GALACTIC DISTRIBUTION, RADIAL VELOCITIES AND MASSES OF PN

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1. INTRODUCTION

Since the discovery in 1779 of the first planetary nebula in the Lyra constellation by Antoine Darquier, the total number of objects known as PN has been steadily increasing. About 1600 PN have been identified in the Galaxy, although 10-20% are probably misclassified objects, which include H II regions, reflection nebulae, symbiotic stars, etc. (see for example Kohoutek, 1987; Acker et al., 1987; Stenholm and Acker, 1987).

Several hundred nebulae have been discovered in other systems, especially in Andromeda and in the Magellanic Clouds. In the Galaxy, however, the higher resolution achieved permits more detailed analysis and classification, so that PN are becoming increasingly useful as tools for the study of galactic structure.

Recent work show that 4-6 different types of PN can be identified, regarding their space distribution, kinematics and chemical composition (Peimbert, 1978; 1983; Peimbert and Serrano, 1980; Peimbert and Torres-Peimbert, 1983; Maciel and Faúndez-Abans, 1985; Faúndez-Abans and Maciel, 1987). A possible scheme of PN classification is given below, where the original types introduced by Peimbert (1978) have been extended to include a subdivision of the type II PN and the galactic centre objects as well.

Disk	Type I		pop. I old
	Type II	IIa	pop. I old ?
		IIb	pop. II disk ?
	Type III		pop. II intermediate
Halo	Type IV		pop. II extreme
Centre	Type V ?		pop. II extreme

S. Torres-Peimbert (ed.), Planetary Nebulae, 73–82.

Other somewhat different schemes may be found in the literature (cf. Greig, 1971; 1972; Kaler, 1983; Heap and Augensen, 1987). However, the classification proposed by Peimbert seems more suitable, as it contains criteria stemming from the three main sources of data, namely, spatial distribution, kinematics, and chemical composition. Generally speaking, type I PN belong to class B (Greig, 1971), whereas type II PN are of classes B and C.

In the present work, an attempt is made to review the recent results concerning the galactic distribution, radial velocities, and masses of galactic planetary nebulae. Especially related reviews appearing in this conference are presented by Kohoutek (new and reclassified PN), Lutz (distances), Clegg (compositions) and Phillips (formation rate). Previous reviews on the subject of galactic distribution of PN include Minkowski (1965), Perek (1968), Cahn (1968), Cahn and Wyatt (1978), Terzian (1980), and the more general works of Pottasch (1984) and Aller (1984). Radial velocities have been reviewed by Schneider et al. (1983), and the determination of masses of planetary nebulae has been treated recently by Pottasch (1980; 1983; 1984; 1987).

2. STATISTICS

Most known PN are within 5 kpc from the Sun, and correspond to a small fraction of the total number in the Galaxy. The estimate of statistical parameters concerning PN strongly depends on two different facts: (1) most observationally determined parameters are derived for the solar neighbourhood, and have to be extrapolated for the whole Galaxy; (2) the main conclusions depend heavily on the adopted distances, which remain poorly known. Although recent distance determinations using individual methods may reach accuracies of 30-50% (Pottasch, 1983; 1984), most statistical studies on PN are based in statistical methods, which may have uncertainties of a factor 2 for individual objects (Maciel, 1981a; 1984).

Table I shows a selection of the main results obtained in the past 15 years. Here n_v is the space density of PN in the solar neighbourhood, n_s is the density projected on the galactic plane, h is the scale height, χ is the PN formation rate, t is the lifetime of the PN stage, and n is the total number of PN in the Galaxy.

Most recent work on the statistics of PN tend to agree with each other, except for the much larger values of the space density and formation rate given by Ishida and Weinberger (1987), which are based on PN closer to the Sun than 500 pc. However, it seems that this result depends rather strongly on the distances adopted, which are uncertain in many cases. An average increase of 50% in the distances would be sufficient to bring the formation rate close to the remaining values of Table I. On the other hand, the results by Ishida and Weinberger (1987) are interesting in the sense that they call attention to the large, evolved nebulae, which contribute to the galactic population of PN, but are difficult to detect at large distances, due to their low surface brightness.

