PLANETARY NEBULAE: THEIR EVOLUTION AND ROLE IN THE UNIVERSE
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PN and galactic chemical evolution

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Abstract. Recent applications of PN to the study of galactic chemical evolution are reviewed, such as PN and stellar populations, abundance gradients, including their space and time variations, determination of the He/H radial gradient and of the helium-to-metals enrichment ratio, and the [O/Fe] $\times$ [Fe/H] relation in the solar neighbourhood and in the galactic bulge.

1. Introduction

Chemical evolution models must satisfy a series of observational constraints, such as the metallicity distribution, the age-metallicity relation, the existence of abundance gradients and their spatial and temporal variations.

Planetary nebulae have an important role in the establishment of some of these constraints. Basically, two classes of elements can be considered. First, elements such as He and N, which are clearly affected by the stellar evolution. Second, most of the heavier elements, such as S and Ar, which are probably unaltered during the evolution of the PN progenitor star, so that the nebular abundances of these elements are essentially the same as the interstellar abundances at the time when the progenitor stars were formed.

In this paper, some recent results concerning the application of PN to the study of galactic chemical evolution are reviewed, including PN abundances and stellar populations, abundance gradients and their variations, the He/H radial gradient, the helium-to-metals enrichment ratio, and the determination of the [O/Fe] $\times$ [Fe/H] relation in the solar neighbourhood and in the galactic bulge. Some recent related reviews are Maciel (1997; 2000a).

2. PN and Stellar Populations

In the framework of the classification scheme originally proposed by Peimbert (1978), PN can be classified into five types: Type I are disk objects with relatively massive progenitors; Type II are disk objects with average mass progenitors; Type III are thick disk objects, kinematically detached; Type IV are halo objects, and Type V are bulge nebulae. The main criteria used in this classification scheme are the nebular abundances, the average distance z to the galactic plane, and the peculiar radial velocity Δv. Morphological aspects have also some connection with the different types as discussed by Stanghellini (this volume).

Average values of the abundances are given by Maciel (2000a; see also Costa et al. 1996). From such data, it can be concluded that the He/H ratio increases in the disk along the sequence III–II–I, similarly to N/H, S/H, Ar/H and Cl/H. For O/H and Ne/H, there is an increase from Type III to Type II, but the average abundances of Type I PN are not clearly higher than for Type II, which may be partially due to ON cycling in the progenitor stars.

The abundances relative to oxygen of the elements Ne, S, Ar, and Cl can be considered as representative of the interstellar medium at the time of formation of these stars. Except for halo PN, all objects have essentially constant ratios, a result that has been confirmed for S, Ne and Ar for galactic and extragalactic HII regions (Henry & Worthey 1999).

3. Abundance Gradients from PN

The magnitude of the abundance gradients can be derived from a number of different sources, such as HII regions, PN, supernova remnants, and several types of stars, such as B stars, open cluster stars and cepheids (Henry & Worthey 1999; Smartt 2000). Average values are $d\log(\mathrm{O/H})/dR \simeq -0.06$ to -0.07 dex/kpc, with an uncertainty of about 0.02 dex/kpc.

Recent work on photoionized nebulae have established the presence of gradients for O/H and other elements such as N/H, S/H, Ne/H and Ar/H (see for example Maciel 1997; 2000a). Similar gradients are also observed in spiral galaxies (see for example Ferguson, Gallagher & Wyse 1998).

Stellar data based on O and B stars have been more controversial, but most recent determinations imply gradients of the same order as the one derived from photoionized nebulae (Rolleston et al. 2000). Data on cepheid variables should in principle agree with the B star results, which is confirmed by a recent analysis by Caputo et al. (2001), but a flatter gradient and/or a discontinuity around 10 kpc is suggested from the high resolution data by Andrievsky et al. (2002).

