nebulae: general – stars: evolution

1. Introduction

Planetary Nebulae (PN) are considered as part of the evolutionary scheme of intermediate mass stars (1-8 $M_{\odot}$), and represent the connecting link between red giants and white dwarfs (Pottasch 1984, 1992; Peimbert 1990; Kaler 1985; Ortiz & Maciel 1994). Hence, like other stars, central stars of planetary nebulae (CSPN) must occupy distinct positions on the HR diagram according to their main sequence masses, as predicted by evolutionary models (Paczyński 1971; Shaw & Kaler 1989).

The location of CSPN on a theoretical HR diagram is a difficult problem, as their masses are not individually known. On the other hand, giant stars are expected to enrich their outer layers in helium, nitrogen, and carbon as a result of processes that dredge-up material from the core (Kaler 1983, 1985; Peimbert 1990), and the N/O and He/H ratios are expected to increase with the initial stellar mass (Becker & Iben 1979, 1980; Renzini & Voli 1981; Kaler et al. 1990). Furthermore, the initial and remnant masses are directly related (Iben & Truran 1978; Kwok 1983; Iben & Renzini 1983; Weidemann 1987; Ciotti et al. 1991), so that the He/H and N/O ratios should correlate with the remnant mass (Renzini 1979; Iben & Renzini 1983), although presently available evidences are controversial (Stasinska & Tylenda 1990; Pottasch 1993).

Another possibility is to investigate the location of CSPN on the "observed" HR diagram, through estimates of their total luminosities and effective temperatures (cf. Pottasch 1981, 1983). Here again several difficulties arise, especially due to (i) uncertainties in the distance determinations, which strongly affect the luminosities, and (ii) variations of the stellar temperature, as determined from blackbodies, Zanstra method, energy balance, etc.

Despite these problems, previous results on the evolution of CSPN have included the location of these objects on the HR diagram. Schönberner (1981) and Schönberner & Weidemann (1981) used a sample of density bounded PN with statistical distances, and found that the central stars are distributed on the HR diagram within a remarkably narrow range of core masses. Kaler (1983) used statistical distances and a sample containing very extended PN only. His main conclusion was that nebular enrichment is correlated with CSPN position on the HR diagram, as predicted by dredge-up theory. According to his results, stars with larger initial masses will produce larger nuclear masses and, due to their evolutionary lifetimes, would be generally observed on their cooling tracks in the lower corner of the HR diagram (see also Kaler & Jacoby 1989). Pottasch (1983, 1984, 1989) and Gathier & Pottasch (1989), considered PN with individually determined distances. The agreement with the theoretical tracks and CSPN positions on the HR diagram was poor, but like Kaler (1983) they found a correlation between nebular enrichment and their position on this diagram. Peña et al. (1992) analyzed central stars of 8 halo PN, and found that the range of stellar masses is very narrow (0.55-0.57 $M_{\odot}$), lower than for disk PN. Finally, Maciel et al. (1990) have studied the position on the HR diagram of a sample of metal-poor PN, using different methods to determine their temperatures and luminosities. They concluded that most central stars in their sample are extremely low mass objects, probably formed out of metal-poor protostellar clouds (see also Maciel 1994).

In the present paper, we propose to extend the work by Maciel et al. (1990) in order to include the complete sample of galactic PN for which reliable data is available (cf. Maciel & Dutra 1992; Maciel & Köppen 1994). Recent work has emphasized the importance of the Peimbert classification scheme (cf. Peimbert 1978, 1990) in terms of the space distribution and kinematics (Maciel & Dutra 1992), chemical composition and radial gradients (Maciel & Köppen 1994; Maciel & Chiappini 1994), He abundance (Chiappini & Maciel 1994), and the PN-OH/IR connection (Ortiz & Maciel 1994). Our main purpose here is to study the distribution of galactic PN on the HR dia-

Send offprint requests to: W.J. Maciel gram according to the PN types, so that another property (the stellar mass) can be included.

