RevMexAA (Serie de Conferencias), **3**, 133–140 (1995)

ABUNDANCE GRADIENTS IN THE GALAXY

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RESUMEN

Se presenta una revisión sobre las determinaciones de gradientes de abundancias químicas en la Galaxia hechas a partir de observaciones de nebulosas ionizadas y estrellas. Se hace especial hincapié en los problemas debidos a la presencia de fluctuaciones espaciales de temperatura en nebulosas ionizadas. Se discuten datos recientes sobre las zonas internas de la Galaxia y del anticentro galáctico. Por último, se plantean futuros campos de acción en el tema utilizando los nuevos telescopios de gran apertura y los telescopios espaciales

ABSTRACT

A review of the determinations of chemical abundance gradients in the Galaxy from observations of ionized gas and stars is presented. The problems derived from the presence of spatial temperature fluctuations on the abundance determinations from ionized nebulae are discussed. The newest observations of H II regions located in the inner regions of the Galaxy and in the direction of the galactic anticenter are reviewed. We also discuss some ideas that could be carried out with the ground and space telescopes that are —or will be soon— put into operation.

Key words: **H II REGIONS — PLANETARY NEBULAE — ISM: ABUNDANCES**

1. INTRODUCTION

The presence of radial abundance gradients in the disks of external spiral galaxies is well established from spectroscopic observations of ionized nebulae. The precise form of such gradients is well determined only for a few galaxies and seems to change from one object to another. Many studies devoted to determine the radial distribution of chemical elements in external galaxies have been performed since the pioneering works of Aller (1942) and Searle (1971) (e.g., Pagel & Edmunds 1981; see also the recent compilations and analyses by Vila-Costas & Edmunds 1992; Oey & Kennicutt 1993; Zaritski, Kennicutt, & Huchra 1994). These gradients are the result of galactic chemical evolution, which depends on: the star formation rate, the initial mass function, the stellar yields and the gas flows of all these quantities as a function of time and position in each galaxy. There are several objects that can be used as elemental abundance gradient tracers: (a) stars, (b) supernova remnants (SNRs), (c) planetary nebulae (PNe), and (d) H II regions. The presence of abundance gradients in the Galaxy has been well established from observations of H II regions and PNe. Alternatively, some contradictory results have been obtained from recent studies of hot stars in the galactic disk (e.g., Pagel 1992 and references therein).

2. STARS

Studies of B stars covering galactocentric distances from 5 to 12 kpc do not show a gradient in chemical abundances (Fitzsimmons et al. 1990; Rolleston et al. 1993). Conversely, the young association Dolidze 25, located at $R_G = 13.5$ kpc, appears to be underabundant in heavy elements by a factor of six, indicating the presence of a gradient (Lennon et al. 1990). Furthermore, disk stars, cepheids and supergiants present Fe/H gradients similar to the O/H gradient determined from observations of ionized gas (see Pagel 1985), although there are contradictory results from deep surveys of red giants (Neese & Yoss 1988; Lewis & Freeman 1989).

3. SUPERNOVA REMNANTS

Old supernova remnants (SNRs) are expected to be composed mainly of shocked, swept-up ISM. Their emission line spectra are very difficult to reconstruct but shock modeling has been successfully applied to SNRs in M33 by Dopita, D'Odorico, & Benvenuti (1980), revealing a galactic abundance gradient which is consistent with that determined independently from observations of H II regions in that galaxy. Binette et al. (1982) applied these techniques to published data on Hα, [N II] and [S II] for old galactic SNRs. They found gradients for S and N that agree very well with those derived from H II regions. González (1983) also found a gradient in [N II]/[S II] for old galactic SNRs that could be explained by radial variations in N/S.

4. PLANETARY NEBULAE

The existence of abundance gradients from PNe observations appears well established in the Galaxy but the precise values of their slopes are still quite controversial. We have restricted our analysis to the results for Type II PNe because these objects are not expected to suffer substantial contamination from their stellar progenitors. There have been discrepant results among the different research groups working on this subject. Kaler (1980), based on data gathered from different sources, did not obtain evidence for a radial gradient in O/H. More recently, Pasquali & Perinotto (1993), using a compilation of chemical abundances for 227 PNe of all types, taken from the literature, found low values for the slopes of all elements considered —O, C, N, Ne— and a flat gradient for He. On the other hand, Faúndez-Abans & Maciel (1986), Amnuel (1993), and Maciel & Köppen (1994), also from a compilation of data for about two hundred objects, found a well defined gradient for oxygen —consistent with that obtained for H II regions— in Type II PNe, and somewhat different gradients for other elements. In Table 1 we present the different values given by the authors cited.

