CHEMICAL EVOLUTION OF STELLAR POPULATIONS

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ABSTRACT. Stars can now mostly be separated into disk and halo members when *both* Galactic rotation velocity and metallicity are considered. New O/Fe data give results similar to α/Fe data and enable the O or α-element distribution function for the halo to be fitted to Hartwick's modification of the Simple Model up to nearly solar abundances, implying strong overlap with the disk and no sharp break in [O/Fe] when [Fe/H] $\simeq -1$. The G-dwarf problem and large-scale radial abundance gradients are discussed; in both cases, there are deficiencies in the data and too many alternative hypotheses capable of explaining them.

1. Introduction

In this talk, I make some remarks on chemical evolution of stellar populations in our Galaxy, with a few references to those of nearby galaxies such as the Magellanic clouds. Topics include: ingredients of GCE models with comments thereon, the Simple Model, the systematics of oxygen and α-element abundances relative to iron, abundance distribution functions in the halo, bulge and disk, and abundance gradients in the Milky Way and some nearby spirals.

2. Ingredients of Galactic Chemical Evolution (GCE) Models

2.1. INITIAL CONDITIONS

The most natural initial abundances to assume are the pre-galactic ones, believed to result from the Big Bang (e.g. Boesgaard and Steigman 1985). Pagel et al. (1992) have re-worked the data on helium in extragalactic H II regions and its regression relations with oxygen (cf. Peimbert and Torres-Peimbert 1974, 1976; Lequeux et al. 1979) and nitrogen (cf. Pagel, Terlevich and Melnick 1986) with various improvements including deletion of objects with definite detections of broad WR features, some of which appear to be biased by local enhancements of helium and nitrogen from stellar winds, and find the same result from both regressions: $Y_p = 0.228 \pm 0.005$ (s.e.), which does not differ significantly from our earlier estimates (e.g. Pagel 1991). More surprising is that we still find a large value of the slope of the He–O regression, corresponding to a dY/dZ of at least 3 and probably 4, which is six or seven times the value recently predicted theoretically by Maeder (1991) for these low-metallicity objects (I Zw 18 to the LMC and NGC 5461 in M 101). Pre-galactic enrichment in carbon and heavier elements now looks unlikely in view of the metallicity distribution function of halo field stars (see below), but there are still interesting question marks hanging over beryllium (cf. M. Spite in this volume).

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B. Barbuy and A. Renzini (eds.), The Stellar Populations of Galaxies, 133–142.

2.2. END-RESULTS OF STELLAR EVOLUTION

The general idea is clear: nuclear reactions in massive stars synthesize elements that are ejected into the interstellar medium (ISM) via supernova explosions and stellar winds, whereas small stars merely serve to lock up diffuse material. However, the details are far from clear, involving reaction rates, convection, mass loss, the range of masses within which stars ultimately explode, and effects of rotation and close binary evolution. Maeder (1991) has recently given theoretical estimates of yields as a function of initial mass and metallicity, assuming mass loss rates proportional to $Z^{0.5}$, but because of dY/dZ, I do not feel that this scheme is yet very close to the final answer.

2.3. INITIAL MASS FUNCTION

The IMF is another grey area. How does it go and does it vary in space or time in systematic ways that need to be taken into account in GCE theory? In our own neighbourhood, one can observe only the present-day luminosity function and the IMF depends on the past star formation rates assumed as well as on the mass–luminosity relation. In the Magellanic Clouds, steep power laws have sometimes been claimed, but recent results (Melnick 1987; Richtler, de Boer and Sagar 1991) are in agreement with Salpeter's law between 1 and 100 $M_{\odot}$, which is nominally flatter than the solar neighbourhood IMF after Scalo (1986), resulting in about three times as large a proportion of total mass in massive stars. Flattening of the slope towards low metallicities, once invoked to explain the appearance of increasing effective temperatures of ionising stars of extragalactic H II regions (Terlevich 1985), has gone away (McGaugh 1991) thanks to Maeder's (1990) models for the zero-age main sequence, but there are still cases including some blue compact galaxies and infra-red luminous starburst galaxies where "top-heavy" IMFs have been invoked for various reasons (Scalo 1990). This leads to the vexed question of bimodal star formation, which is still wide open.