We have considered a sample of 200 planetary nebulae, all of which have been classified in types I, II, III, and IV according to the classification scheme originally proposed by Peimbert (1978). The objects are listed in Maciel & Dutra (1992), Maciel & Köppen (1994), and Maciel & Chiappini (1994), including the distances, chemical composition and kinematical properties needed for the classification of the nebulae.

2. Temperatures

There are several ways of determining the CSPN temperatures. Zanstra's method assumes that the nebula is optically thick to ionizing photons and that the brightness of the nebula is proportional to the total UV energy radiated by the star. The optical Balmer line or HeII line spectrum can be used to determine the number of photons capable of ionizing H^o or He^+, which combined with the visual magnitude give the so-called HI or HeII Zanstra temperatures. In this work we have used Zanstra temperatures [T_z(H), T_z(HeII)] from: Peña et al. (1992), Méndez et al. (1992), Preite-Martinez et al. (1991), Kaler et al. (1990), Gleizes et al. (1989), Kaler & Jacoby (1989), Jacoby & Kaler (1989), Shaw & Kaler (1989, 1985), Golovatyi (1988), Sabbadin (1986), Freitas Pacheco et al. (1986), Viadana & Freitas Pacheco (1985), Pottasch (1984), Reay et al. (1984), Kaler (1983), Preite-Martinez & Pottasch (1983), Martin (1981). Another method is the energy balance or Stoy method, which uses the ratio of the total flux in collisionally excited nebular lines to the Hβ flux. This method can be used even when the nebula is optically thin to ionizing radiation (see Preite-Martinez & Pottasch 1983). The most important disadvantage of this method is that measurements in the UV or IR are necessary to determine the total collisionally excited flux. Stoy temperatures (T_{Stoy}) have been taken from Preite-Martinez et al. (1989, 1991), Preite-Martinez & Pottasch (1983), with a few objects from Méndez et al. (1992), Kaler & Jacoby (1989), Golovatyi 1988, Pottasch (1984), and Kaler (1976).

Finally, reliable temperatures can also be obtained by the NLTE model atmosphere method (T_{MA}), where model atmospheres are fitted to observed H and He absorption line profiles (Méndez et al. 1981, 1983, 1985, 1988). We have used data from Méndez et al. (1992), Kudritzki & Méndez (1989), Kaler & Jacoby (1989), Golovatyi (1988), Preite-Martinez & Pottasch (1983), and Pilyugin et al. (1979).

Figure 1 shows correlations involving the different stellar temperatures. The well-known discrepancy between T_z(HI) and T_z(HeII) is seen in fig. 1c, and T_z(HeII) appears to be on average 20% larger than T_z(HI) for CSPN with temperatures below 125000 K. Above this temperature the discrepancy disappears (cf. Stanghellini et al. 1993; Gleizes et al. 1989). Such behaviour is consistent with the idea that these nebulae are optically thick in the He^+ Lyman continuum, but thin in that of H^o. On the other hand, for low temperatures ($T_* < 50000K$), where He II Zanstra temperatures are inadequate, only very few stars are included, which are further well correlated with the remaining temperature determinations.

Figure 1 shows a reasonable agreement of the Zanstra He II temperature with the Stoy (cf. Preite-Martinez et al. 1991) and model atmosphere temperatures, although the latter includes only a small part of the sample. Therefore, we would not expect large discrepancies in the HR diagram from this source, so that most of it could be ascribed to the luminosity and distance scale. Given the observational and theoretical uncertainties inherent to each method and taking into account the poorer quality of the T_{Stoy} and T_{MA} correlation, we suggest that T_z(HeII) better represents the CSPN temperature, a conclusion that is supported by recent work (cf. Kaler & Jacoby 1991; Méndez et al. 1992).

3. Luminosities

The luminosities of the central stars of galactic PN are very uncertain, especially due to their dependence on the distance, which may be affected by errors of a factor 2 in average. In this paper we have adopted a statistical approach, so that we will attempt to show that there is a tendency for PN of different types to occupy different regions on the HR diagram.

