RADIAL ABUNDANCE GRADIENTS IN THE GALACTIC DISK: OBSERVATIONS AND THEORY

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Abstract

The radial abundance gradients observed in the disks of the Galaxy and other spiral galaxies are reviewed, in the context of the chemical evolution of these galaxies. A detailed account is given of the main observational evidences for the gradients, both in the Galaxy and other galaxies, on the basis of observations of HII regions, planetary nebulae, and stars. The origin of the gradients is discussed according to the main physical processes proposed so far. The so-called "simple model" is invoked in order to obtain some physical insight on the origin of the gradients.

1 Introduction

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

In this paper, we stress on the importance of abundance gradients in the framework of the chemical evolution of the Galaxy and galactic evolution in general (section 2). The main observational evidences for radial gradients are reviewed in section 3. The models proposed to explain the gradients are briefly discussed in section 4, especially the so-called "simple" model in its original form and including later developments, in order to stress the physical insight that follows from its application.

Previous reviews on abundance gradients include Peimbert (1979), Pagel and Edmunds (1981), Shaver et al. (1983), Güsten and Mezger (1983), Díaz (1989), Dinerstein (1990) and Pagel (1992). Recent work on chemical evolution models both for the Galaxy and spiral galaxies in general are discussed and referenced by Audouze and Tinsley (1976), Pagel (1979, 1987, 1991), Tinsley (1980), Twarog (1985), Güsten (1986), and Rana (1991).

2 Abundance gradients and chemical evolution

Galactic evolution generally comprises the *dynamical evolution*, the *chemical evolution*, and the *evolution of the photometric properties* (cf. Tinsley 1980). Although frequently considered separately, these aspects basically refer to the same phenomenon - galaxy evolution - so that the usual treatment is largely a matter of convenience. The interplay of dynamical and chemical processes is made clear for example by the well known two phase evolution of the Galaxy, which gave origin to the spheroidal and disk components, respectively. Or, as confirmed by recent models, by the influence of infall from the halo and radial flows within the disk.

The structure of chemical evolution models includes a series of characteristics sometimes called "ingredients" (cf. Pagel 1979, 1987, 1991, 1992). In the following we will consider the most important of these ingredients, emphasizing the application to the solar neighbourhood and the galactic disk, where radial abundance gradients are observed.

(a) Initial conditions

These refer to the pregalactic - often primordial - abundances. The main species considered are D, ^{3}He, ^{4}He, and ^{7}Li, and the observed abundances must be interpreted in terms of galactic evolution effects in order to determine primordial values, thus providing a link with theoretical models. Of particular importance is the ^{4}He pregalactic abundance, which is claimed to be known to the third decimal place (Pagel et al. 1992; Pagel and Kazlauskas 1992; Chiappini and Maciel 1994). Recent determinations, based both on helium vs. oxygen and helium vs. nitrogen correlations in galactic and extragalactic HII regions and planetary nebulae, indicate that the He pregalactic abundance by mass is $Yp = 0.233 \pm 0.003$ (Chiappini and Maciel 1994). A related parameter is the helium to metals enrichment ratio, $\Delta Y/\Delta Z = 5.2 \pm 1.1$, according to the same source. It is interesting to note that this ratio does not seem to be very sensitive to the evolutionary stage of the data, implied by a metallicity range from the metal poor blue compact galaxies to the type IIb planetary nebulae. This is an indication that these objects (and host galaxies) have undergone similar evolutionary processes (cf. Maciel 1988; Chiappini and Maciel 1994).

The heavy element abundance by mass is originally small, $Z \approx 0$, but very often evolution models include some kind of initial enrichment, which brings the metal abundances to values up to [Fe/H] ≈ -2 to -3, where [Fe/H] is the logarithmic difference of the iron abundance by number of atoms relative to the solar abundance.

(b) The initial mass function (IMF)

From the pioneering work of Salpeter (1955) to the extensive study by Scalo (1986), this is a relatively well known function of the stellar mass, derived from present-day luminosity function and a mass-luminosity relation. However, there is a long standing controversy on whether *time* and *space* variations are important. Results from HII regions, HII galaxies, and stellar clusters are consistent with some mild variations of this function. On the other hand, a dip in the luminosity function can be interpreted as an evidence for a bimodal IMF.