Folding-in end products of stellar evolution with the IMF leads to two important quantities for GCE theory: the *returned fraction* and the *yield* of one or more elements. I refer to the yield derived in this way as the *true yield*, which is predicted on a theoretical basis to be comparable to solar abundance for carbon and heavier elements but has enormous uncertainties, as indicated above. One can define also an *effective yield*, deduced by fitting a GCE model to a set of observed abundance data. This again has considerable uncertainties, but these are probably less than those of the true yield.

2.4. STAR FORMATION RATES

The SFR is often parameterised as a power law in gas volume density or surface density. My prejudice is that only laws involving the first power make any physical sense, although the coefficient may vary as a function of ambient conditions. Two modifications of a simple linear law seem to be of particular interest:

2.4.1. *A Threshold Gas Surface Density* $\sim 8\ M_{\odot}\ \mathrm{pc}^{-2}$ for all (or just for massive) star formation (e.g. Kennicutt 1989). As discussed by Phillipps, Edmunds and Davies (1990), this can lead to a correlation between surface brightness and mean metallicity related to radial abundance gradients, and possibly to changes in the abundance ratio of intermediate-mass star products like carbon to massive-star products like oxygen.

2.4.2. *Self-Regulating Star Formation.* This can lead to wild oscillations in SFR (Hensler and Burkert 1990; Arimoto 1989) that may be relevant to bursting modes of star formation seen, for example, in blue compact galaxies. In less extreme form, it can again help to account for radial abundance gradients (Dopita 1990; Matteucci et al. 1989; Parravano 1989; Phillipps and Edmunds 1991). Stochastic self-propagating star formation (Gerola and Seiden 1978; Dopita 1985) can perhaps also be regarded as a form of self-regulation.

2.5. THE GALACTIC CONTEXT

From the theoretical point of view, this includes different scenarios of galactic evolution – one-zone models or models with inflow and/or outflow affecting the outcome. From the observational point of view, we have stellar populations – the subject of this Symposium. Their definition has been greatly clarified in recent years by the beautiful work of Norris and Ryan (1989), Carney, Latham and Laird (CLL 1990) and Nissen and Schuster (1991) on proper motion stars, which give a kinematically biased sample of disk stars (favouring the "thick disk") but a relatively unbiased sample of halo stars. While there is substantial overlap between disk and halo (as between cats and dogs) in any one property – either kinematic or chemical, or even in age – the two-dimensional scatter diagram of Galactic rotational velocity versus [Fe/H] shown by CLL and by Nissen (1991) shows a marked diagonal gap (the "Nissen line") between halo and disk stars that enables nearly all of them to be classified unambiguously as belonging to one or the other. The distinction between these two populations is confirmed by their very different metallicity distribution functions, discussed below. Bulge stars, with a different distribution function yet again, are entitled on this basis to be treated as yet another separate population, with its own distinct evolutionary history.

More controversial is the idea that the thick disk constitutes a separate population as opposed to being just what is left over from the disk before it became thin. This idea seems to be gaining popularity, but I am not convinced that the evidence for discontinuity in metallicities from the rest of the disk – to the extent that it is statistically significant – does not result from selection biases.

3. Simple GCE Models

Owing to the numerous unknowns, I prefer to deal with very simple analytically soluble models with yields chosen at will to fit the data and simple prescriptions for SFR, gas flows and time delays. A good reference standard is still provided by the Simple Model with a capital S, which is a one-zone model treated in the instantaneous recycling approximation with constant yields for "primary" nucleosynthesis products from short-lived massive stars, e.g. oxygen and α-elements (maybe). This model leads to the characteristic abundance distribution function

$$\frac{ds}{d\ln z} \propto z\, e^{-z}; \qquad z \leq \ln\left(\frac{m}{g}\right) \tag{1a}$$

$$= 0; \qquad z > \ln\left(\frac{m}{g}\right), \tag{1b}$$

where s is the mass of stars with abundance $\leq z$ in units of the yield, g the mass of gas (and dust), and $m = g + s =$ the (constant) total mass of the system. Hartwick (1976) extended this model to include loss of diffuse material from the system at a rate proportional to the (net) SFR with a factor Λ. This leads to a similar distribution but with m no longer constant and with an effective yield a factor $(1 + \Lambda)$ less than the true yield.