The reason of these apparently discrepant results is difficult to understand. The first and more obvious explanation is the use of inhomogeneous sets of data taken from several authors using different instrumentation, different atomic parameters and, perhaps, different ionization correction factors (*icf*). Another point is the uncertainty in the statistical methods for determining the distances to PNe, which can be as large as a factor of two. However, as discussed by Maciel & Köppen (1994), apparently the use of different sets of distances does not produce a substantial change in the slopes derived.

A common fact that can be noted in PNe abundance gradient studies is the large dispersion in O/H, as well as in other elements, obtained for a given galactocentric distance. At first instance, this fact could be due to the inhomogeneity of the sample data and especially to the contamination of the sample with objects having non-circular orbits. This problem can be eliminated by avoiding type III PNe —those with high peculiar radial velocities and high z values. It is notorious that the local dispersion of O/H is of the order of 1 dex, substantially larger than the 0.3 dex of the data of Shaver et al. (1983) for H II regions. Pasquali & Perinotto (1993) suggest that this behavior is due to the chemical inhomogeneity of the ISM in O at the time of the birth of the PNe progenitors, 0.5 to 5 Gyr ago. These authors suggest that such inhomogeneities change with time and may be produced by changes in the infall rate of gas from the halo to the galactic disk with time. On the other hand, there is increasing evidence in favor of large values of t^2 (mean-square temperature fluctuations) ranging from 0.03 to 0.053 for all types of PNe including Type II objects (Peimbert 1971; Dinerstein, Lester, & Werner 1985; Liu & Danziger 1993; Peimbert, Storey, & Torres-Peimbert 1993). Moreover, Liu et al. (1995) obtain values around 0.08 for NGC 7009, the same number that Kingsburgh & López (1995) find for NGC 6543. Values of $t^2 \approx 0.08$ could produce differences of 0.6 dex in O/H, and could contribute to the observed dispersion. In this sense, it is important to remark that the values of t^2 reported for PNe seem to be larger than those obtained for H II regions, as we will comment in the next section.

5. H II REGIONS

In the late 1970's, an intense effort was made to determine the abundance gradient in the Galaxy (e.g., Peimbert, Torres-Peimbert, & Rayo 1978; Hawley 1978; Talent & Dufour 1979). However, the classic work on the subject was that by Shaver et al. (1983), who observed a larger set of H II regions covering a wide range of galactocentric distances (R_G) from about 4 to 12 kpc, using radio recombination line measurements to determine T_e. For comparison, we have corrected their points using the assumption of $R_\odot = 8.5$ kpc. From our point of view, the most important results of the work by Shaver et al. (1983) are the following:

- The existence of a gradient in T_e of 433 K kpc^{-1}, first reported by Churchwell & Walmsley (1975).

TABLE 1

RADIAL GRADIENTS FOR TYPE II PLANETARY NEBULAE

Gradient (dex kpc^{-1})	Maciel's Group	Amnuel (1993)[c]	Pasquali & Perinotto (1993)	Average
Δlog(He/H)/ΔR	−0.019[a]	−0.002	−0.009	−0.010
Δlog(O/H)/ΔR	−0.069[b]	−0.079	−0.030	−0.060
Δlog(N/H)/ΔR	−0.072[a]	−0.102	−0.050	−0.074
Δlog(C/H)/ΔR	−0.069[a]	−0.074	—	−0.072
Δlog(S/H)/ΔR	−0.067[b]	−0.030	—	−0.049
Δlog(Ne/H)/ΔR	−0.056[b]	−0.072	−0.050	−0.059
Δlog(Ar/H)/ΔR	−0.051[b]	+0.002	—	−0.024

[a] Faúndez–Abans & Maciel (1986).
[b] Maciel & Köppen (1994).
[c] Results for his L type.

- The differences between the T_e values obtained from radio recombination and optical forbidden lines yield values of $t^2 \leq 0.015$.
- Quite similar O/H, N/H and Ar/H gradients.
- Almost flat He/H and S/H gradients.
- No evidence for flattening of the O/H and N/H gradients at large galactocentric distances.
- Weak evidence for steeper gradients over the inner regions of the galactic disk.
- The observed scatter of the abundances at a given distance can be accounted for by observational errors in the line intensities.