(c) The star formation rate (SFR)

This is a rather complex function, which is still largely unknown, basically because the physical processes involved in stochastic star formation are not adequately known (cf. Larson 1977). Therefore, different approximations are frequently used. From the work of Schmidt (1959), a dependence with some power n of the surface gas density of interstellar material is often assumed, SFR $\propto g^n$. Current work include self-regulating, bimodal and non-monotonic time dependence of the SFR, which is supported by growing evidence on starburst galaxies and in the solar neighbourhood itself.

(d) Nucleosynthesis yields

A basic ingredient of chemical evolution models is the stellar yield, or the fraction of processed material returned to the interstellar medium relative to that stored in stars and remnants. The determination of the yields requires detailed nucleosynthetic calculations involving stars in the mass range $M \simeq 0.1-100 M_\odot$. Basically, low mass stars ($M < 1 M_\odot$) live longer than the age of the Galaxy, and do not return a significant amount of mass to the interstellar medium. Intermediate mass stars ($1 M_\odot < M < 10 M_\odot$) eject planetary nebula material that has had some secondary processing, which implies some enrichment in He, N and C, but not of oxygen and other heavy metals. The massive ($M > 10 M_\odot$) stars eject the primary nucleosynthesis products, built from H and He during stellar evolution. Elements such as O, Ne and Ar are produced this way.

The basic equations are given by Tinsley (1980), and recent results have been obtained by Henry (1990) and Köppen and Arimoto (1991). These results depend strongly on the adopted mass limits, the IMF/SFR functions, and also on physical processes and parameters of nuclear reaction rates, opacities, mass loss, convection, etc., apart from the adopted chemical composition.

(e) Contamination processes

These may include *infall* of largely unenriched gas from the halo, as well as *radial flows* into the concentrical cylindrical zones in the disk itself. The inclusion of these processes may account for most of the constraints (see below), but generally introduces several parameters such as the metallicity of the infalling gas or the velocity of the gas flows, which are difficult to determine observationally, so that the problem of uniqueness of solutions still remains (cf. Tosi 1988).

(f) Constraints

- *Stellar populations:* These include stars and gas observed in the galactic halo, thick disk, thin disk, and bulge, as defined by their chemical composition, space distribution, and kinematics. As a consequence, important relationships such as the metallicity distribution are often different for each of these populations. For example, the average scale height from the galactic plane increases according to the sequence of HII regions and planetary nebulae of types I (population I old), II (population I old), III (population II intermediate) and IV (population II extreme), indicating the population differences of these objects (cf. Maciel and Dutra 1992).

- *Metallicity distribution:* This is the main constraint to the chemical evolution models, which originated the (in)famous G-dwarf problem, namely, the lack of low metallicity stars as compared to the predictions of the simple model (cf. Pagel 1991). Recent work is able to solve this problem, at least partially, with widely differing processes, such as infall, radial flows, presence of remnants, as well as modifications of the structure of the simple model ("bells and whistles"). Also, the observational data itself is subject to some controversy, as the adoption of a expansion law for the stars in the z-direction can alter the number of stars in a given metallicity bin, so that the general metallicity distribution is modified.

- *The age-metallicity relation:* The "metallicity index" [Fe/H] is often a convenient way to measure stellar abundances other than H and He, in contrast with the oxygen abundances (log O/H + 12) better determined for gaseous nebulae. Adopting [Fe/H] as representative of the stellar metallicity at a given time, several age-metallicity relations have been proposed for the disk, all of which include a relatively steep initial metallicity increase followed by a slower, nearly constant plateau (cf. Twarog 1980; Nissen et al. 1985).

- *The [O/Fe] vs. [Fe/H] relation:* As discussed by several papers (cf. Pagel 1991), some heavy elements display variations with the [Fe/H] ratio, which places important constraints on chemical evolution models. The ratio [O/Fe] vs. [Fe/H] is particularly important in this respect, and a different behaviour is observed for older, subsolar objects, and high metallicity, younger stars (cf. Nissen 1992).

- *Radial gradients:* Radial gradients are the most important large scale trend in the galactic disk, and are probably related to the distribution of gas and stars in the Galaxy. In the following section, a detailed account of the observational evidences will be given, followed by a brief discussion of the main theoretical models.