Table I - Statistics of planetary nebulae

	n_v (kpc^{-3})	n_s (kpc^{-2})	h (pc)	$10^3\ \chi$ ($kpc^{-3}\ yr^{-1}$)	t (yr)	n
Cahn and Kaler (1971)	50	13	90	3.2	16000	300000
Cahn and Wyatt (1976)	80	19	115	5.0	16000	38000
Alloin et al. (1976)						
Cahn and Kaler	50	13		3.1	16000	9000
Cudworth	15	6		0.6	24000	4000
Smith (1976)	150	30	100	11.0	14000	
Weidemann (1977)	36	11	150	1.8	20000	20000
Acker (1978)	48	13		3.0	16000	25000
Khromov (1979b)	430	170	200			190000
Maciel (1981a)	41	12	144	2.0	20000	31000
Daub (1982)	53	13	125	5.0		28000
Mallik (1982, 1983)	44	15	160	2.4	16000	28000
Amnuel et al. (1984)	117	26	130	4.6	25000	40000
Pottasch (1984)	50	25	250	2.0	30000	
Aller (1984)	50	12	120	2.0	30000	15000
Ishida and Weinberger (1987)	326	81	100	8.3		140000

The number of planetary nebulae in the Galaxy is not expected to be lower than $2\pi R^2 h\, n_v \simeq 10000$, where we have used R = 15 kpc, h = 140 pc and $n_v = 50\ kpc^{-3}$. An upper limit is more difficult to establish, and may be in excess of 10^5, depending on the adopted space density in the solar neighbourhood. Observations of PN in other galaxies may help solving this problem. Data on PN in the Local Group suggest that the specific number of PN is $k \simeq 1\text{-}4\ 10^{-7}\ M_\odot^{-1}$ (see for example Pottasch, 1984), which would imply n = 15000-60000, if the mass of the Galaxy is $M = 1.5\ 10^{11}\ M_\odot$.

From stellar evolution theory, the PN formation rate is expected to be similar to the rate at which stars in the mass range 1-5 M⊙ leave the main sequence, and to the white dwarf formation rate. As seen in Table I, this seems to be true for most recent estimates of the formation rate (cf. Phillips, 1987). On the other hand, the formation rate of cool giants, comprising Miras, OH/IR stars and other cool evolved giants is a factor of 3 lower than the PN rate. However, such rates are particularly uncertain, and a significative fraction of the white dwarfs may originate from AGB stars which do not produce PN, or even from stars not massive enough to climb the AGB (Drilling and Schonberner, 1985).

The rate at which stars leave the main sequence depends on the mass range of stars producing PN. Generally assumed to be 0.8-1.0 M⊙, the lower limit may reach 1.2-1.3 M⊙ (Wood and Cahn, 1977) or even higher values (Mallik, 1983; 1985). As for the upper limit, stars having masses between 5 and 8 M⊙ may also form PN (cf. Terzian, 1983), although such stars do not strongly affect the formation rate, as the IMF decreases sharply towards higher masses (Tinsley, 1978).

The mass ejected per year in a column perpendicular to the galactic plane is $(dM/dt)s = 2\text{-}4\ 10^{-10}\ M_\odot\ pc^{-2}\ yr^{-1}$ (Maciel, 1981a; Pottasch, 1984). Therefore, the PN, Miras, OH/IR stars, and other cool giants are the main responsible for the mass returned to the interstellar medium, corresponding about 30% to the PN alone (Alloin et al., 1976; Pottasch, 1984; Knapp and Wilcots, 1987). Explosive events such as supernovae and novae are comparatively less important, due to their lower frequency and higher volume of ocurrence. On the other hand, the disk PN have no influence on the injection of kinetic energy in the interstellar medium, which is essentially due to the supernovae, novae and hot stars.