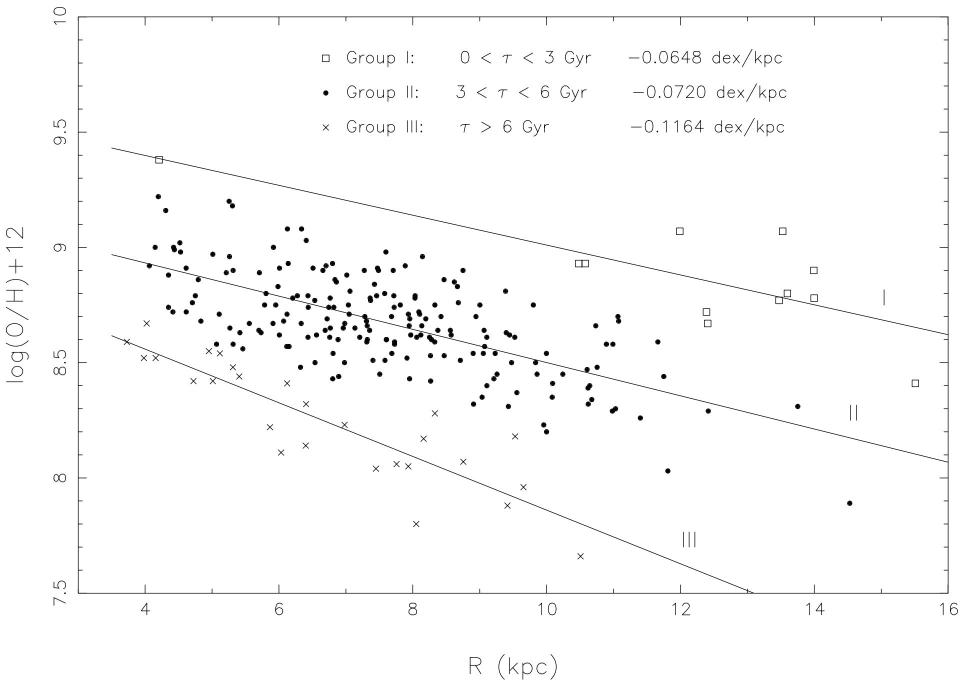
The most detailed work on abundance gradients from PN is that of Maciel & Quireza (1999), who have increased and updated the sample by Maciel & Köppen (1994) and studied gradients of the ratios O/H, Ne/H, S/H and Ar/H. Results show that linear fits to the gradients are -0.058, -0.036, -0.077, and -0.051 dex/kpc for O/H, Ne/H, S/H and Ar/H, respectively.

From the study of Maciel & Quireza (1999), some evidence is found for a flattening of the gradients at large radial distances, especially for the O/H and S/H ratios. However, there are very few nebulae at distances $R > 12$ kpc, so that these results cannot be considered as definitive. Preliminary results of a project to derive abundances for PN in the anticentre direction (Costa, Maciel & Uchida, this volume) suggest that the flattening is real. Some flattening in the observed gradients has been obtained in some recent work on HII regions (cf. Vílchez & Esteban 1996), but regarding the stellar data, current results reported by Smartt (2000) apparently show no evidences of flattening up to 16 kpc from the galactic centre.

The time variation of the abundance gradients is still poorly known. The best determined gradient from Type II PN, which is that of O/H, is similar to the average value derived from the younger population of HII regions and hot stars, within the uncertainties. Earlier work by Maciel & Köppen (1994) suggested that Type III PN show flatter gradients than Type II PN, but part of this may be due to orbital diffusion. On the basis of these results, Maciel and Quireza (1999) have made a rough estimate of the average steepening rate as -0.004 dex kpc^{-1} Gyr^{-1}. An update of this estimate, taking into account HII regions, B stars and Type II PN leads to a lower value, -0.002 dex kpc^{-1} Gyr^{-1}. Although this result is clearly uncertain, it shows that any time variation in the gradients is probably small, so that the possibility of a constant gradient cannot be ruled out, at least for the last 5 Gyr, which approximately corresponds to the ages of the majority of the PN central stars. This agrees with the fact that most non-barred spiral galaxies have similar gradients, so that their gradients have probably not changed very much during their evolution.