3 Observational evidence of abundance gradients

(a) Spiral galaxies

Radial abundance gradients in spiral galaxies are well established, at least for the ratios O/H, N/H and S/H (cf. Villa-Costas and Edmunds 1992, 1993). The first study on the systematic variations in the spectra of HII regions located near or far from the galaxy centre was that by Aller (1942), who have considered 18 HII regions in M33. It was noted that the ratio [OIII]/Hβ increased with the distance ρ to the centre. A more detailed study was made later by Searle (1971) on several galaxies like M33, M51, M101, etc., where the excitation gradient was further observed. Among the possibilities to explain the gradient, Searle (1971) 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 (Shields 1974; Shields and Searle 1978), and gradients of O/H, and N/H were determined, remaining some doubts on a S/O gradient. A temperature gradient of the order of 500 K/kpc was quoted in the last reference.

The past five years have witnessed an increase in the amount and quality of the data, especially with the advent of CCD detectors. Not only the number of HII regions observed in a given galaxy increased (cf. Vilchez et al. 1988), but also the spectral range, which produced new data on elements such as Ne, Ar and S. Coupled with HII region model or empirical calculations, these investigations led to well defined abundance gradients, which also include some data from supernova remnants, apart from HII regions. Newly determined O/H gradients have been given recently by Kennicutt et al. (1993) and Zaritsky et al. (1994), with average slopes of -0.10 dex/kpc. It seems that all galaxy types can have rather steep gradients *except* pure barred spirals, which seem to show small or no gradients at all. A recent work on environmental effects on abundance gradients in galaxies in the Virgo cluster has produced some very interesting results, as shown in figure 1 for O/H (Henry et al. 1992, 1994), to which we will return later. Here we have used in the abscissa the quantity ρ_{eff}, the effective galaxy radius, that is, the radius at which half of the optical emission is contained.

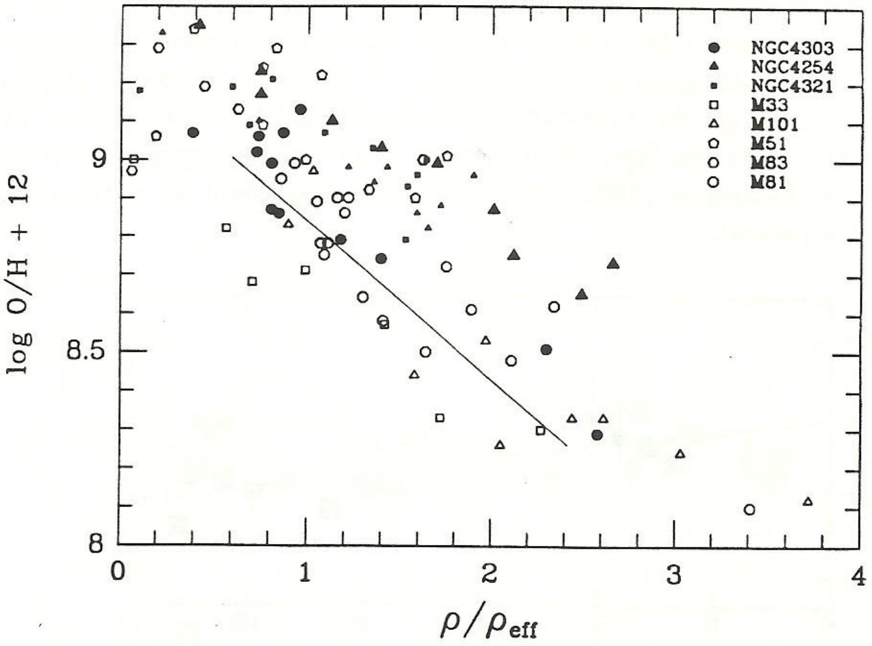

Figure 1 - O/H gradients for spiral galaxies (Henry et al. 1994). The PN galactic gradient is also plotted (straight line).

The S/H and S/O ratios have been subject to some controversy, especially regarding the existence of a S/O gradient in spiral galaxies. An anticorrelation of this ratio with O/H has been reported (cf. Díaz et al. 1991), which can be seen for the 5 HII regions studied in the high metallicity spiral M51. In principle, several HII regions should be selected at different distances from the centre, but in practice those close to the nucleus are difficult to measure, either due to the nuclear contamination, or to the fact that the abundances are higher, so that the electron temperature and the excitation of the nebulae are too low. As shown by Díaz et al. (1991), this anticorrelation is apparent in the merged plot including the Galaxy, M33, M101 and M51. However, this does not necessarily mean that S/O decreases as ρ increases, since the individual galaxies have different metallicities. On the other hand, the evidence for an S/H gradient in external galaxies is becoming more clear, as shown by Vilchez et al. (1988). This can be associated with the negative results for an S/O gradient, suggesting that the S/H gradient is similar to the O/H one (see also Díaz 1989).