Many models with SFR proportional to g predict a more or less linear increase in z with time; slightly higher powers of g lead to a flattening that is barely perceptible on a logarithmic scale. Figure 1 shows the prediction of such a linear model going through the Sun and assuming a Galactic age of 16 Gyrs compared to the data for a sample of field stars from the HD Catalogue by Gustafsson (in this volume) and collaborators. The arithmetic mean abundance at a given age is fairly well fitted by this linear model, but the scatter is large and well above likely experimental errors, and there are undoubtedly significant selection effects. Ages less than a few Gyrs may also need to be increased to allow for convective overshoot (Maeder and Meynet 1989).

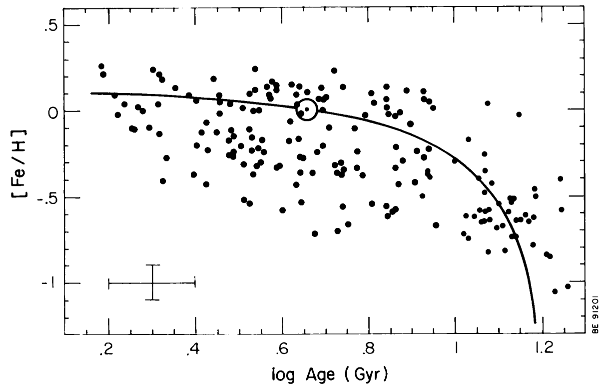

Figure 1. Age–metallicity relation for F stars in the HD catalogue by Gustafsson (these proceedings) and collaborators. The curve is based on a naive GCE model which assumes [Fe/H] = log{(16 – A)/11.4}, where A is the age in Gyr. The position of the Sun is shown, as is an estimated error bar of ±0.1 dex in each coordinate.

4. α/Fe and O/Fe Relations

Aller and Greenstein (1960) discovered a so-called α-rich effect (cf. Wallerstein 1962) in metal-deficient stars, i.e. Mg, Si, Ca, S and Ti are deficient by smaller factors than iron in Galactic disk and halo stars for which [Fe(H] < 0. A corresponding effect was later discovered for oxygen in Arcturus (Gasson and Pagel 1966) and in a sample of red giants in general (Conti et al. 1967) using the forbidden [O I] line λ 6300. Tinsley (1979) suggested that the effects result from a failure of the instantaneous recycling approximation for iron, to which a substantial contribution comes from Type I supernovae taking a significant amount of time (~1 Gyr) to complete their evolution, and this kind of model has been studied in detail by Matteucci et al. (e.g. Matteucci and François 1989) and also analytically (Pagel 1989a). In such models, halo stars are expected to have a plateau with [α/Fe] = [O/Fe] $\simeq$ 0.5, as is suggested by many observations, and then at some point in [Fe/H], depending on the time scale for SN I relative to the time scales for formation and enrichment of the halo and disk, [α/Fe] and [O/Fe] go down with increasing Fe/H to hit and pass through solar values. This subject has been well reviewed by Wheeler, Sneden and Truran (1989), who point out that [O/H] (rather than [Fe/H]) forms the best available "clock" to provide a (nonlinear) time-equivalent to measure progressive enrichment of the ISM. However, the existence of this plateau has been challenged by Abia and Rebolo (1989), who measured permitted, high-excitation O I lines in halo dwarf stars and found a continuous rise in [O/Fe] towards lower [Fe/H]. Furthermore, there could be a different sort of explanation for the [O/Fe] effect if the relative yields vary systematically as a function of metallicity (Maeder 1991) or something else.