In order to obtain the stellar luminosities, we have adopted a linear approximation to the relation between the bolometric correction and the logarithm of the stellar temperature derived from NLTE model atmospheres:

$$BC = 27.462 - 6.8144 \log T_* \quad (1)$$

(Méndez 1994, private communication; for a comparison with semi-empirical bolometric corrections see also Code et al. 1976, and Howarth & Prinja 1989). The luminosities can then be obtained from

$$\log(L/L_\odot) = -0.4V + a \log T_* + 2\log d + 1.28E_{B-V} + b \quad (2)$$

where $a = 2.726$, $b = -11.08$. The distances d are in pc, and are listed by Maciel & Köppen (1994). They are basically statistical distances from Maciel (1984), supplemented by some recent individual determinations. In eq. (2) V is the visual magnitude basically taken from Tylenda et al. (1989, 1991) and Shaw & Kaler (1985, 1989), with a few objects from Peña et al., (1992), Kaler et al. (1990), Jacoby & Kaler (1989), Kaler & Jacoby (1989), Freitas Pacheco et al. (1986), Viadana & Freitas Pacheco (1985), Pottasch (1984), Reay et al. (1984), Kaler (1983), and Preite-Martinez & Pottasch (1983). We have taken the interstellar absorption as $A = 3.2E_{B-V}$, where the extinction coefficients E_{B-V} are basically from Cahn et al. (1992), supplemented by some results from Peña et al. (1992), Tylenda et al. (1991), Kaler et al. (1990), Shaw & Kaler (1989, 1985), Viadana & Freitas Pacheco (1985), and Kaler (1983). In this method the main sources of uncertainty in the luminosity are those affecting the stellar temperature T_* (implicit in the bolometric correction), the uncertainty in the distance scale and systematic errors in the magnitudes of the CSPN, in general due to the difficulty of separation of stellar and nebular continua.