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; Vilchez et al. 1988), but recent work seems to indicate an exponential gradient with constant slope (Henry and Howard 1994).

(b) The Galaxy: HII regions

As it is often the case, evidences for large scale trends in the Galaxy are more difficult to understand than for nearby, face on spirals. The basic evidence for abundance gradients in the Galaxy comes from direct oxygen data and indirect electron temperature gradient determinations in galactic HII regions. The basic reference is Shaver et al. (1983), where reasonable gradients for the O/H, He/H and N/H ratios were established, amounting to about - 0.06 dex/kpc. More recent work on the oxygen gradient from HII regions are given by Edmunds (1992), and the derived gradient is of the order of -0.07 dex/kpc (figure 2, squares).

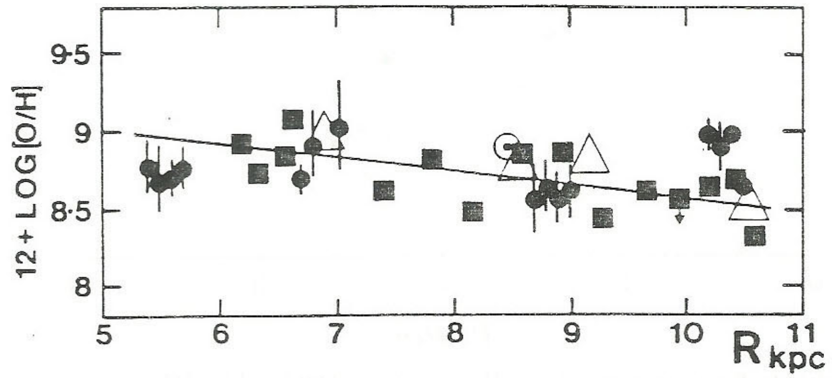

Figure 2 - The galactic O/H gradient from HII regions and stars (Edmunds 1992).

Galactic HII regions also show evidences for an electron temperature gradient, observed from radio recombination lines (Churchwell and Walmsey 1975). Although other processes may affect the nebular temperatures, such as the stellar effective temperatures, both HII and planetary data suggest similar gradients, which are further consistent with the abundance gradients.

(c) The Galaxy: planetary nebulae

Evidences of abundance gradients from planetary nebulae have been hampered in the past basically due to (i) the existence of a mixed population of planetary nebulae in the Galaxy, and (ii) the lack of a reliable distance scale that could be applied to a statistically large number of nebulae. Earlier work include D'Odorico et al. (1976) and Aller (1976) and references therein. The first detailed determination of abundance gradients of the main chemical elements in galactic planetary nebulae was given by Faúndez-Abans and Maciel (1986, 1987), where it was established that O, S, Ne and Ar had 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 has been completely revised and expanded to include a larger sample of nebulae and chemical elements (Maciel and Köppen 1994; Maciel and Chiappini 1994). The main results have been recently reviewed (Maciel 1994), and can be summarized as follows: all disk nebula, which comprise Peimbert types I, II and III, display measurable gradients of the order of -0.04 to -0.07 dex/kpc. The small differences in the 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 (figure 3, from Maciel and Köppen 1994). In other words, the gradients have become steeper with time, so that type I planetary nebulae have generally steeper gradients than type II, and these relative to type III. Therefore, the planetary nebula gradients that best resemble those of HII regions are those derived from type I and II objects. This can be seen in figure 4, where we plot the O/H gradient for type II objects using two different distance scales. The first panel uses basically the distance scale developed by Maciel (1984), while the second uses the new Cahn et al. (1992) distance scale. The gradients are essentially the same, namely - 0.06 dex/kpc, and should be compared to the HII region gradient of figure 2. A similar conclusion can be observed in figure 1, where we have included the type II nebulae (straight line) from Maciel and Köppen (1994) with the galaxies studied by Henry et al. (1994). We have used $\rho_{eff} = 5.98$ kpc for the Galaxy (Henry et al. 1992, de Vaucouleurs and Pearce 1978). An idea of the intrinsic dispersion of these plots can be obtained by studying a ratio such as Ne/O. This ratio is expected to be constant in planetary nebulae, so that a comparison with the O/H, etc. gradients shows clearly that the gradients are real.