Recent studies of [O I] (Nissen 1991) and OH (Bessell, Sutherland and Ruan 1991) have tended to cast doubt on the results derived from permitted oxygen lines at all metallicities; they could be incorrect partly because of non-LTE effects (Kiselman 1991), but mainly because these high-excitation lines are sensitive to small changes of temperature in relatively deep layers of stellar atmospheres, where the models are still uncertain. In contrast to the old picture accepted by Matteucci and François (1989), Pagel (1989a) and Gilmore, Wyse and Kuijken (1989), in which halo stars were thought to have a plateau with [O/Fe] $\simeq$ 0.5 extending to [Fe/H] $\simeq -1$ (sometimes regarded as a transitional metallicity between halo and disk), followed by a roughly linear descent through the Sun, the new oxygen data of Bessell, Sutherland and Ruan, as well as the ensemble of α-element data presented by Andersen, Edvardsson, Gustafsson, Nissen and Lambert, and by Ryan, Norris and Bessell (1991) seem to be better represented by the relation

$$[\mathrm{O/Fe}] \simeq [\alpha/\mathrm{Fe}] \simeq 0.5;\ [\mathrm{Fe/H}] \leq -1.7 \tag{2a}$$

$$\simeq -0.3\ [\mathrm{Fe/H}];\ [\mathrm{Fe/H}] \geq -1.7, \tag{2b}$$

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which means that halo stars with [Fe/H] > -1.7 are already affected by whatever it is that leads to the production of additional iron (relative to oxygen and α-elements) over and above the production from the first massive stars that presumably caused the initial enrichment of the halo. On the differential time-scale hypothesis, this suggests a longer time scale than 1 Gyr for formation of the halo (plausible on other grounds, such as age differences) and/or a contribution to iron from stars with larger masses than the standard SN Ia models. The hypothesis also implies that there should be cosmic scatter in the O, Fe relation, which may well be the case.

Can one discriminate between the above-mentioned differential time-scale hypothesis and the alternative suggestion that Fe/O production ratios increase with metallicity, either owing to mass loss and other factors in stellar evolution (Maeder 1991) or owing to changes in IMF? In principle we can, by comparing [Fe/O] in young metal-deficient stars of the Magellanic Clouds with the values in old metal-deficient stars of the Milky Way (Dopita 1990), or in old metal-rich stars of the Galactic Bulge with younger metal-rich stars of the solar neighbourhood (Matteucci and Brocato 1990; Barbuy and Grenon 1990; Matteucci 1991). Data available at present seem to marginally favour the differential time-scale hypothesis, but the full picture is not yet clear.

5. Metallicity Distribution Functions

The nice thing about the Simple Model with instantaneous recycling is that the abundance distribution function (equation 1) is independent of the star formation history. The price that one has to pay for this is that one needs to study an element to which the assumptions of instantaneous recycling and constant yield apply, and they clearly do not apply to iron (except along the [O/Fe], [α/Fe] plateau). They may apply well enough to oxygen and α-elements, so that it is their distribution function that should be compared to the prediction.

In fig. 2, I have taken the [Fe/H] distribution function for halo field stars lying below the gap near the Nissen line in the (V_{rot}, [Fe/H]) diagram of Carney, Latham and Laird (1990) and converted [Fe/H] into [O/H] using a relation similar to equation 2. It fits quite well on to Hartwick's modification of the Simple model with an effective yield $p/(1 + \Lambda) = 10^{-1.1}\, Z_{\odot}$, suggesting that 90% of the halo gas was lost in parallel with star formation if the true yield for oxygen and α-elements is $10^{-0.1}\, Z_{\odot}$, which fits the solar neighbourhood abundance distribution (Pagel 1989a).