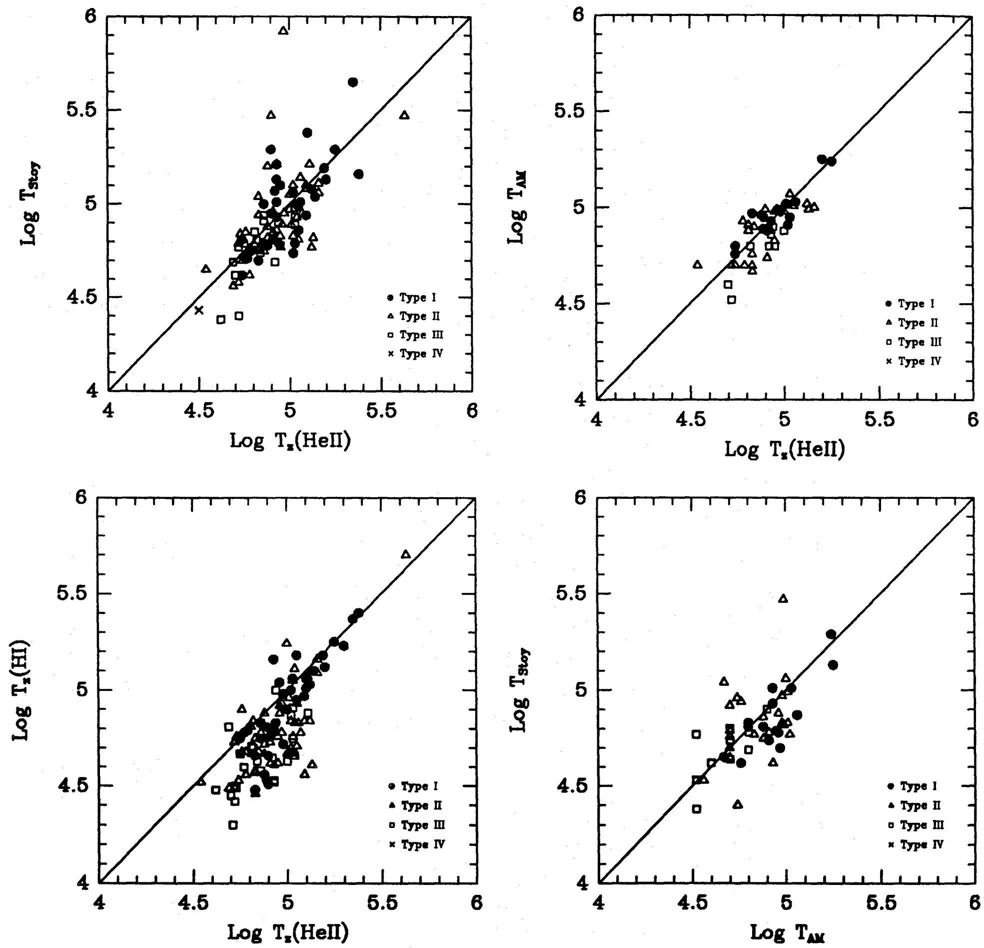

Fig. 1. Correlations involving Stoy, Zanstra and model atmosphere temperatures

According to the original sources, the estimated average uncertainties in the adopted stellar parameters are $\sigma[\log F(H\beta)] \simeq 0.02$, $\sigma(V) \simeq 0.20$, and $\sigma(E_{B-V}) \simeq 0.05$. Therefore, the estimated average uncertainties in the adopted temperatures and luminosities are $\sigma(\log T) \simeq 0.06$ and $\sigma[\log(L/L\odot)] \simeq 0.5$, respectively (cf. Maciel et al. 1990; Peña et al. 1992; Preite-Martinez 1990). This roughly corresponds to a 15% uncertainty in the temperatures and a factor of 2-3 in the luminosity.

4. The HR diagram

The main results are shown in fig. 2. Evolutionary tracks from Shaw & Kaler (1989) are also shown. These include tracks from Schönberner (1983, 0.546, 0.565, 0.598 and 0.644 M⊙); Paczyński (1971, 0.8 and 1.2 M⊙, scaled by Shaw 1989); Shaw (1989, 1.4 M⊙, estimate). Typical error bars are shown in the lower right corner of the diagrams. As previously mentioned, the main source of error lies in the distance scale, which translates directly to the luminosities. A comparison of the distances adopted here (Maciel 1984; Maciel & Köppen 1994) with recently published distances (cf. Cahn et al. 1992) indicates that the present results are not sensibly altered provided the whole PN sample is considered.

The first striking feature of the observed HR diagram is the large spread of points, indicating a large range in progenitor masses. The figures appear to be consistent, in that the majority of CSPN studied are confined within the region delimited by the 0.545 and 1.40 M⊙ post-AGB tracks. Moreover, most objects are concentrated around the intermediate ($\simeq 0.8 M_\odot$) and low ($\simeq 0.6 M_\odot$) mass stars, with comparatively few objects near the larger ($1.2 - 1.4 M_\odot$) mass tracks. This is to be expected, as the evolutionary times of the latter can be shorter by a factor $\simeq 100$, so that few objects can be observed on the tracks (cf. Preite-Martinez 1990; Kaler 1985).

Although the position of each object in the diagrams is uncertain, and may change according to the method used, the CSPN classified as Peimbert's type I show a tendency to fall in a region to the left and above the remaining objects, corresponding to the larger core mass stars, confirming thus the underlying idea of the Peimbert (1978) classification scheme, that is, larger masses imply in general larger N/O and He/H enhancements. This is particularly true in the plots of $T_z(HeII)$ (fig. 2d), which we consider as the most accurate temperature determinations. In this respect our results are in agreement with previous findings on type I PN reported by Peimbert (1990) and Pottasch (1989).