We have taken into account the PN sample of Maciel and Köppen (1994) and Maciel and Quireza (1999), supplemented by about 40 PN near the anticentre direction from Costa et al. (this volume). For these objects, we have estimated [Fe/H] metallicities and individual ages, according to the [O/H] $\times$ [Fe/H] and the age-metallicity relations given by Edvardsson et al. (1993). As a result, relatively accurate gradients can be derived for PN in a given age group, which in principle allows for a better determination of the time evolution of the gradients as compared with previous estimates based entirely on the Peimbert types. In fact, there is some evidence for some mass – and therefore age – overlapping for a given Peimbert type (see for example Peimbert and Carigi 1998), so that the determination of individual ages probably gives a more accurate gradient variation. Preliminary results are shown in figure 1. In figure 1a, O/H gradients are shown for PN with ages under 3 Gyr (squares), between 3 and 6 Gyr (solid dots) and higher than 6 Gyr (crosses). Figure 1b shows a similar plot, except that the age groups are: under 4 Gyr (squares), between 4 and 5 Gyr (solid dots) and higher than 5 Gyr (crosses). Different definitions of the age groups are made in order to obtain groups of similar sizes. It can be seen that younger PN show flatter gradients. This tendency is clear in both figures, and is particularly strong for Groups III and II (figure 1a) and Groups II and I (figure 1b). In figure 1a, the gradients have flattened from -0.11 dex/kpc to -0.06 dex/kpc, while for figure 1b we have -0.09 dex/kpc for the oldest group and -0.05 dex/kpc for the youngest one. Overall, once could conclude that the gradients flattened out from -0.11 dex/kpc to -0.06 dex/kpc in about 9 Gyr, or from -0.08 dex/kpc to -0.06 dex/kpc in the last 5 Gyr only. From these data, we can estimate an average flattening rate of 0.002 dex kpc^{-1} Gyr^{-1} (figure 1a) or a rate of about 0.004 dex kpc^{-1} Gyr^{-1}, considering the last 5 Gyr, suggesting that the O/H gradient has not changed more than about 30% in average during the last few Gyr. At earlier times, however, our results are consistent with a steeper rate, although the corresponding uncertainties are larger.

Spatial and time variations of the gradients are extremely important as constraints to chemical evolution models. For example, recent classical models predict similar gradients as observed, showing some flattening near the outer Galaxy and a time steepening (Matteucci 2000), while multiphase models (Mollá et al. 1997) generally produce gradientes that were steeper in the past. Hou et al. (2000) derived a flattening rate for O/H of about 0.004 dex kpc^{-1} Gyr^{-1} for the last 10 Gyr, in remarkable agreement with our recent results.



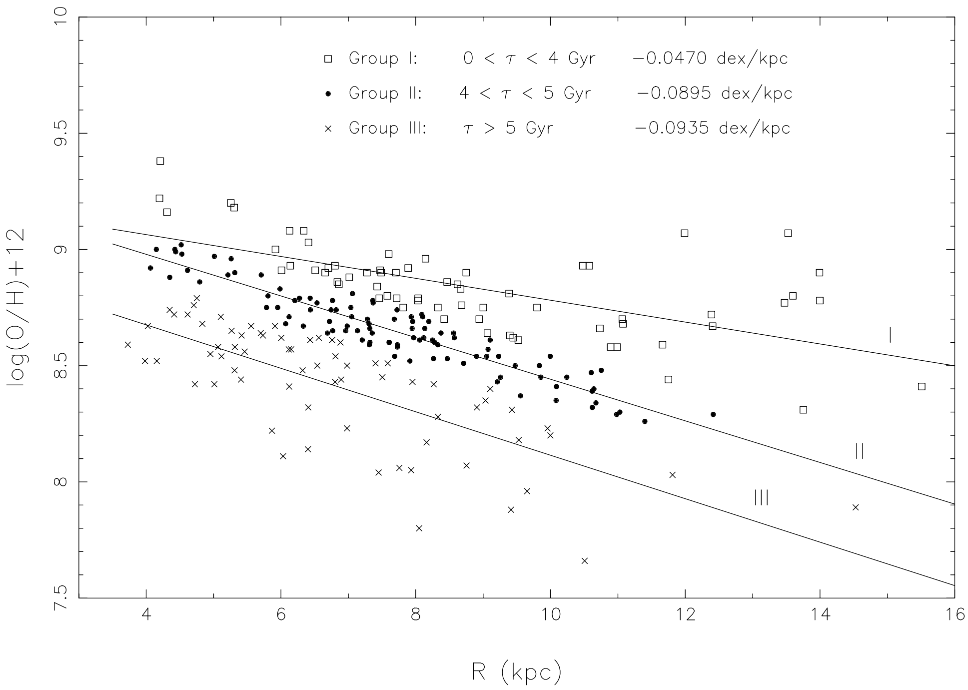


Figure 1. Time variation of the O/H gradient from PN.

4. He: PN and Chemical Evolution

In order to use PN to investigate the chemical evolution of ^{4}He in the Galaxy, it is necessary to take into account the He contamination by the progenitor stars. In some previous work, this contamination has been introduced in an approximate way (Chiappini and Maciel 1994). Maciel (2000b; 2001a) has used recent determinations of helium yields in order to estimate the ^{4}He contamination for a sample of disk planetary nebulae. Taking into account some relationships involving the nebular abundances, the central star mass and the stellar mass on the main sequence, such contamination can be individually determined. In practice, the pregalactic He abundance Y_p is not sensitive to the PN data, as these nebulae are more metal rich than the dwarf galaxies and blue compact galaxies usually considered to determine Y_p, so that this parameter is essentially fixed by these objects. As a consequence, the pregalactic value has been taken as a parameter, with the values $Y_p = 0.23$ and $Y_p = 0.24$.

