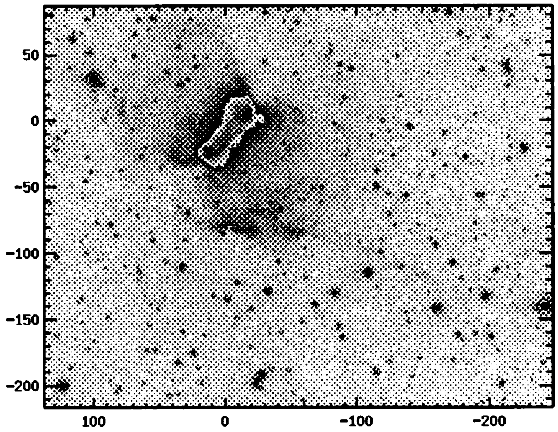
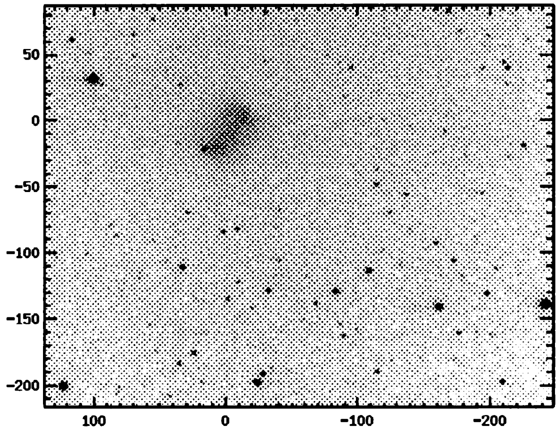
VII. PLANETARY NEBULAE IN THE GALACTIC CONTEXT

https://doi.org/10.1017/S0074180900131560 Published online by Cambridge University Press

Hα



[OIII]



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From: "The IAC Morphological Catalog of Northern Galactic Planetary Nebulae", A. Manchado, M.A. Guerrero, L. Stanghellini, M. Serre-Ricart.

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ABUNDANCE GRADIENTS FROM PLANETARY NEBULAE IN THE GALACTIC DISK

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1. Introduction

Radial abundance gradients in the disks of spiral galaxies are made evident from observations of ionized nebulae (HII regions, planetary nebulae, and SNRs) and stars. They have been observed for several chemical elements, and their presence is an established fact, despite some inconsistencies in the results. Therefore, these gradients can be considered as an additional constraint to the chemical evolution models, as the age-metallicity relation or the metallicity distribution of the G-dwarfs.

Previous reviews on abundance gradients include Peimbert (1979, 1990, 1995), Pagel and Edmunds (1981), Díaz (1989), Dinerstein (1990), Pagel (1992), Esteban and Peimbert (1995), and Maciel (1996).

2. Abundance gradients in spiral galaxies

Radial gradients in spiral galaxies are well established for the ratios O/H, N/H and S/H, as measured in HII regions (Díaz 1989, Villa-Costas and Edmunds 1992). Earlier studies of galaxies like M33, M51, and M101 (Aller 1942, Searle 1971) showed that the ratio [OIII]/Hβ *increased* with the distance ρ to the centre of the galaxy. In order to explain this excitation gradient, it was assumed that the cooling rates were higher in the inner regions, so that the electron temperature was lower there, and the oxygen abundance was higher. This would explain the higher excitation seen in the outer HII regions, and predict an electron temperature gradient in the same direction as the excitation gradient. Later work developed and extended these ideas, and the general picture was confirmed by the detection of O/H and N/H gradients (cf. Dinerstein 1990). On the other hand, the

H. J. Habing and H. J. G. L. M. Lamers (eds.), Planetary Nebulae, 397–404.
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https://doi.org/10.1017/S0074180900131960 Published online by Cambridge University Press