On the other hand, type II PN lie near the central and lower mass tracks, suggesting that their progenitor stars had comparatively smaller masses. Peimbert type III objects have interme-

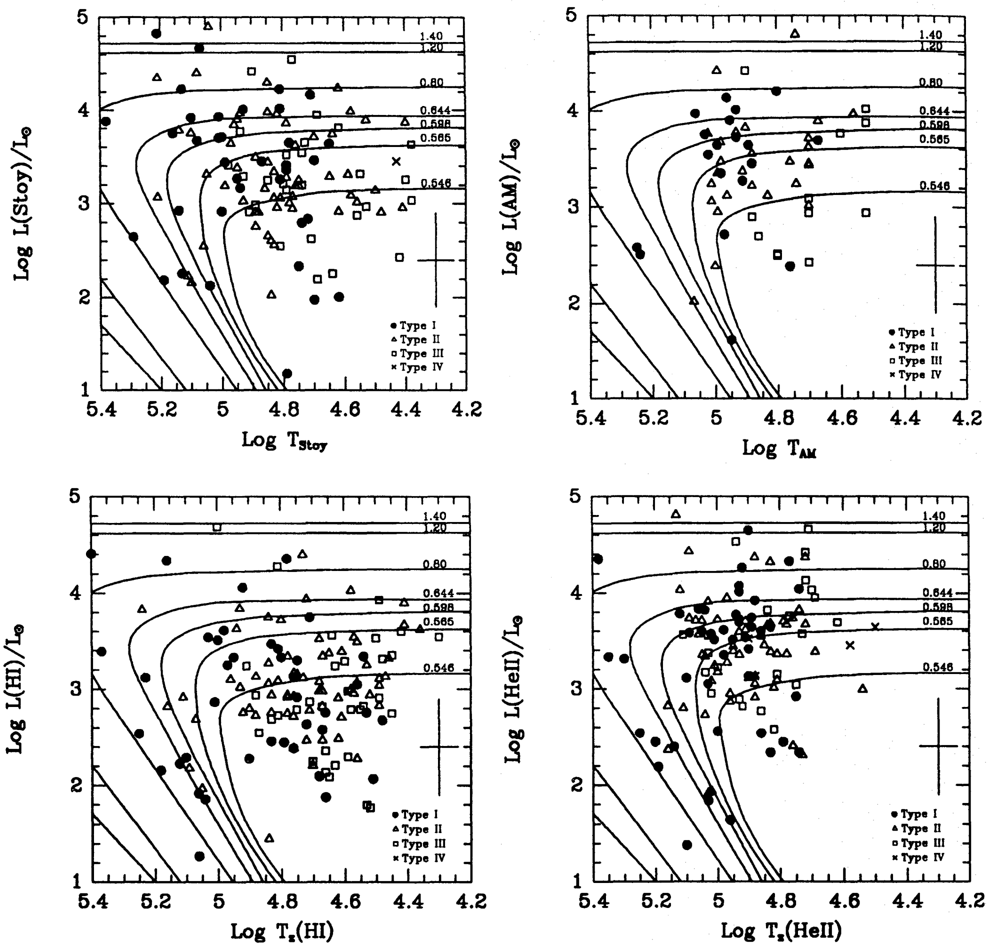

Fig. 2. HR diagrams for galactic planetary nebulae

diate and cool central stars, and show some tendency to present low luminosities.

The positions of type IV PN show some tendency to cluster near the 0.5 $M_\odot$ track, in agreement with the results by Peña et al. (1992). However, their small number and the uncertainties in the stellar and nebular parameters make their position uncertain.

As a general conclusion, the positions of the majority of CSPN in our sample are in good agreement with what is predicted for post-AGB stars with typical white dwarf masses (see e.g. Weidemann & Koester 1984). The choice of a different family of post-AGB evolutionary tracks would not significantly affect our results. Furthermore, taking into account two different set of distances (Cahn et al. 1992 and Zhang 1993), a similar result is obtained, in the sense that the precise location of individual nebulae on the HR diagram may change, but the average location of the different PN types remains the same.

Some preliminary comparisons can also be made of the results shown in figs. 2 and those by Stanghellini et al. (1993). Their B+BM objects (bipolar nebulae) seem to be preferentially associated with the large mass tracks, in agreement with our conclusions for type I PN, although their sample includes a small number of bipolars. On the other hand, the E (elliptical) nebulae are scattered throughout the diagram, similarly to our type II objects.