Another confirmation of the gradients can be observed in figure 5, where we have plotted the electron temperatures of type II planetary nebulae in the sample of Maciel and Köppen (1994). The derived gradient is now of the order of 500 K/kpc, somewhat lower than the original result by Maciel and Faúndez-Abans (1985), and closer to the HII region value.

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

Finally, although independent analysis have confirmed the existence of radial gradients from planetary nebulae (cf. Acker et al. 1992; Köppen et al. 1991), the separation of the PN classes still produces some inconsistencies (cf. Pasquali and Perinotto 1993), as well as the use of different classification systems, which are sometimes difficult to compare (cf. Amnuel 1993).

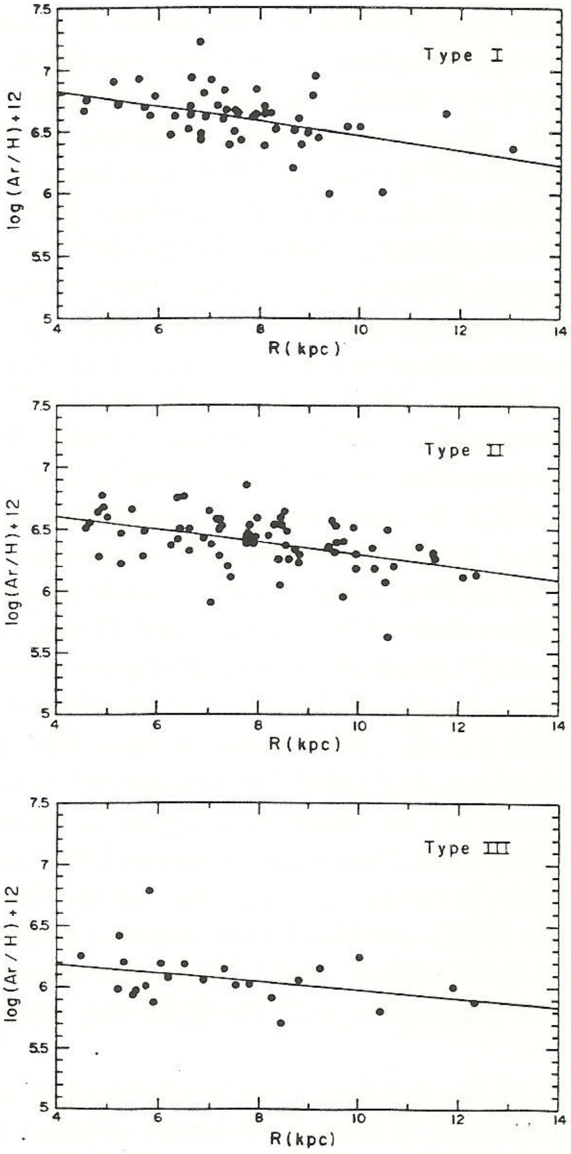

Figure 3 - The Ar/H gradient from galactic PN (Maciel and Köppen 1994)

(d) <u>The Galaxy: stars</u>

Other indicators than photoionized nebulae also give some information on galactic abundance gradients, such as *cepheid variables, supergiants* (cf. Pagel 1985, 1992), and *open cluster stars* (cf. figure 2, triangles). Some discrepancies are apparent from deep surveys of *red giants* (Neese and Yoss 1988; Lewis and Freeman 1989), and *B stars* in young associations (Fitzsimmons et al. 1990; cf. figure 2, dots), which seem to indicate small or no measurable gradients. Some of these results may be explained by other causes such as the time evolution of the gradients (see section 4), so that the general conclusion on the existence of the gradients remain positive.