3. GALACTIC DISTRIBUTION

The space distribution of planetary nebulae shows a pronounced concentration to the galactic plane (GP), although not as intense as in the case of H II regions (Figure 1). A general concentration towards the galactic centre (GC) is also observed, which is particularly true for the PN having small apparent sizes (angular diameters smaller than about 10 seconds of arc), which constitute the majority of the observed objects. PN with larger apparent sizes, typically having diameters greater than 50 seconds of arc, are not concentrated in the direction of the GC, and reach relatively high galactic latitudes, indicating that they are nearby objects. As reviewed by Pottasch (1984), most of the nebulae in the direction of the galactic centre lie actually close at it. Although a selection effect may artificially increase the number of PN in such direction, a reduction of discoveries in the direction of the anticentre is observed, so that a density gradient $dn/dr = 5\ 10^{-9}\ pc^{-3}\ kpc^{-1}$ can be estimated.

The latitude distribution of PN close to the GC shows relatively few objects with $b = 0$. Moreover, some differences exist between the number of objects above and below the GP, especially for $l = 0$, 1 and 2 degrees (Pottasch, 1984). Both effects are attributed to the inhomogeneity of the extinction near the galactic plane (see also Terzian, 1980).

Adopting a distance scale (Maciel, 1984), a distribution perpendicular to the GP can be obtained for about 600 PN, 47% of which have $|z| < 200$ pc. To avoid incompleteness effects, one could take into account only PN within 1 kpc from the Sun, which imply that 2/3 of the objects are within 250 pc from the plane (Pottasch, 1984).

Planetary nebulae of types I and II have a shorter scale height as compared to the remaining types, in agreement with the classification scheme presented in section 1. Given the relatively small sample of well classified objects, type II nebulae of both subtypes seem to have a similar distribution above the galactic plane, so that the main differences between them lie in the heavy-element abundances and progenitor masses.

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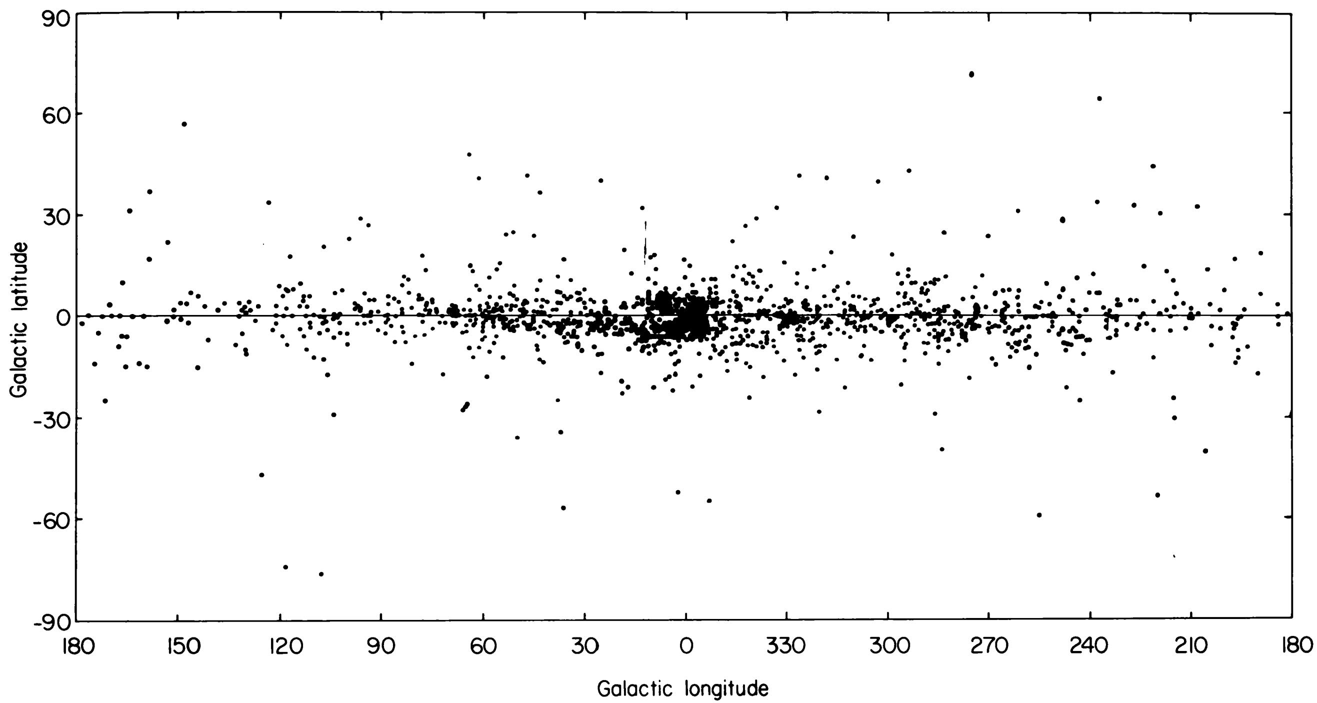