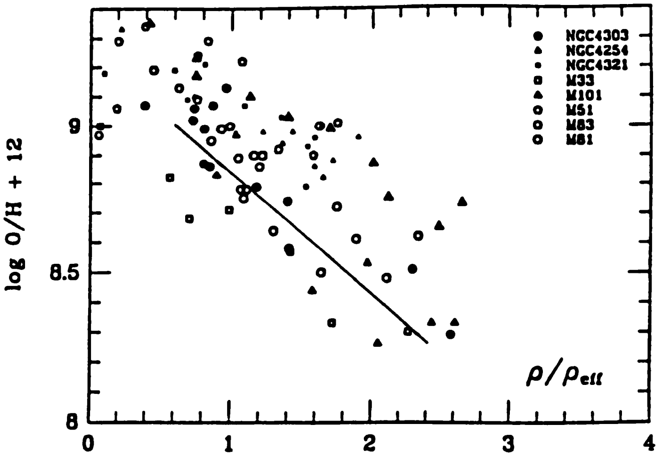

Figure 1. O/H gradients for spiral galaxies, adapted from Henry et al. (1994). The straight line represents the galactic gradient from type II PN.

application of shock modelling to spectrophotometric data of SNRs in M33 and M31 has revealed N/H and O/H abundance gradients similar to those derived from HII regions (Dopita et al. 1980, Blair et al. 1981).

Recently determined O/H gradients have been given by Zaritsky et al. (1994) and Kennicutt and Garnett (1996), with average slopes of −0.10 dex/kpc. It seems that all galaxy types display steep gradients, except pure barred spirals (Martin and Roy 1994). A recent work on environmental effects on abundance gradients in galaxies of the Virgo cluster led to the results shown in figure 1 for O/H (Henry et al. 1992, 1994). The abscissa the effective galaxy radius ρ_{eff}, that is, the radius at which half of the optical emission is contained. Filled symbols represent galaxies in the Virgo cluster, and open symbols are field spirals. The straight line represents PN data, and will be discussed later.

The shape of the gradients is still subject to discussion. Some flattening in the outer regions of the spiral disks has been proposed (Díaz 1989), but recent results on M33, M81, and M101 are consistent with an exponential gradient with constant slope (Henry and Howard 1995), so that the actual shape may vary for different galaxies.

3. The Galaxy: HII regions, stars, and SNRs

Evidences for large scale trends in the Galaxy are usually more difficult to understand than for nearby, face on spirals. The basic evidences for abundance gradients in the Galaxy come from direct oxygen abundances

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and indirect electron temperature determinations from galactic HII regions (Churchwell and Walmsley 1975). The classic reference is Shaver et al. (1983), who found gradients from radio recombination line measurements for O/H, N/H and Ar/H amounting to about -0.06 dex/kpc. More recent work on the oxygen gradient from HII regions (cf. Edmunds 1992) shows that the derived gradient is of the order of -0.07 dex/kpc. The analysis of HII regions in the anticentre region is especially important, and recent work in the radio, infrared and optical spectral regions (Simpson et al. 1995, Esteban and Peimbert 1995, Vilchez and Esteban 1996) shows some flattening for the O/H, N/H, and S/H gradients for $R \geq 12$ kpc.

Also for galactic supernova remnants, the application of shock modelling techniques shows the presence of S/H and N/H gradients compatible with those derived from HII regions (Binette et al. 1982).

Some information on galactic abundance gradients can also be obtained from stars, such as open cluster stars, associations, cepheid variables, supergiants, and B stars. Data from open cluster stars generally produce consistent results with HII regions (cf. Edmunds 1992, Janes 1995, Tosi 1995). Also, evidences for gradients are apparent from the very low metallicity cluster Dolidze 25 located at $R = 13.5$ kpc (Lennon et al. 1990), and from the observed Fe/H gradients in cepheids and supergiants (cf. Pagel 1992). On the other hand, results from B stars in young associations in a galactocentric distance range of about 7 kpc (Fitzsimmons et al. 1990, Rolleston et al. 1993) seem to indicate small or no measurable gradients. Similarly, flat O/H and N/H gradients are observed for main sequence B stars from LTE model atmospheres by Kaufer et al. (1994). However, these results apply to the *outer* Galaxy only ($R \geq 6$ kpc for $R_0 = 8.5$ kpc), so that they do not exclude a steeper gradient in the inner Galaxy, followed by some flattening near the anticentre. A similar analysis by Kilian-Montenbruck et al. (1994) shows some gradients for O, N, Ne and other elements in the range $5 < R$ (kpc) < 10, with lower values for larger galactocentric distances.