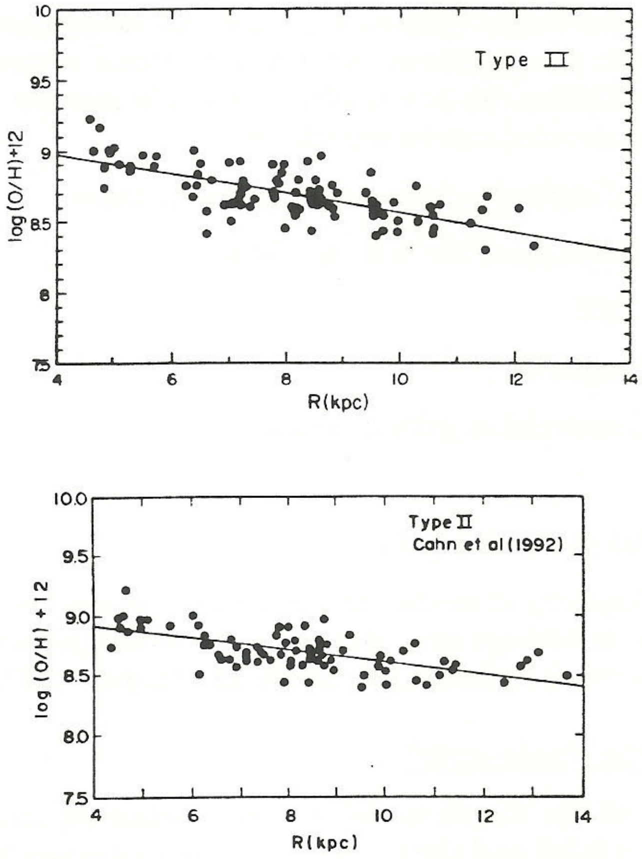

Figure 4 - The O/H gradient for type II PN with two distance scales (Maciel and Köppen 1994).

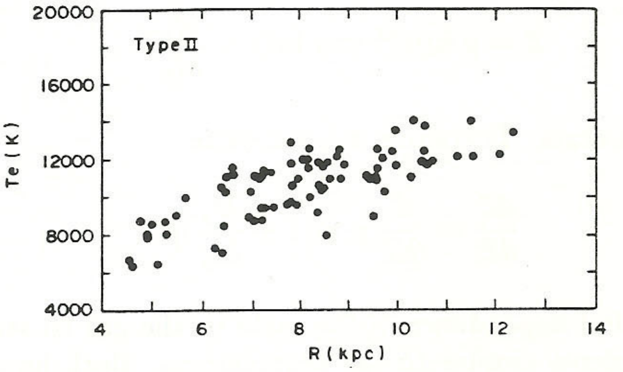

Figure 5 - The electron temperature gradient from type II PN.

4 Theory of abundance gradients

(a) Causes of abundance gradients

The connection of the abundance gradients with the chemical evolution of the host galaxy was recognized from the earliest studies (cf. Shields 1974). However, the physical processes causing the abundance variations are not well determined, despite the large number of possibilities in the literature. According to recent reviews (cf. Pagel 1992), about half a dozen possibilities can be considered, which in practice can be increased, as some of the hypotheses involved can be interchanged:

- Variations in the gas distribution in isolated concentric zones;
- Variations in the distribution of the ratio gas/stars
- Variable or bimodal IMF
- Infall of unprocessed material
- Ejection of processed material in galactic winds, etc.
- Variable yields
- Variable or self regulated star formation

In view of the multiplicity of models and associated parameters used to explain the abundance gradients, it is perhaps more instructive to investigate some consequences of the simple model of chemical evolution (cf. Searle and Sargent 1972; Tinsley 1980).

(b) An application of the simple model

In the framework of the simple model, we will assume an interstellar medium of uniform composition, no infall and the instant recycling approximation (IRA). Calling y the metal yield, the heavy element abundance Z is given as a simple function of the gas fraction $\mu = M_g/M$ (cf. Tinsley 1980; Maciel 1992), where M_g is the total surface gas mass and M is the total (gas + stars) mass:

$$Z = y \ \ln\mu^{-1} = y \ \ln(1 + \frac{M_s}{M_g}) \qquad (1)$$

where M_s is the mass in stars. Therefore, we can write

$$\frac{dZ}{dR} = \frac{d}{dR}[y \ \ln(1 + \frac{M_s}{M_g})] \qquad (2)$$

so that a convenient radial dependence of the yield or the gas to star mass ratio could produce abundance gradients similar to the observations. Both have been proposed in the literature, but let us assume for a while that the yield is constant. According to Pagel (1979), a larger fraction of the gas has turned into stars in the inner regions of the Galaxy as compared to the outer regions, which implies abundance variations in the right direction. From the calibration of Maciel (1992), we have

$$1 + \frac{M_s}{M_g} \simeq C \exp(-\alpha R) \qquad (3)$$

where $\ln C \simeq 4.6$ and $\alpha \simeq 0.3$. Adopting $Z = 26$ O/H for type II planetary nebulae (cf. Maciel 1992; Chiappini and Maciel 1994), we can calculate from (1) the oxygen abundances as a function of R for a given yield, as shown in figure 6 (Maciel 1992). The curves are labelled 1 to 6 according to the yield, from $y = 0.002$ to $y = 0.012$. It can be seen that the agreement is better for $0.004 < y < 0.010$, and some variation of the yield itself is implied from the data points, unless some flattening occurs. as proposed for some galaxies (cf. Díaz 1989). These yield values are close to the "canonical" value of 0.01, and agree with recent determinations of the oxygen yield for reasonable IMFs (Köppen and Arimoto 1991).