Figure 1. Galactic distribution of planetary nebulae.

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4. RADIAL VELOCITIES

The main progress in kinematical studies of PN, apart from their internal motions, lies in the determination of radial velocities. Accurate measurements of proper motions remain difficult, basically due to the large distances involved (Kaler, 1985). About a hundred objects have known proper motions (Khromov, 1979a; Kiosa and Khromov, 1979; Cudworth, 1974). Most old values are uncertain, and the new measurements imply a considerably large discrepancy in the distance scale (cf. Maciel, 1981a; Kaler, 1985).

The first determinations of radial velocities of PN were made by Keeler (1894), for 13 nebulae at a dispersion of 20 A/mm. The classical work of Campbell and Moore (1918) includes a list of radial velocities for 99 PN, which has been considerably extended by N. U. Mayall, R. Minkowski and others (see for example Minkowski, 1965).

Presently, some 550 PN have measured radial velocities (Acker, 1985), corresponding to about 35% of the known PN in the Galaxy. The main source of reference is the catalogue by Schneider et al. (1983), which lists heliocentric as well as LSR velocities for 524 PN. The catalogue is based on 102 different sources, including 920 velocity measurements and new observations for 19 nebulae. Most recent work is based on (1) spectroscopic techniques, especially using image tubes, (2) Fabry-Perot interferometry, and (3) observations of radio recombination lines.

The errors in the determination of radial velocities have been discussed by Schneider et al. (1983) and Acker (1985), and are lower than or equal to 10 km/s for half of the objects in the catalogue. For reciprocal dispersions up to 150 A/mm, the errors increase approximately linearly with the dispersion. Dispersions better than 100 A/mm produce, in average, errors smaller than 10 km/s (Schneider et al., 1983). As a consequence, variations of the radial velocities with periods from a few hours to a few days have been detected, and are used to investigate the binary nature of nuclei of some planetary nebulae (Augensen, 1985).

The galactic distribution of the radial velocities of PN relative to the LSR is shown in Figure 2. As discussed more than 20 years ago by Minkowski (1965), important differences exist between the distribution of the PN and the distribution of the galactic plane objects which participate in the circular rotation motion around the galactic centre. The curves show the limits for the radial velocities compatible with a recent galactic rotation curve (Clemens, 1985).

A large dispersion of about 140 km/s exists near the galactic centre (Pottasch, 1984), and several objects lie outside the curves, probably indicating non circular orbits. Apart from the galactic centre objects, the position of most nebulae in Figure 2 is in agreement with the curves of circular rotation for distances to the Sun smaller than 12 kpc, and an average dispersion of about 40 km/s. The galactic centre objects display a characteristic behaviour typical of population II systems, such as the globular clusters and RR Lyrae variables. The distribution of the OH/IR maser sources is also remarkably similar to the PN in the direction of the galactic centre, which is clearly seen by considering in Figure 2 only the PN with small angular dimensions (cf. Pottasch, 1984).