Regarding older solar neighbourhood stars, Nissen (1995) concludes for the existence of a radial gradient of about -0.1 dex/kpc. Some discrepancies are also apparent from deep surveys of red giants (Neese and Yoss 1988, Lewis and Freeman 1989). Some of these results may be explained by the time evolution of the gradients (section 5), but the general relation of the nebular and stellar gradients remains unclear.

4. The Galaxy: planetary nebulae

Evidences of abundance gradients from PN have been hampered in the past, basically due to the existence of a mixed population of planetary nebulae in the Galaxy and the lack of a reliable distance scale. Earlier work pointing

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to a measurable gradient includes D'Odorico et al. (1976), Aller (1976) and references therein. Kaler (1983) sees no compelling evidences for radial gradients, and suggested that they are a reflection of vertical gradients.

The first detailed determination of abundance gradients of the main chemical elements in galactic PN was given by Faúndez-Abans and Maciel (1986, 1987), who established that O, S, Ne and Ar have gradients similar to the HII region gradient. These results were confirmed by the determination of an electron temperature gradient of the order of 600 K/kpc from the same data, which was interpreted as a mirror image of the abundance gradients (Maciel and Faúndez-Abans 1985). This work was recently revised and expanded (Maciel and Köppen 1994; Maciel and Chiappini 1994), and the main results can be summarized as follows: all disk nebulae, which comprise Peimbert types I, II and III, display measurable gradients of the order of -0.04 to -0.07 dex/kpc. Bulge, or type V PN (cf. Maciel 1989) are excluded from this analysis, as their abundances are generally about $0.2 - 0.4$ dex lower than implied by the extrapolation of the disk gradients all the way to the bulge (cf. Ratag et al. 1992). The small differences in the measured gradients have been interpreted in terms of a chemical evolution model, for the elements that are *not* produced by the progenitors of the central stars, namely O, S, Ne, Ar, and Cl. According to these results, the gradients have become steeper with time, so that type I planetary nebulae have generally steeper gradients than type II (except for O and Ne), and these relative to type III. Therefore, the PN gradients that best resemble those of HII regions are derived from type I and II objects. This can be seen in figure 1, where we have included the type II PN gradient (straight line) from Maciel and Köppen (1994) along with the galaxies studied by Henry et al. (1994). We have used $\rho_{eff} = 5.98$ kpc (Henry et al. 1992). The revised electron temperature gradient is about 500 K/kpc, closer to the HII region value.

Regarding the elements that *are* produced by the progenitor stars, namely He, N and C, the situation is less clear (Maciel and Chiappini 1994). "Raw" abundances of N and C suggest similar gradients as for O/H, but detailed calculations must take into account the contamination of the nebular gas by the central star (cf. Chiappini and Maciel 1994).

These results are generally supported by investigations based on smaller, more homogeneous samples (Köppen et al. 1991, Samland et al. 1992). However, some discrepancies arise when different sets of nebulae and a different classification system are considered, especially regarding the magnitude of the gradients. Pasquali and Perinotto (1993) find somewhat flatter O/H and Ne/H gradients for a sample of type II PN defined according to modified selection criteria, and Amnuel (1993) obtains a lower gradient for the S/H ratio and an essentially flat Ar/H ratio, while his O/H and Ne/H gradients are steeper. Several reasons can be suggested to explain such discrepancies:

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First, the different populations that comprise the galactic system of PN must be properly taken into account, which involves the knowledge of their space distribution, kinematics and chemical composition (cf. Maciel and Dutra 1992, Ortiz and Maciel 1994). Otherwise, a mixed sample would result, masking any existing gradients, as their magnitudes are similar to the intrinsic abundance dispersion.

Second, the adopted samples are generally inhomogeneous, which is presently a necessary limitation, as no single set of observations is large enough for a reliable determination of the gradients.

Third, the distance scale obviously plays a role, especially for the nebulae that are farther away from the sun, $d > 3$ kpc. In practice, this effect is limited by the fact that the gradient is essentially defined by the objects inside a ring of about 3 kpc around the sun (Maciel and Köppen 1994).