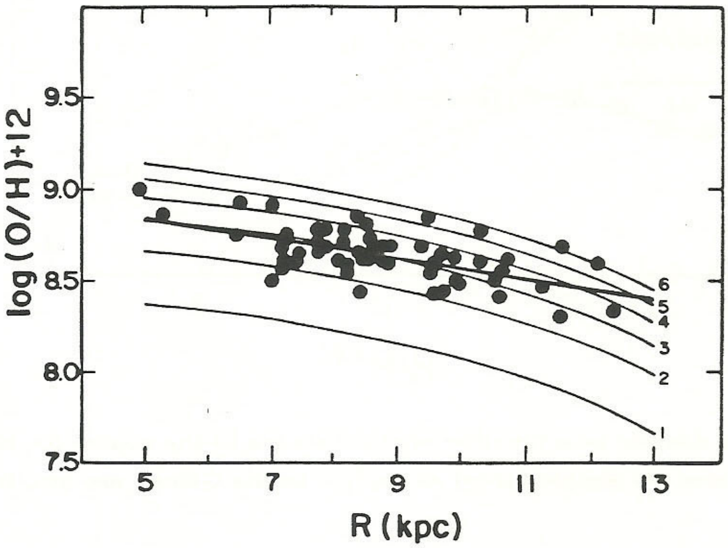

Figure 6 - Results from the simple model applied to the O/H gradient (Maciel 1992).

How can we be sure about the gas/stars variations implied by equation (3)? this is a difficult question, which is confirmed by some recent work both on the Galaxy and in other galaxies. Although the gas surface density cannot be considered constant throughout the disk (it decreases as R increases), the stellar mass decreases *faster*, so that, at least qualitatively, equation (3) holds. This can be seen from the recent calculations by Henry et al. (1992) for NGC 4303. As can be seen from figure 7, the HI gas density does not change appreciably in the inner parts of the galaxy, while the H_2 density steadily decreases, so that the total gas density also decreases. From the total disk mass variation given, the *stellar* mass can be obtained, which shows that the ratio M_s/M_g decreases as ρ increases. From the data on this galaxy, we can determine the ratio $1/\mu = M/M_g$, which is also plotted against ρ/ρ_{eff} in the figure (broken line). Also, we can calculate $1/\mu$ for the simple model from equation (3), adopting again $\rho_{eff} = 5.98$ kpc for the

Galaxy. The results are also plotted (solid line), showing that a steady decrease in the ratio $1/\mu$ is observed, although not as strong as implied by our exponential relation for the inner disk.

Apart from the yield values and implicit radial variations, other conclusions can be drawn from the application of the simple model to the observed gradients, namely, some information on the stellar mass above which black hole formation takes place, and possible variations of the IMF.