The recent analysis by Maciel (2000b, 2001a) has shown that the He/H gradient is essentially flat, irrespective of the contamination corrections, that is, the correction procedure simply shifts the He abundances downwards, without affecting the slope. The amount by which the abundances are reduced depends somewhat on the input yields, being typically in the range Δ(He/H)$\sim$ $0.006 - 0.012$. The main conclusion is that it is unlikely that any He/H radial gradient could be presently detected from PN. These results are used in order to estimate an upper limit to the He/H gradient, which is given by $|d(\mathrm{He/H})/dR| <$ $0.004\ \mathrm{kpc}^{-1}$, corresponding to $d\log(\mathrm{He/H})/dR \simeq -0.02$ dex/kpc. Therefore, the existence of a He/H radial gradient similar to the O/H gradient is extremely unlikely, and any He/H gradient should be lower than the O/H gradient by at least a factor of 3. Such a conclusion is in good agreement with the small gradients recently derived for galactic HII regions by Esteban et al. (1999) and with recent chemical evolution models (Chiappini and Matteucci 2000).

The helium to metals enrichment ratio $\Delta Y/\Delta Z$ is an important parameter in the chemical evolution of the Galaxy, and is usually determined from HII regions and HII galaxies. Maciel (2000b, 2001a) has taken into account all PN in the sample by Maciel and Quireza (1999) having metal abundances up to $10^6\,\mathrm{O/H} \simeq 700$, which corresponds approximately to the solar value, $\epsilon(\mathrm{O}) =$ $\log(\mathrm{O/H}) + 12 = 8.83$. The relation $Z \simeq 25$ O/H was adopted, where O/H is the oxygen abundance by number relative to hydrogen. Results indicate that the correction procedure not only reduces the average He abundances and the derived $\Delta Y/\Delta Z$ ratio, but also decreases the uncertainty of the derived slopes. The average results are $2.8 < \Delta Y/\Delta Z < 3.6$ for $Y_p = 0.23$ and $2.0 < \Delta Y/\Delta Z <$ 2.8 for $Y_p = 0.24$, with a good agreement with independently derived ratios (cf. Maciel 2000b, 2001a).

5. Oxygen and Iron Abundances

The [O/Fe] $\times$ [Fe/H] ratio is one of the basic relationships in the study of the chemical evolution of the Galaxy, linking the main metallicity indicators and stressing the different contribution of Type II and Type Ia supernovae. Chemical evolution models usually predict different [O/Fe] $\times$ [Fe/H] relationships for the galactic disk and bulge, reflecting the different rates at which these elements are produced in different scenarios, being usually faster in the bulge. Recently, some discrepancy has been observed between different sets of observational data and among theoretical models regarding the value of the [O/Fe] abundance ratio at low metallicites (see Maciel 2001b,c for references). Generally speaking, studies based on the [OI] forbidden line doublet at 6300 Å, 6364 Å lead to [O/Fe] $\simeq 0.5$ for [Fe/H] $\simeq -2$, showing a plateau in the [O/Fe] ratio at low metallicities; on the other hand, oxygen abundances from the OI infrared lines and some recent studies based on ultraviolet OH bands in metal-poor subdwarfs reach a much higher ratio, [O/Fe] $\simeq 1$ at low metallicities, with an essentially constant slope of about -0.30 to -0.40 for the [O/Fe] $\times$ [Fe/H] relation.

Some contribution to the understanding of this problem can be obtained by the analysis of the radial abundance gradients in the galactic disk. Apart from O/H gradients, [Fe/H] gradients can also be derived, especially from open cluster stars. Maciel (2001b,c) has taken both sets of data into account and derived an independent [O/Fe] $\times$ [Fe/H] relation appropriate to the galactic disk, roughly at metallicities [Fe/H] ≥ -1.5.