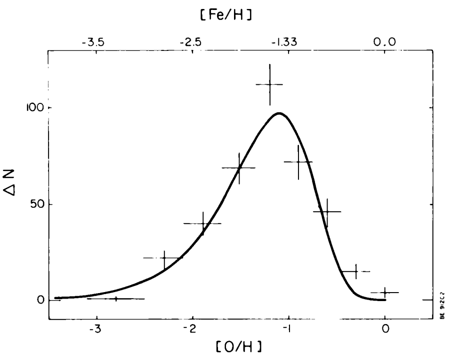

Figure 2. Distribution function of oxygen abundances in stars of the Galactic halo taken from CLL's (1990) plot of rotational velocity against [Fe/H] and assuming

$$[O/Fe] = 0.5;\ [Fe/H] \leq -2$$
$$= -0.25\ [Fe/H];\ [Fe/H] > -2.$$

ΔN is the number of stars in a bin of width 0.3 dex in [O/H]. Vertical error bars are $\pm\sqrt{\Delta N}$ and horizontal bars show the widths of the bins actually used. The curve is based on the Simple model, with an effective yield $10^{-1.1}\, Z_{\odot}$ for oxygen.

Of course, the true yield could have been higher with more than 90% mass loss, in which case there might have been enough material initially in the halo and bulge to form the disk. Alternatively, the halo distribution function can be fitted by a different model involving an inhomogeneously collapsing halo (Malinie, Hartmann and Mathews 1991). The most striking feature about this distribution function is the wide range in metallicities, corresponding to a Simple model that has gone to complete gas exhaustion (cf. Searle and Zinn 1978). As first noted by Beers, Preston and Shectman (1986) and Beers (1987), the Simple model works towards extremely low metallicities, indicating that there is no evidence for pre-galactic oxygen or metal production; but equally striking is the fact that high metallicities are also found overlapping very extensively with disk stars up to about solar abundance. Disk stars themselves go down as far as the peak of the halo distribution function at [Fe/H] = −1.6 (Morrison, Flynn and Freeman 1990), and there no longer seems to be a sharp halo–disk transition near [Fe/H] = −1, such as was deduced from the metallicity and spatial distributions of globular clusters (Zinn 1985; Pagel 1989b). How these fit into the new picture is not yet clear, owing to small-number statistics and some problems in their metallicity scale.

The Simple model also gives a good fit to the metallicity distribution in the Galactic Bulge (Rich 1988, 1990; Geisler and Friel 1990), but this time with a large effective yield of twice solar metal abundance (mainly, though not exclusively, iron), which may correspond to a still higher factor in oxygen abundance if the bulge stars are very old. This figure could perhaps represent the true yield in both the bulge and the halo, with applications to the G-dwarf problem in the solar neighbourhood, the problem consisting in the fact that the Simple model does not fit in this case (van den Bergh 1962; Schmidt 1963; Pagel and Patchett 1975); cf. fig. 3.

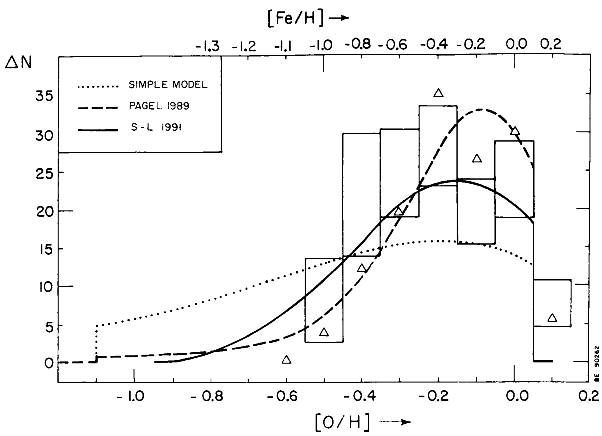

Figure 3. Distribution function of oxygen abundances for G-dwarf stars in a cylinder through the Sun perpendicular to the Galactic plane after Pagel (1989a,b: triangles) and Sommer-Larsen (1991: boxes). Curves represent a Simple model with modest prior enrichment from the halo and inflow models by Pagel (1989a) and Sommer-Larsen (1991), respectively. ΔN is the number of stars in a bin of width 0.1 dex in [O/H] and the heights of the boxes include both sampling errors and uncertainties in the correction from the solar neighbourhood to the solar cylinder.