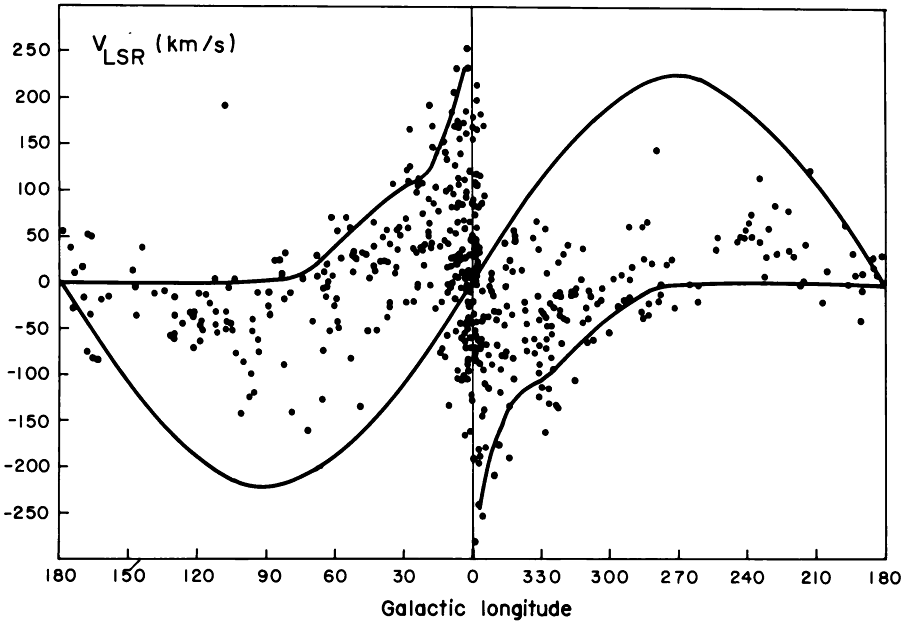

Figure 2. Distribution of radial velocities of PN according to their galactic longitudes.

The general interpretation of these distributions is that both PN and OH/IR objects in the galactic centre form a spherical population with high dispersion, superimposed on which there is a younger, flattened population, which approximately obeys the galactic rotation curve. According to the classification scheme given in section 1, PN of types I and II are expected to show smaller differences relative to the galactic rotation curve, which was found to be true for the more numerous type II objects (Maciel, 1987). This places the interesting possibility of determining the galactic rotation curve from a selected sample of PN. An obvious advantage of such procedure lies in the large number of known PN, their brightness, and accuracy of the radial velocity measurements. On the other hand, uncertainties in the distance scale and the lack of a large number of carefully classified objects have limited the applicability of this method. A tentative investigation along these lines has been made by Schneider and Terzian (1983), who found that the rotation curve does not fall after the solar circle, in agreement with independent determinations of the rotation curve based on the CO molecule (Blitz et al., 1980).

Also referring to the given classification scheme, it is interesting to comment on the halo type IV nebulae. Having radial velocities in excess of 100 km/s, these nebulae have less massive progenitors, do not participate in the galactic rotation motion, and present a strong underabundance in heavy-elements, showing therefore a distinctively population II behaviour.

5. MASSES

The problem of mass determination in planetary nebulae is closely related to the difficult problem of establishing a distance scale. To this date, no direct mass determinations exist for PN, so that one has to rely on indirect estimates which usually involve the distance. According to the Shklovsky method, popularly used through the seventies, the derived distances are $d \propto M^{2/5}\ \theta^{-3/5}\ F^{-1/5}$, where M is the ionized mass, θ is the angular radius, and F is the observed flux. Therefore, from this method one would obtain that $M \propto d^{5/2}$, so that an uncertainty in the distance scale of a factor two would imply an uncertainty of a factor 6 in the ionized mass.

The total masses of planetary nebulae are essentially in the range 0.1-0.5 $M_\odot$ (Pottasch, 1980; 1984; 1987; Maciel, 1981b; Mallik, 1982; Wood, 1987; Gathier, 1987; Barlow, 1987). The ionized mass can be a small fraction of the total mass for optically thin nebulae. Most determinations refer to the ionized masses, whereas the neutral material - essentially atomic and molecular H - has masses similar to the average ionized masses (Phillips and Pottasch, 1984; Kaler, 1985; Pottasch, 1987).