5.1. The Role of Temperature Fluctuations

As stated above, Shaver et al. (1983) found almost negligible values of t^2 in their sample. However, a number of careful determinations for the brightest galactic H II regions in the solar vicinity —the Orion Nebula, M 8 and M 17— give substantially larger values of t^2 (see the very recent review by Peimbert 1995). The use of different methods such as: (a) the combination of T_e(Bac/Hβ) and T_e([O III]), and (b) the comparison between C^{++}/H^+ and O^{++}/H^+ ratios obtained using forbidden and recombination lines, give consistent values of t^2 in the 0.03 to 0.05 range. These t^2 values are considerably higher than those predicted by photoionization models for chemically homogeneous nebulae with constant density (e.g., Garnett 1992; Gruenwald & Viegas 1992). The latest estimate of t^2 for the Orion Nebula is that obtained by Esteban et al. (1995). They derive O^{++}/H^+ and C^{++}/H^+ from well-resolved and high S/N optical recombination lines and find that these abundances are higher than those based on abundance determinations from forbidden lines measured in the same spectrum or given by other authors. They find that a moderate value of $t^2 = 0.025 \pm 0.015$ can reconcile the discrepancy between the ionic abundances derived using both kinds of lines. This number is in the lower limit of the range of values determined for H II regions and is clearly lower than the t^2 obtained for some PNe using the same methods.

Although there is increasing evidence for the presence of temperature fluctuations in bright H II regions in the solar neighborhood, we have to wait for a homogeneous and deeper set of observations of those nebulae to settle this issue definitively. Other questions remain open, like the presence of such fluctuations in distant H II regions and a hypothetical dependence of t^2 on structural nebular parameters, chemical abundances, or even galactocentric distance with its effects on the derived abundance gradients. The answers to these questions will probably come with the new generation of large aperture ground-based telescopes.

5.2. Infrared Studies: The Extension to the Galactic Center

Traditionally, optical studies have been restricted to the unobscured zones of the Milky Way due to the effects of interstellar extinction, and consequently leaving out the inner parts of the Galaxy. An improvement of this situation has been reached with IR observations based on new infrared detectors placed in stratospheric and space telescopes. NASA's Kuiper Airborne Observatory (KAO) and the *IRAS* Low Resolution Spectrometer (LRS) have become powerful complementary tools to the optical observations. The IR spectral region contains several important emission lines of [O III], [N III], [Ne II], [Ne III], [S III], and [S IV], among others. The observations have been extended to the galactic center and the range covered in R_G by these studies extends from 0 to 12 kpc.

IR studies have contributed to a better knowledge of the Ar/H, S/H, Ne/H and N/O gradients. The Ar/H gradient has been derived by Pipher et al. (1984) from measurements of [Ar II] 7.0 μm and [Ar III] 9.0 μm IR lines deriving total abundances almost independent of *icf* corrections. The S/H gradient has been obtained using [S III] 19.0 μm and [S IV] 10.5 μm lines by Pipher et al. (1984), Simpson & Rubin (1990) and Simpson et al. (1995). These authors find a S/H gradient steeper than that obtained by Shaver et al. (1983). The S/H and Ne/H gradients obtained with these observations are similar to the O/H gradient derived from the optical data, a result that is consistent with stellar nucleosynthesis prescriptions.

The most striking result from IR observations is that the N/O ratio obtained from N^{++}/O^{++} appears to be at least a factor of two larger than the optical N/O derived from N^{+}/O^{+}. The reason for this difference is not yet well understood (Dinerstein 1990), but two ideas have been proposed: ionization structure effects (Rubin 1985) or the enhancement of optical [O II] lines by recombination (Rubin 1986). Lester et al. (1987) and Rubin et al. (1988) found that there is no clear-cut evidence for a linear gradient in N/O. On the other hand, this ratio appears to be significantly higher at the "5 kpc ring"; this ring coincides with a peak in the radial distribution of ionized gas obtained by Güsten & Mezger (1982). Simpson et al. (1995) find that, instead of showing a monotonic gradient, the Galaxy shows an abundance discontinuity (step) at least for N/H and N/O and to a lesser extent for S/H. The discontinuity is located at $R_G \approx 6$ kpc, where there is a peak in N/O coincident with the so-called "5 kpc ring". These authors suggest that this "step" may be due to radial mixing in the galactic disk.

The form of the N/O gradient obtained from IR lines favors the scenario of primary production of ^{14}N. The fact that the two galactic center objects studied do not show an enhancement in N/O argues against secondary nuclear processes, but suggests copious SF processes in the galactic center and in the "5 kpc ring" (Rubin et al. 1988).