Numerous (really too many) solutions to the G-dwarf problem have been proposed, including:

1. The oldest stars have either evolved away (Biermann and Biermann 1977; Bazan and Mathews 1990; but cf. Mould 1976) or moved away towards central parts of the Galaxy (Grenon 1989), so No Problem!

2. Larger yields at low metallicities owing to IMF (Schmidt 1963) or effects on stellar evolution (Maeder 1991). However, data on extragalactic H II regions rather suggest the opposite effect (Peimbert and Serrano 1982; Edmunds and Pagel 1984).

3. Prior enrichment from the halo and bulge (Ostriker and Thuan 1975; Binney and Tremaine 1987; Köppen and Arimoto 1991), viable if the true yield is large enough to accommodate the present halo : disk ratio deduced from star counts.

4. Inflow of unprocessed (or only slightly processed) material, corresponding to gradual formation of the disk (Larson 1976; Lynden-Bell 1975, 1991; Clayton 1985; Pagel 1989a; Sommer-Larsen 1991). This is still my favourite, partly because it makes dynamical sense and partly because it

readily accommodates the "metal-weak thick disk" (Morrison, Flynn and Freeman 1990). However, there should probably be a moratorium on discussions of the G-dwarf problem until there is an improved data base generally available.

6. Radial Abundance Gradients in Spiral Galaxies

Abundance trends between and across galaxies, deduced from observations of emission lines in H II regions, can provide a useful perspective supplementing the picture derived from individual stars in our Galaxy and members of the Local Group. Pagel (1981), Edmunds and Pagel (1984), and Axon et al. (1988) have given some comparisons between oxygen abundances in extragalactic H II regions and rough estimates of the gas fraction (a more detailed discussion is in preparation by Vila-Costas and Edmunds 1992), which suggest a crude fit to the Simple model prediction

$$z = \ln(m/g) \tag{3}$$

(Searle and Sargent 1972) with a rather low yield $p \simeq 0.2\ Z_\odot$ for oxygen in dwarf and Magellanic irregulars. There is a rather more impressive correlation between oxygen abundance and absolute luminosity of the parent galaxy (Skillman, Kennicutt and Hodge 1989) or maybe its mean surface brightness (Phillipps, Edmunds and Davies 1990). McCall (1982) and Edmunds and Pagel (1984) found a good correlation of oxygen abundance with total local mass surface density in different parts of spirals, while other authors have suggested a universal radial gradient in spirals of about -0.07 dex kpc^{-1} (Dufour et al. 1980; Belley and Roy 1991) similar to the one found for Milky Way H II regions (Shaver et al. 1983) and planetary nebulae (Maciel 1991). Other indicators like cepheids, open clusters and supergiants give a similar result in our Galaxy (see review by Pagel 1985), but there are also discrepant results from deep surveys of red giants (Neese and Yoss 1988, Lewis and Freeman 1989) and from B stars in young associations (Fitzsimmons et al. 1990), both of which suggest negligible gradients, apart from the young association Dolidze 25 at a galactocentric distance of 13 kpc (Lennon et al. 1990). These discrepancies are difficult to understand, but we believe that the existence of appreciable gradients in ISM abundances is well attested by the data on H II regions in external spirals (cf. Vila-Costas and Edmunds 1992).

Numerous causes for abundance gradients have been suggested, including:

1. Straightforward gas fraction effect in isolated concentric zones (Searle and Sargent 1972), driven by time-scale variations in SFR and/or a gas surface density threshold for star formation (Phillipps, Edmunds and Davies 1990 and references therein) and/or self-regulated star formation (Dopita 1985; Matteucci et al. 1989; Parravano 1989; Phillipps and Edmunds 1991), which two latter can also lead to the surface density effect. The Simple model can account for a part, but not for the whole, of the range of H II region abundances deduced from observation.

2. Varying true yields from a bimodal IMF (Güsten and Mezger 1982). This would not account for the existence of a shallower gradient in old stars compared to the ISM.