In view of the large uncertainties on the stellar luminosities, both for statistical and individual distances, it seems that other methods should be used in order to obtain more detailed information on the stellar masses (cf. Shaw 1989; Tylenda 1993). Schönberner (1981) suggested to plot evolutionary tracks in the M_V-time diagram. Nebular distances are necessary for this method to be applied. Méndez et al. (1981, 1983, 1985) have proposed an alternative method, involving the evolution on the log$g$-log$T$ diagram. The main advantage of this method is that it is independent of nebular distances; its main shortcoming is that there are model atmospheres for only a few CSPN, for which high resolution profiles of H and He lines are available.

Acknowledgements. We thank Dr. R. H. Méndez for supplying us with Eq. (1) and for some helpful comments on an earlier version ot this paper. This work was partially supported by FAPESP and CNPq.

References

Becker, S.A. & Iben, I. Jr.: 1979, ApJ 232, 831.
Becker, S.A. & Iben, I. Jr.: 1980, ApJ 237, 111.
Cahn, J.H., Kaler, J.B. & Stanghellini, L.: 1992, A&AS 94, 399.
Chiappini, C.M.L. & Maciel, W.J.: 1994, A&A (in press).
Ciotti, L., D'Ercole, A., Pellegrini, S. & Renzini, A.: 1991, ApJ 376, 380.