In Table 2 we compare the observed gradients for different kinds of objects with the predictions from some chemical evolution models. There is good agreement between the observed gradients for H II regions, PNe (we have included the average of the values given in Table 1) and SNRs. The models by Matteucci & François (1989) reproduce fairly well the observed behavior. The results by Ferrini et al. (1994) are presented for two galactic ages: for 13 Gyr, that would correspond to the present abundance gradients, and for 8.5 Gyr that would correspond to the gradients present 4.5 Gyr ago, these results can be compared with the H II and the PNe gradients respectively. The results of Ferrini et al. (1994) appear less consistent with the observed values. Moreover, the expected differences between young and old objects are not present in the H II regions and PNe data.

5.3. The Anticenter Region

The optical and IR studies on abundance gradients in the Milky Way have been traditionally restricted to the "inner" parts of the Galaxy, from about 12 kpc to the galactic center. The extension of the abundance gradient determination to the anticenter region is a difficult task due to the faintness and the low number of the H II regions in that particular zone. Fich & Silkey (1991) have performed a spectroscopic study of H II regions in the outer parts of the Galaxy. The most significant result of this study is the derivation of the N/H abundances. On the other hand, the lack of measurements of the [O II] λ3727 line, together with those of [O III] $\lambda\lambda$4959, 5007 in their data, precludes the determination of O/H abundances. The derived N/H abundance seems apparently high and the behavior of its gradient is rather flat. The work on S266 —one of the most external H II regions in the Galaxy— by Manchado, Esteban, & Vílchez (1989) points in the same direction.

More recently, Vílchez & Esteban (1995) have studied a sample of 18 H II regions located towards the galactic anticenter in the range of galactocentric distances between 11.5 and 18 kpc. The sample includes 15 H II regions with known galactic distances, having their ionizing stars identified from previous work. The sample

TABLE 2

OBSERVED AND COMPUTED RADIAL GRADIENTS

Gradient (dex kpc^{-1})	H II	SNR[a]	PN[b]	Matteucci & François (1989)	Ferrini et al. (1994) Young objects	Ferrini et al. (1994) Old objects
Δlog(He/H)/ΔR	−0.001[c]	—	−0.010	−0.0085	—	—
Δlog(O/H)/ΔR	−0.070[c]	—	−0.060	−0.065	−0.078	−0.105
Δlog(N/H)/ΔR	−0.090[c]	−0.100	−0.074	−0.085	−0.160	−0.195
Δlog(C/H)/ΔR	−0.080[d]	—	−0.072	−0.066	−0.080	−0.107
Δlog(S/H)/ΔR	−0.070[e]	−0.070	−0.049	−0.050	−0.089	−0.114
Δlog(Ne/H)/ΔR	−0.080[e]	—	−0.059	−0.048	—	—
Δlog(Ar/H)/ΔR	−0.060[c,f]	—	−0.024	—	—	—

[a] Binette et al. (1982).
[b] Average values given in Table 1.
[c] Shaver et al. (1983).
[d] Peimbert et al. (1992).
[e] Simpson et al. (1995).
[f] Pipher et al. (1984).

corresponds to nebulae from low to intermediate degree of ionization, ionized by one or a few late O/early B stars. The global and physical parameters of the H II regions and of the ionizing stars, U, f, N_e, T_e, T_{eff} and N_{Ly-C} have been derived from radio and optical observations. Abundances have been computed using direct optical or radio determinations of T_e for some of the objects or alternatively, adopting T_e from model fitting. The main result is a nearly flat gradient of O/H and N/H abundances up to a R_G of 18 kpc.

In Figure 1 we show the behavior of the abundance gradients in O, N and S for the Galaxy from 0 to 18 kpc from the compilation of H II region data obtained by Simpson et al. (1995), Shaver et al. (1983), Peimbert (1979) and Vílchez & Esteban (1995). The O/H gradient seems to flatten at distances larger than 14 kpc but the flattening is more evident in the N/H and S/H gradients.

In Figure 2 we show the behavior of N/O and N/S using the data presented in Figure 1. If we exclude the IR data of Simpson et al. (1995), the N/O ratio seems almost constant along the galactic disk. The N/O values obtained by the IR data are systematically higher than the optical ones in the "inner Galaxy" and show a steep increase to the galactic center. On the other hand, Dinerstein et al. (1993) find a value of log(N/O) of −0.90 for three H II regions in common with Vílchez & Esteban (1995), only slightly higher than the average of −1.05 obtained from the optical sample by these authors. These values of N/O are clearly higher than the value of log(N/O) = −1.5 obtained for the Magellanic Clouds (e.g., Dufour 1984) and suggest different chemical evolution histories for the three systems.