3. Ejection of hot gas in galactic winds, fountains or chimneys (Tinsley and Larson 1979; Vigroux, Chièze and Lazareff 1981; Arimoto and Yoshii 1987; Vader et al. 1988; Franx and Illingworth 1990; Lynden-Bell 1991). This is often assumed to account for low abundances in small galaxies with shallow potential wells and low escape velocities, and can be applied to isolated concentric zones to produce abundance gradients. The winds may involve the ISM in general or just hot, metal-enhanced material from supernovae; the latter hypothesis has some difficulties in accounting for the relative constancy of N/O in dwarf irregular and blue compact galaxies (Pagel et al. 1992).

The remaining hypotheses abandon the Simple one-zone model:

4. Inflow of unprocessed material from outside the disk (good for the G-dwarf problem), with radial variations in the inflow and star formation rates (Tinsley and Larson 1978; Chiosi 1980; Díaz

and Tosi 1984; Pagel 1989a; Sommer-Larsen 1991). The numerical model by Matteucci and François (1989) gives separate abundance gradients for different elements, taking into account non-instantaneous recycling, and explains some otherwise mysterious differential gradients that we seem to observe, in particular a flatter gradient in sulphur than in oxygen (Shaver et al. 1983; Vilchez et al. 1988; Díaz et al. 1991; Henry et al. 1992). It seems that sulphur (and presumably neon) may be better candidates for instantaneous recycling than oxygen itself! However, Garnett (1990) finds no significant change in S/O in extragalactic H II regions with abundances below solar.

Abundance gradients are not necessarily generated, but they can be substantially modified, by:

5. Radial gas flows arising either from a mismatch of angular momentum between infalling gas and the part of the disk on which it falls (Mayor and Vigroux 1981; Lacey and Fall 1985; Pitts and Tayler 1989) or from viscous transfer of angular momentum, which is also helpful in accounting for exponential disks (Sommer-Larsen and Yoshii 1989, 1990; Clarke 1989, 1991).

Playing with all these ideas is fun, but we do need better data, not only on abundances but also on ambient structural parameters such as H I and H_2 column densities, mass surface densities, disk–bulge deconvolution, and the nature and distribution of dark matter, in order to gain some more understanding of how abundance gradients arise.

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DISCUSSION

A. Maeder: In order to derive the dY/dZ ratio from H II regions, you have with reason removed those regions showing WR signatures, since these H II regions are polluted by the winds of WR stars which enrich them in helium. I want to emphasize that the other H II regions may also be severely polluted for two reasons: (1) New helium is not only ejected in WR stars, but in all phases before; (2) the ages of WR stars are very small: after about 4–5 millions of years, they are turned off. Thus, you do not see them, but their pollution is there, contributing to increase the dY/dZ ratio. Thus, I would suggest that future analyses carefully consider this important effect before making comparisons with the models.

B. Pagel: A necessary (though not suffient) condition for local pollution by winds to be suspected is the appearance of "secondary" nitrogen, i.e. an excess of N/O above the value of about 0.035 that is typical of low-abundance extragalactic H II regions, the excess increasing with oxygen abundance. No such excess is noticeable in any but the three most oxygen-rich of the 19 objects that we have used, and the deletion of these does not affect the result significantly.

G. Meurer: How long do starbursts last – especially those in dwarf galaxies? I ask because the standard timescales of $10^6 - 10^7$ years are derived by assuming closed box models, and we know that dwarf galaxies not only can undergo stellar winds but are observed to do so (NGC 1705, Meurer et al. 1991, A.J. submitted). If you look at these starburst dwarf galaxies, we see strong emission lines but relatively red colours, even after correcting for underlying populations. If continuous star formation models are adopted, these bursts may have ages of the order of Gyrs.

B. Pagel: A possible way might be to study the strength of WR features relative to model predictions (Arnault, Kunth & Schild, AA 224, 73, 1989). The problem is that I do not really trust the model predictions.

H. Dottori: About the duration of the starbursts. I want to point out that the simultaneous presence of WR and red supergiant features in the spectrum of the jumbo H II region of NGC 3310 implies, within the framework of Maeder's models, that at least in this case the burst duration must be of the order of 10^7 years.