Fourth, the intrinsic abundance dispersion introduces some further uncertainties. As discussed by Esteban and Peimbert (1995), such dispersion is considerably higher for PN than for HII regions, so that an intrinsic limitation is imposed on the magnitude of the gradients. Such a dispersion can be caused by several sources, including the chemical inhomogeneity of the interstellar medium (Pasquali and Perinotto 1993), and temperature fluctuations (Esteban and Peimbert 1995). The latter source implies that forbidden line electron temperatures are overestimated, so that an increase in the abundances derived from these lines is to be expected (Barlow 1995). However, it is not clear whether objects at different galactocentric distances would be affected differently, which is a necessary condition in order to alter the gradients.

The shape of the PN gradient is still under investigation, as most objects studied so far are located inside or close to the solar circle. A recent analysis of spectrophotometric data of PN in the direction of the anticentre (Costa et al. 1996) suggests the existence of some flattening in this region, although more work is needed to settle the question.

The problem of vertical gradients was analyzed by Faúndez-Abans and Maciel (1988), who concluded that the abundances of galactic PN are consistent with the known halo-disk abundance variations, as measured by the [Fe/H] ratio in stars. Actual vertical gradients in the disk, as defined by type II PN, are probably smaller than could be detected by present techniques (Faúndez-Abans and Maciel 1988, Pasquali and Perinotto 1993), a result supported by a recent analysis of more homogeneous data by Cuisinier (1993), Köppen (1994a), and Köppen and Cuisinier (1996).

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5. Theoretical aspects

The abundance gradients can be qualitatively understood in terms of the simple model of chemical evolution as shown by Maciel (1992) for yield values in the range $0.004 < y < 0.010$, close to the canonical value $y = 0.01$. In this model, however, some steepening is obtained for larger galactocentric distances, for which there is no observational support. This result is but one of the limitations of the simple model, so that detailed chemical evolution models must be taken into account. These models, although based on widely differing assumptions, are generally able to predict average gradients that are consistent with the observed values. As a conclusion, the physical processes causing the abundance variations are not well determined, and several possibilities have been considered in the literature (Pagel 1992, Peimbert 1995), namely: (i) variations in the gas distribution in isolated concentric zones; (ii) variations in the distribution of the ratio gas/stars, including the variation with O/H of the fraction of massive stars, due to the production of black holes; (iii) variable or bimodal IMF, including the variation of the IMF with the O/H ratio at the low mass end, and the variation of the slope of the IMF with O/H at the high mass end; (iv) variations of the yields with the oxygen abundance for a given IMF; (v) infall of unprocessed material, and variations with the galactocentric distance of the infall rate over the star formation rate (SFR); (vi) ejection of processed material in galactic winds, etc., and variations with the galactocentric distance of the outflow rate over the SFR; (vii) existence of gas flows influenced by the angular momentum of the gas in the disk.

The chemical evolution models are able to predict not only the magnitude of the abundance gradients, but also their *temporal variations.* Most results suggest that the gradients steepen with time (Lewis and Freeman 1989, Matteucci and François 1989, Mollá et al. 1992, Tosi 1995, Chiappini and Maciel 1995, Chiappini and Mateucci 1996). Other models, based on unbiased infall and a quadratic SFR (Josey and Arimoto 1992) or on the multiphase galactic model (Ferrini et al. 1992) predict an opposite behaviour (cf. Mollá et al. 1992, 1996).

Recent models by Götz and Köppen (1992), Köppen (1994a,b), and Chiappini and Maciel (1995) are able to account for the observed gradients and their time evolution based on (i) the existence of radial variations of the metal yield, (ii) radial variations of the star formation timescale, (iii) a non linear dependence of the SFR on the gas density, (iv) radial variations of the infall parameters, and (v) radial gas flows. The first three processes are responsible for the creation of the gradient, while their modifications are due to the radial gas flows, depending on the infall timescale. Also, the time evolution of the abundance gradients may be responsible for the flat

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gradients implied by some analyses of old stars, as mentioned earlier (cf. Tosi 1995). However, several problems remain, including the age determination of the PN types, parameter dependence of the chemical evolution models, and the physical reason for the gradients. This situation is expected to improve as new chemodynamical models for galactic evolution are developed.

Planetary nebulae already have a considerable importance in the study of abundance gradients in the Galaxy and, hopefully, will play a similar role regarding nearby galaxies in the near future.

Acknowledgements

This work was partially supported by CNPq and FAPESP.

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