Due to the dependence with distance, few determinations of masses of PN have been made until recently. Early estimates featured Magellanic Cloud objects, whereas Perinotto (1975) used optical and radio data to estimate the masses of 40 galactic PN. However, several of the distances implicitly assumed by him are unnaceptable today (cf. Pottasch, 1980; Maciel, 1981b). More recently, Pottasch (1980) determined masses for 25 objects having independent distance estimates. It was shown that the ionized masses could vary over about 3 orders of magnitude, being strongly correlated with the electron density and the nebular size, suggesting that most objects are optically thick (see also Pottasch, 1983). Maciel (1981b) determined ionized masses and distances for 202 nebulae based on the empirical mass radius relationship developed by Maciel and Pottasch (1980), a procedure that was followed and modified later by others (see for example Daub, 1982). A larger set of distances, and hence masses, has been given by Maciel (1984). For these objects, an average uncertainty of a factor 3 was estimated, based on the masses of selected objects given by Pottasch (1980).

Recent work by Pottasch (1987) shows that the strong correlation between mass and size holds for PN in the galactic bulge and Magellanic Clouds, apart from a selected sample of nearby PN whose distances are well known. Although selection effects may play a role, it seems clear that a real correlation exists, supporting the conclusion that most objects are optically thick or do not deviate very much from this condition. The correlation shows some real scatter, however, which has been interpreted as to indicate the need of an additional parameter, such as the mass of the central star. In fact, the different tracks in the mass-radius plane can be interpreted as due to central stars with different luminosities.

The objects of the galactic centre and Magellanic Clouds are from the sample of Gathier (1987) and Wood (1987), respectively, who have presented similar mass-radius correlations. It is interesting to notice that, in the radius interval 0.01-0.4 pc, the average masses of both samples do not deviate very much from the masses derived with the empirical relationship of Maciel and Pottasch (1980).

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References

Acker, A. 1978, Astron. Astrophys. Suppl. **33**, 367
Acker, A. 1985, Bull. Inf. CDS Strasbourg n. 28, 5
Acker, A., Chopinet, M., Pottasch, S. R., Stenholm, B. 1987, Astron. Astrophys. Suppl. (in press)
Aller, L. H. 1984, Physics of thermal gaseous nebulae, Reidel
Alloin, D., Cruz-González, C., Peimbert, M. 1976, Astrophys. J. **205**,74
Amnuel, P. R., Guseinov, O. H., Novruzova, H. I., Rustamov, Yu. S. 1984, Astrophys. Space Sci. **107**, 19
Augensen, H. J. 1985, Monthly Notices Roy. Astron. Soc. **213**, 399
Barlow, M. J. 1987, Monthly Notices Roy. Astron. Soc. **227**, 161
Blitz, L., Fich, M., Stark, A. A. 1980, IAU Symp. 87, ed. B. H. Andrew, Reidel, p. 213
Cahn, J. H. 1968, IAU Symp. 34, ed. D. E. Osterbrock, C. R. O'Dell, Reidel, p. 44
Cahn, J. H., Kaler, J. B. 1971, Astrophys. J. Suppl. **22**, 319
Cahn, J. H., Wyatt, S. P. 1976, Astrophys. J. **210**, 508
Cahn, J. H., Wyatt, S. P. 1978, IAU Symp. 76, ed. Y. Terzian, Reidel, p. 3
Campbell, W. W., Moore, J. H. 1918, Publ. Lick Obs. **13**, 75
Clegg, R. E. S. 1987, IAU Symp. 131, ed. S. Torres-Peimbert, Reidel
Clemens, D. P. 1985, Astrophys. J. **295**, 422
Cudworth, K. M. 1974, Astron. J. **79**, 1384
Daub, C. T. 1982, Astrophys. J. **260**, 612
Drilling, J. S., Schonberner, D. 1985, Astron. Astrophys. **146**, L23
Faúndez-Abans, M., Maciel, W. J. 1987, Astron. Astrophys. (in press)
Gathier, R. 1987, Late Stages of Stellar Evolution, eds. S. Kwok, S. R. Pottasch, Reidel, p. 371
Greig, W. E. 1971, Astron. Astrophys. **10**, 161
Greig, W. E. 1972, Astron. Astrophys. **18**, 70