Assuming that the O/H and [Fe/H] gradients apply essentially to the same region in the disk and adopting average linear gradients $d\log(\mathrm{O/H})/dR \simeq -0.07$ dex/kpc and $d[\mathrm{Fe/H}]/dR \simeq -0.085$ dex/kpc, Maciel (2001b,c) obtained a relation given by $[\mathrm{O/Fe}] = \alpha + \beta\ [\mathrm{Fe/H}]$, where $\alpha \simeq 0.098$ and $\beta \simeq -0.176$. This can be seen in Figure 2 (solid line), which shows the [Fe/H] $\times$ log(O/H) + 12 relationship, where $[\mathrm{Fe/H}] = \gamma + \delta\,[\log(\mathrm{O/H}) + 12]$, with $\delta = 1/(1+\beta) \simeq 1.214$ and $-\gamma/\delta = \alpha + [\log(\mathrm{O/H})_\odot + 12]$, or $\gamma \simeq -10.841$. Figure 2 is particularly useful for photoionized nebulae such as HII regions and PN, for which the [Fe/H] abundance is usually difficult to obtain directly. In this case, an average relation could be used to estimate the expected [Fe/H] for a given O/H ratio. Also, if a determination of [Fe/H] is available, this relation could be used to estimate the amount of iron condensed in solid grains. The dotted line shows results of theoretical models by Matteucci et al. (1999), which predict a maximum [O/Fe] $\simeq 0.5$ and the dot-and-dashed line are models by Ramaty et al. (2000), which are consistent with higher [O/Fe] ratios at low metallicities. The figure also shows some representative observational data from several sources. It can be seen that the gradient data support the lower [O/Fe] regime, at least for metallicities larger than [Fe/H] $\simeq -1.5$. Extrapolating the solid line towards lower metallicities (broken line), we obtain an upper limit for the [O/Fe] ratio of 0.4 dex. Therefore, these results are consistent with a maximum [O/Fe] $\simeq 0.4$ for the galactic disk for metallicities as low as [Fe/H] $\simeq -1.5$.

The recent results by Cuisinier et al. (2000) and Costa & Maciel (1999) show that bulge PN have O/H abundances comparable with their disk counterparts, both regarding the highest oxygen abundances attained in the bulge and the metallicity range. Since underabundant nebulae are also present, these results suggest that the bulge contains a mixed population, so that star formation in the bulge spans a relatively wide time interval.

The PN metallicity distribution can be compared with the stellar abundance distributions, provided we are able to convert the measured nebular O/H abundances into the usual [Fe/H] metallicities. Direct measurements are of limited usefulness, in view of the depletion attributed to grain formation, but it is

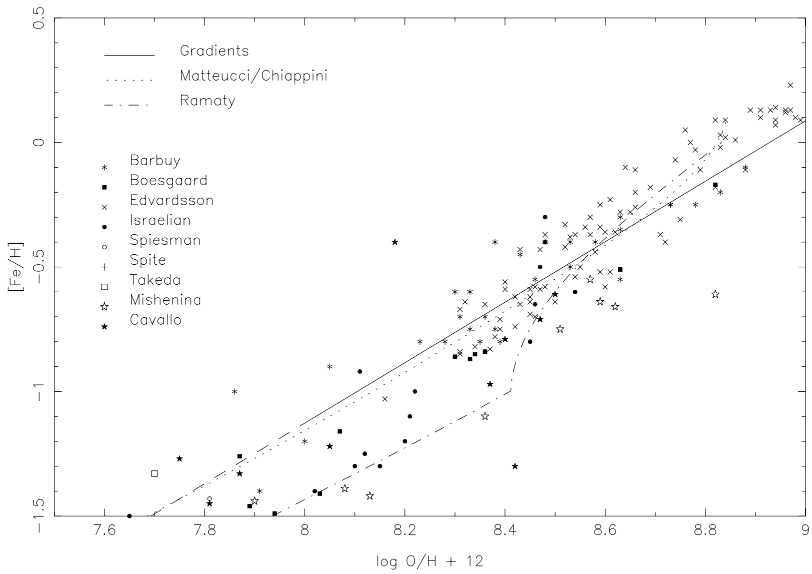


Figure 2. The [Fe/H] $\times$ log(O/H) relation in the galactic disk.

possible to convert O/H abundances into [Fe/H] metallicities using theoretical [O/Fe] $\times$ [Fe/H] relationships, as given by Matteucci et al. (1999). Maciel (1999) has derived the bulge PN [Fe/H] distribution, which can be compared with the metallicity distribution of bulge K giant stars in Baade's Window (McWilliam & Rich 1994) and with the distribution of bulge Mira variables (Feast & Whitelock 2000). It results that the PN distribution looks similar to the K giant distribution if the *solar neighbourhood* relation is adopted, but when the *bulge* relation is taken into account the derived distribution is displaced towards lower metallicities by roughly 0.5 dex. Maciel (1999) concludes that this discrepancy can be attributed to the uncertainties in the adopted [O/Fe] $\times$ [Fe/H] relationship for the bulge, which overestimates the [O/Fe] enhancement by 0.3 to 0.5 dex. Therefore, the [O/Fe] $\times$ [Fe/H] relation for the bulge is closer to the solar neighbourhood relation than implied by the theoretical models, which is equivalent of saying that the [O/Fe] ratio in the bulge reaches a maximum value of [O/Fe] ~ 0.5 at metallicities [Fe/H] $\simeq -2.0$.