The N/S gradient shows an interesting behavior. The data of Simpson et al. (1995) show a clear decrease of N/S with R_G, consistent with the N/O behavior from the IR lines. On the other hand, the data of Vílchez & Esteban (1995) show a constant N/S value with galactocentric distance. In contrast, the points of Shaver et al. (1983) for N/S are clearly below the other data and show a strong negative gradient. For the ionization degree of typical H II regions, S^{++} is expected to be the most important ion. Simpson et al. (1995) and Vílchez & Esteban (1995) use far and near IR [S III] lines respectively to derive S^{++}/H^+ while Shaver et al. (1983) use the optical [S III] λ6311 line. This line is rather faint and the measurement of its flux can have problems of sky subtraction, when using low resolution spectroscopy, due to the [O I] λ6300 line intensity, which varies during the night. Moreover, λ6311 depends strongly on T_e. The combination of both effects could be producing the observed behavior in the data of Shaver et al. (1983).

6. FUTURE PROSPECTS

The future availability of large-aperture ground-based telescopes will provide us with a better knowledge of the abundance gradients in the Galaxy. It will be possible to observe bright stars at larger distances, to derive gradients for fainter main sequence stars, and to observe highly obscured, compact PNe at larger galactocentric distances. It will be possible also to study line intensity changes as a function of position inside extended