Heap, S. R., Augensen, H. J. 1987, Astrophys. J. 313, 268
Ishida, K., Weinberger, R. 1987, Astron. Astrophys. 178, 227
Kaler, J. B. 1983, IAU Symp. 103, ed. D. R. Flower, Reidel, p. 245
Kaler, J. B. 1985, Ann. Rev. Astron. Astrophys. 23, 89
Keeler, J. E. 1894, Publ. Lick Obs. 3, 161
Khromov, G. S. 1979a, Astrofizika 15, 269
Khromov, G. S. 1979b, Astrofizika 15, 445
Kiosa, M. N., Khromov, G. S. 1979, Astrofizika 15, 105
Knapp, G. R., Wilcots, E. M. 1987, Late Stages of Stellar Evolution, eds. S. Kwok, S. R. Pottasch, Reidel, p. 171
Kohoutek, L. 1987, IAU Symp. 131, ed. S. Torres-Peimbert, Reidel
Lutz, J. H. 1987, IAU Symp. 131, ed. S. Torres-Peimbert, Reidel
Maciel, W. J. 1981a, Astron. Astrophys. 98, 123
Maciel, W. J. 1981b, Astron. Astrophys. Suppl. 44, 123
Maciel, W. J. 1984, Astron. Astrophys. Suppl. 55, 253
Maciel, W. J. 1987, Late Stages of Stellar Evolution, eds. S. Kwok, S. R. Pottasch, Reidel, p. 391
Maciel, W. J., Faúndez-Abans, M. 1985, Astron. Astrophys. 149, 365
Maciel, W. J., Pottasch, S. R. 1980, Astron. Astrophys. 88, 1
Mallik, D. C. V. 1982, Bull. Astron. Soc. India 10, 73
Mallik, D. C. V. 1983, IAU Symp. 103, ed. D. R. Flower, Reidel, p. 424
Mallik, D. C. V. 1985, Astrophys. Lett. 24, 173
Minkowski, R. 1965, Galactic Structure, ed. A. Blaauw, M. Schmidt, Un. of Chicago, p. 321
Peimbert, M. 1978, IAU Symp. 76, ed. Y. Terzian, Reidel, p. 215
Peimbert, M. 1983, II Advanced School of Astrophysics, IAGUSP
Peimbert, M., Serrano, A. 1980, Rev. Mexicana Astron. Astrofís. 5, 9
Peimbert, M., Torres-Peimbert, S. 1983, IAU Symp. 103, ed. D. R. Flower, Reidel, p. 233
Perek, L. 1968, IAU Symp. 34, ed. D. E. Osterbrock, C. R. O'Dell, Reidel, p. 9
Perinotto, M. 1975, Astron. Astrophys. 39, 383
Phillips, P. 1987, IAU Symp. 131, ed. S. Torres-Peimbert, Reidel
Phillips, J. P., Pottasch, S. R. 1984, Astron. Astrophys. 130, 91
Pottasch, S. R. 1980, Astron. Astrophys. 89, 336
Pottasch, S. R. 1983, IAU Symp. 103, ed. D. R. Flower, Reidel, p. 391
Pottasch, S. R. 1984, Planetary Nebulae, Reidel
Pottasch, S. R. 1987, Torino Workshop
Schneider, S. E., Terzian, Y. 1983, Astrophys. J. 274, L61
Schneider, S. E., Terzian, Y., Purgathofer, A., Perinotto, M. 1983, Astrophys. J. Suppl. 52, 399
Smith, H. 1976, Astron. Astrophys. 53, 333
Stenholm, B., Acker, A. 1987, Astron. Astrophys. Suppl. 68, 51
Terzian, Y. 1980, Quart. J. Roy. Astron. Soc. 21, 82
Terzian, Y. 1983, IAU Symp. 103, ed. D. R. Flower, Reidel, p. 487
Tinsley, B. M. 1978, IAU Symp. 76, ed. Y. Terzian, Reidel, p. 341
Weidemann, V. 1977, Astron. Astrophys. 61, L27
Wood, P. R. 1987, Late Stages of Stellar Evolution, eds. S. Kwok, S. R. Pottasch, Reidel, p. 197
Wood, P. R., Cahn, J. H. 1977, Astrophys. J. 211, 499