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References

Andrievsky, S.M., Kovtyukh, V.V., Luck, R.E., Barbuy, B., Lépine, J.R.D., Bersier, D., Maciel, W.J., Klochkova, V.G., Panchuk, V.E., & Karpischek, R.U., 2002 A&A (in press)

Caputo, F., Marconi, M., Musella, I., & Pont, F. 2001, A&A, 372, 544

Chiappini, C., & Maciel, W.J. 1994, A&A, 288, 921

Chiappini, C., & Matteucci, F. 2000, in IAU Symp. 198, ed. L. da Silva, M. Spite, & J. R. de Medeiros, ASP, 540

Costa, R.D.D., Chiappini, C., Maciel, W.J., & Freitas Pacheco, J.A. 1996 A&AS, 116, 249

Costa, R.D.D., & Maciel, W.J. 1999, Ap&SS, 265, 327

Cuisinier, F., Maciel, W.J., Köppen, J., Acker, A., & Stenholm, B. 2000 A&A, 353, 543

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.F., & Tomkin, J. 1993, A&A, 275, 101

Esteban, C., Peimbert, M., Torres-Peimbert, S., & Garcia-Rojas, J. 1999, Rev. Mexicana Astron. Astrof., 35, 65

Feast, M., & Whitelock, P. 2000, in Chemical Evolution of the Milky Way, ed. F. Matteucci & F. Giovannelli (Dordrecht: Kluwer), 229

Ferguson, A.M.N., Gallagher, J.S., & Wyse, R.F.G. 1998, AJ, 116, 673

Henry, R.B.C., & Worthey, G. 1999, PASP, 111, 919

Hou, J.L., Prantzos, N., & Boissier, S. 2000, A&A, 362, 921

Maciel, W.J. 1997, in IAU Symp. 180, ed. H.J. Habing & H.J.G.L.M. Lamers (Dordrecht: Kluwer), 397

Maciel, W.J. 1999, A&A, 351, L49

Maciel, W.J. 2000a, in Chemical Evolution of the Milky Way, ed. F. Matteucci & F. Giovannelli (Dordrecht: Kluwer), 81

Maciel, W.J. 2000b, in IAU Symp. 198, ed. L. da Silva, M. Spite, & J. R. de Medeiros, ASP, 204

Maciel, W.J. 2001a, Ap&SS (in press)

Maciel, W.J. 2001b, New Astron. Rev., 45, 571

Maciel, W.J. 2001c, Rev. Mexicana Astron. Astrof. SC (in press)

Maciel, W.J., & Köppen, J. 1994, A&A, 282, 436

Maciel, W.J., & Quireza, C. 1999, A&A, 345, 629

Matteucci, F. 2000, in Chemical Evolution of the Milky Way, ed. F. Matteucci & F. Giovannelli (Dordrecht: Kluwer), 3

Matteucci, F., Romano, D., & Molaro, P. 1999, A&A, 341, 458

McWilliam, A., & Rich, R.M. 1994, ApJ, 91, 749

Mollá, M., Ferrini, F., & Díaz, A.I. 1997, ApJ, 475, 519

Peimbert, M. 1978, in IAU Symp. 76, ed. Y. Terzian (Dordrecht: Reidel), 215

Peimbert, M., & Carigi, L. 1998, in ASP Conf. Ser. 147, ed. D. Friedli, M.G. Edmunds, C. Robert & L. Drissen, 88

Ramaty, R., Scully, S.T., Lingenfelter,R.E., & Kozlovsky,B. 2000 ApJ, 534, 747

Rolleston, W.R.J., Smartt, S.J., Dufton, P.L., & Ryans, R.S.I. 2000, A&A, 363, 537

Smartt, S.J. 2000, in Chemical Evolution of the Milky Way, ed. F. Matteucci & F. Giovannelli (Dordrecht: Kluwer), 323

Vílchez, J.M., & Esteban, C. 1996, MNRAS, 280, 720