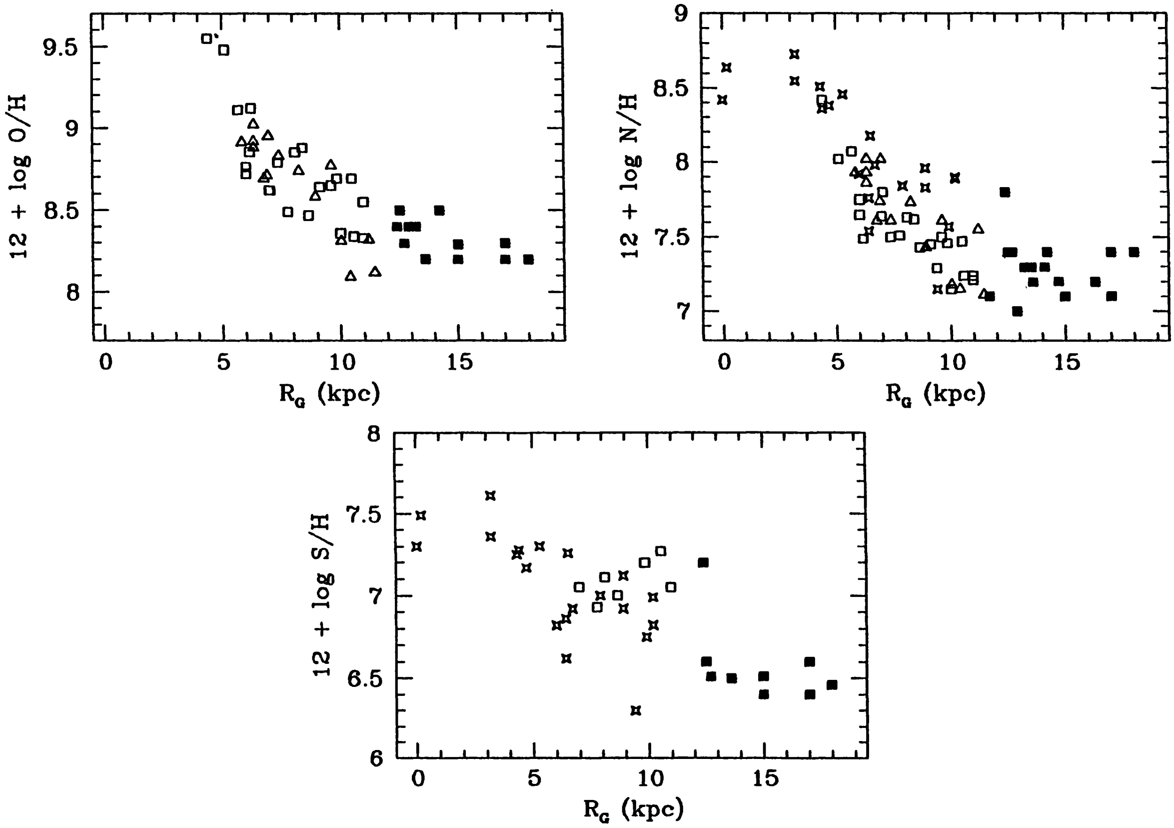

Fig. 1. O/H, N/H and S/H vs. galactocentric distance based on observations of galactic H II regions. The data presented are: open squares —Shaver et al. (1983); open triangles —Peimbert (1979); open stars —Simpson et al. (1995); and filled squares —Vílchez & Esteban (1995). The points of Shaver et al. (1983) and Peimbert (1979) have been corrected to $R_{\odot} = 8.5$ kpc using the compilation by Mollá (1993).

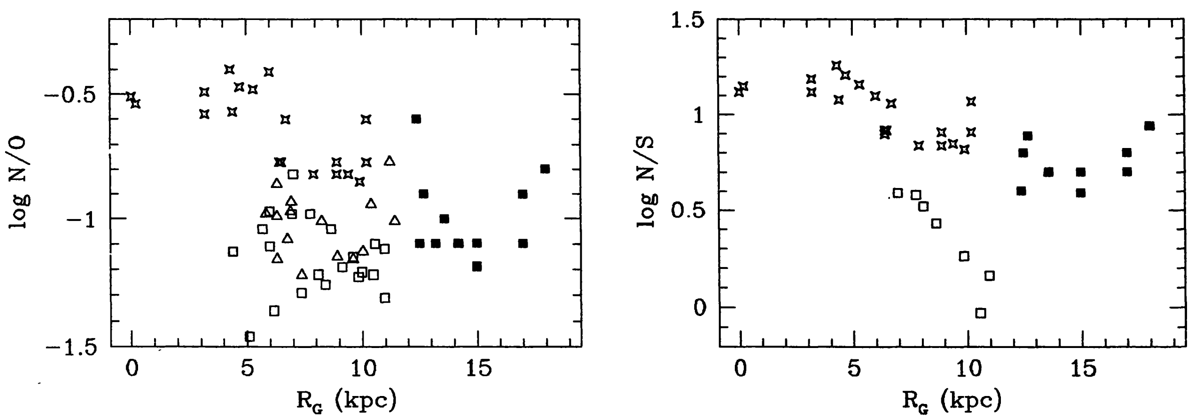

Fig. 2. N/O and N/S vs. R_G based on observations of galactic H II regions. The sources of the data and the symbols are those of Figure 1.

H II regions and PNe, specially those at large distances in the directions towards the galactic center and the anticenter.

The determination of accurate abundances from faint recombination lines of heavy elements in PNe and H II regions is a new research area that shows great promise. In the presence of spatial temperature fluctuations these abundances will be more accurate than those derived from forbidden lines. The comparison of abundances from recombination lines with those from collisionally excited lines could be used to determine t^2 values which would help to produce better models for these objects and to explore whether t^2 changes systematically with PN type or with R_G. Moreover accurate α_{eff} coefficients are only available for a few ions and much work is needed to improve their quality and to obtain new α_{eff}'s for ions of heavy elements whose recombination lines are beginning to be measured.

It would be very important to have a set of T_e values determined from radio recombination lines for H II regions in the anticenter direction. A project along these lines is in the making (Afflerbach & Churchwell 1995, priv. comm.). An interesting question arises: does the T_e gradient flatten at the anticenter? A flat gradient would support the results of Fich & Silkey (1991) and Vílchez & Esteban (1995) on the N/H and O/H gradients.

The currently operating space telescopes, like the *Hubble Space Telescope (HST)*, and those planned for the near future, like the *ISO* for the IR spectral region, can play a key role in improving our knowledge of the abundance gradients. The carbon galactic gradient is poorly known —especially for H II regions— and could be investigated from *HST* observations of UV carbon lines. On the other hand, observations of IR fine-structure lines making use of the *ISO* satellite will extend the IR abundance studies to a larger sample and a larger range of galactocentric distances. It is extremely important to solve the N/O discrepancy by observing the same objects in the optical and in the IR.

C.E. would like to thank all the members of the Instituto de Astronomía for their warm hospitality during his stay in México. This work has received financial support from DGAPA-UNAM through grant IN100994 and was made possible in part by a grant from the Programa Sectorial de Formación de Profesorado Universitario y Personal Investigador (Subprograma General de Becas al Extranjero) of the Ministerio Español de Educación y Ciencia.

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