Code, A.D., Davis, J., Bless, R.C. & Hanbury Brown, R.: 1976, ApJ 203, 417.
Freitas Pacheco, J.A., Codina, S.J. & Viadana, L.: 1986, MNRAS 220, 107.
Gathier, R. & Pottasch, S.R.: 1989, A&A 209, 369.
Gleizes,F., Acker, A. & Stenholm, B.: 1989, A&A 222, 237.
Golovatyi, V.V.: 1988, Sov. Ast. 31, 379.
Howarth, I.D. & Prinja, R.K.: 1989, ApJS 69, 527.
Iben, I. Jr. & Renzini, A.: 1983, Ann. Rev. Astr. Ap. 21, 271.
Iben, I. Jr. & Truran, J.W.: 1978, ApJ 220, 980.
Jacoby, G.H & Kaler, J.B.: 1989, AJ 98, 1662.
Kaler, J.B.: 1976, ApJ 210, 843.
Kaler, J.B.: 1983, ApJ 271, 188.
Kaler, J.B.: 1985, Ann. Rev. Astr. Ap. 23, 89.
Kaler, J.B. & Jacoby, G.H.: 1989, ApJ 345, 871.
Kaler, J.B. & Jacoby, G.H.: 1991, ApJ 372, 215.
Kaler, J.B., Shaw, R.A. & Kwitter, K.B.: 1990, ApJ 359, 392.
Kudritzki, R.P. & Méndez, R.H.: 1989, IAU Symp. 131, ed. S. Torres-Peimbert, Kluwer, p. 273.
Kwok, S.: 1983, IAU Symp. 103, ed. D.R. Flower, Reidel, Dordrecht, p.293.
Maciel, W.J.: 1984, A&AS 55, 253.
Maciel, W.J.: 1994, A&SS (in press).
Maciel, W.J. & Chiappini, C.M.L.: 1994 A&SS (submitted).
Maciel, W.J. & Dutra, C.M.: 1992, A&A 262, 271.
Maciel, W.J. & Köppen, J.: 1994, A&A 282, 436.
Maciel, W.J., Freitas Pacheco, J.A. & Codina-Landaberry, S.J.: 1990, A&A 239, 301.
Martin, W.: 1981, A&A 98, 328.
Méndez, R.H., Kudritzki, R.P., Gruschinske, J. & Simon, K.P.: 1981, A&A 101, 323.
Méndez, R.H., Kudritzki, R.P. & Simon, K.P.: 1983, IAU Symp. 103, ed. D.R. Flower, Reidel, Dordrecht, p. 343.
Méndez, R.H., Kudritzki, R.P. & Simon, K.P.: 1985, A&A 142, 289.
Méndez, R.H., Kudritzki, R.P., Herrero, A., Husfeld, D. & Groth, H.G.: 1988, A&A 190, 113.
Méndez, R.H., Kudritzki, R.P., & Herrero, A.: 1992, A&A 260, 329.
Ortiz, R. & Maciel, W.J.: 1994, A&A (in press).
Paczyński, B.: 1971, Acta Astron. 21, 417.
Peimbert, M.: 1978, IAU Symp. 76, ed. Y. Terzian, Reidel, p. 215.
Peimbert, M.: 1990, Rep. Prog. Phys. 53, 1559.
Peña, M., Torres-Peimbert, S. & Ruiz, M.T.: 1992, A&A 265, 757.
Pilyugin, L.S., Sakhabullin, N.A. & Khromov, G.S.: 1979, Astrophysics 14, 665.
Pottasch, S.R.: 1981, Physical processes in red giants, ed. I. Iben, Jr., A. Renzini, Reidel, Dordrecht, p. 447.
Pottasch, S.R.: 1983, IAU Symp. 103, ed. D.R. Flower, Reidel, Dordrecht, p.391.
Pottasch, S.R.: 1984, Planetary Nebulae, Reidel, Dordrecht.
Pottasch, S.R.: 1989, IAU Symp. 131, ed. S. Torres-Peimbert, Kluwer, Dordrecht, p. 481.
Pottasch, S.R.: 1992, A&AR 4, 215.
Pottasch, S.R.: 1993, IAU Symp. 155, ed. R. Weinberger, A. Acker, Kluwer, Dordrecht, p. 449.
Preite-Martinez, A.: 1990, Chemical and dynamical evolution of galaxies, ed. F. Ferrini, J. Franco, F. Matteucci, ETS Editrice, Pisa, p. 93.
Preite-Martinez, A., Acker, A., Köppen, J. & Stenholm, B.: 1989, A&AS 81, 309.
Preite-Martinez, A., Acker, A., Köppen, J. & Stenholm, B.: 1991, A&AS 88, 121.
Preite-Martinez, A. & Pottasch, S.R.: 1983, A&A 126, 31.
Reay, N.K., Pottasch, S.R., Atherton, P.D. & Taylor, K.: 1984, A&A 137, 113.
Renzini, A.: 1979, Stars and Star Systems, ed. B.E. Westerlund, Reidel, Dordrecht, p. 155.
Renzini, A. & Voli, M.: 1981, A&A 94, 175.
Sabbadin, F.: 1986, AA 160, 31.
Shaw, R.A.: 1989, IAU Symp. 131, ed. S. Torres Peimbert, Kluwer, Dordrecht, p. 473.
Shaw, R.A. & Kaler, J.B.: 1985, ApJ 295, 537.
Shaw, R.A. & Kaler, J.B.: 1989, ApJS 69, 495.
Schönberner, D.: 1981, A&A 103, 119.
Schönberner,D.: 1983, ApJ 272, 708.
Schönberner, D. & Weidemann, V.: 1981, Physical processes in red giants, ed. I. Iben, Jr., A. Renzini, Reidel, Dordrecht, p. 463.
Stanghellini, L., Corradi, R.L.M. & Schwarz, H.E.: 1993, A&A 276, 463.
Stasinska, G. & Tylenda, R.: 1990, A&A 240, 467.
Tylenda, R.: 1993, IAU Symp. 155, ed. R. Weinberger, A. Acker, Kluwer, Dordrecht, p. 423.
Tylenda, R., Acker, A., Gleizes, F. & Stenholm, B.: 1989, A&AS 77, 39.
Tylenda, R., Acker, A., Stenholm, B., Gleizes, F. & Raytchev, B.: 1991, A&AS 89, 77.
Viadana, L. & Freitas Pacheco, J.A.: 1985, Rev. Bras. Fis. 15, 70.
Weidemann, V.: 1987, A&A 188, 74.
Weidemann, V. & Koester,D.: 1984, A&A 132, 195.
Zhang, C.Y.: 1993, ApJ 410, 239.

This article was processed by the author using Springer-Verlag TEX A&A macro package 1992.