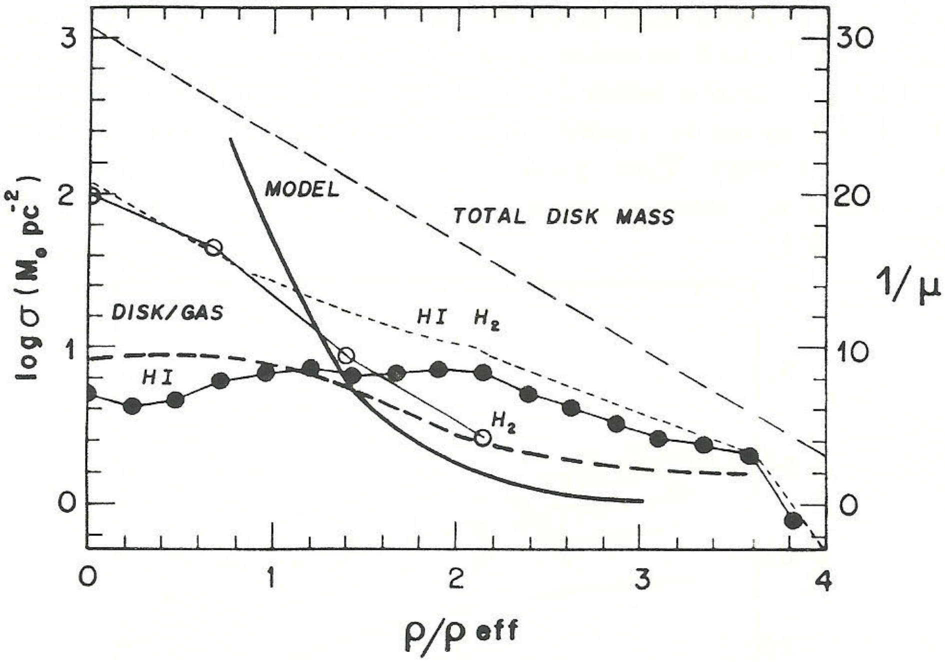

Figure 7 - Disk surface density as a function of the distance to the centre for NGC 4303 (Henry et al. 1992). Results from the simple model as applied to the Galaxy are also included.

(c) Time variations of the gradients

Some recent models have been calculated for the chemical evolution of the Galaxy, which include the effects of infall, radial flows and different gas density dependences of the star formation rate (Götz and Köppen 1992; Köppen 1994). According to these models, the existence of the radial gradients can be predicted, and also their temporal variations. Recent models by Köppen (1994) show that the initial gradient is determined by radial variations of the metal yield and the star formation timescale, and the dependence of the SFR on the gas density. Later on, this gradient can be modified by radial gas flows, depending on the infall timescale. For convenient values of the radial flow velocities (~ 1 km/s), the gradients are expected to steepen with time. This can be seen in figure 8 (Maciel and Köppen 1994), and places some important restrictions on the SFR, in the sense that the index n of the density dependence should be $1.5 > n > 1.0$. Some similar results have been obtained with the chemical evolution models reported by Mollá et al.

(1990). Their results indicate a definite increase of the O/H gradient in the last few Gyr, from calculations of three galactic rings located at different distances from the centre.

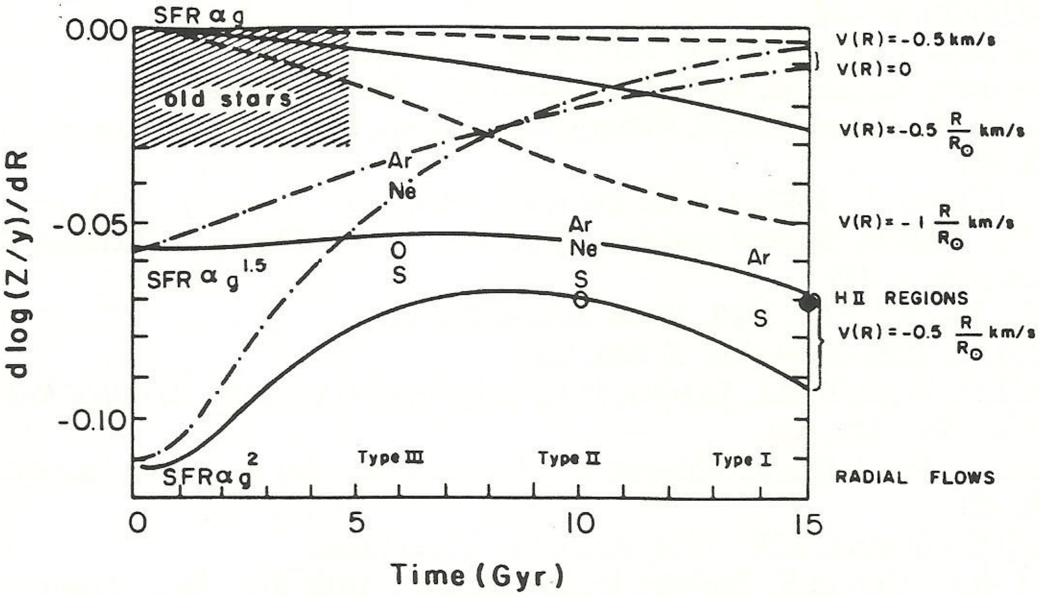

Figure 8 - Time variations of the abundance gradients (Maciel and Köppen 1994).

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