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ABUNDANCES IN STELLAR POPULATIONS AND THE INTERSTELLAR MEDIUM IN GALAXIES

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1. INTRODUCTION

Like ancient Gaul, abundance data relevant to the study of nucleosynthesis in the course of stellar and galactic evolution can be broadly divided into three parts: abundances of the various elements and their isotopes in the Solar System; composition peculiarities in the visible layers of individual stars, planetary nebulae, young supernova remnants, cosmic ray sources, etc. due to thermonuclear (or other) processes that have taken place in the course of the internal evolution of the stars themselves; and the composition of the interstellar medium (ISM) at different places and times as judged either from direct observations of the ISM at the present time or from characteristics of the various stellar populations that are taken as being identical to those of the ISM at the time and place where the respective stars were born.

The Solar System provides the richest source of data that we have, thereby giving us both a cross section through the effects of past nucleosynthesis in the neighborhood of the Sun and a standard to which the more limited data for other objects can be compared; while abundances in evolved stars, planetary nebulae, and young supernova remnants (SNR) provide direct information on nuclear and mixing processes in stellar evolution that are believed to be responsible for continuing enrichment of

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the ISM in heavy elements and to be much like the corresponding processes that have produced the abundance distribution in the ISM today, which—in our own neighborhood—is fairly similar to the standard solar-system distribution.

The present article is concerned with the third aspect of astrophysical abundances, relating to the ISM and stellar populations. This aspect, like the others, has benefited from substantial advances in instrumental technique and theoretical modeling in recent years, which have made it possible to make a number of definite assertions about the composition of individual stars and H II regions, and about certain isotopic ratios in the diffuse ISM. The accuracy still varies widely, ranging from perhaps ± 10 percent for the He/H ratio in some H II regions to ± 0.1 to 0.3 dex for typical spectroscopic determinations of specific elements in individual objects. The study of stellar populations in remote galaxies, where only the integrated light can be observed, still presents severe difficulties, and even when H II regions are present and can be fairly accurately analyzed to give gas-phase abundances in the ISM, one cannot automatically assume that the results apply to the underlying stellar population, which in general will cover a wide range of ages.

Owing to limited space, we cannot review here all topics related to our subject; in particular, we can refer only in passing to models of galactic chemical evolution for which the reader should see the articles by Audouze & Tinsley (1976), Tinsley (1980), and Pagel (1979b, 1981). The entire field of astronomical abundances, as it looked six years ago, has been reviewed by Trimble (1975). Other relevant articles, which we shall essentially take as read, are those of van den Bergh (1975: Stellar Populations in Galaxies), Peimbert (1975: Extragalactic Gaseous Nebulae), Baschek (1979: Abundances in Evolved Stars), Kraft (1979: On the Nonhomogeneity of Metal Abundances in Globular Clusters and the Satellite Subsystems of the Galaxy), and Harris & Racine (1979: Globular Clusters in Galaxies). Globular clusters are also reviewed by K. C. Freeman and J. Norris in this volume.

The plan of the present article is as follows. In Section 2 we review the results in our own neighborhood, which is of special interest because of the relatively large amount of detailed information available for a sufficient number of stars to permit statistical discussions of such important topics as the age-metallicity and number-metallicity relations and primordial variations among different elements. In Section 3 we consider more large-scale trends, i.e. abundance gradients in the disk and halo of our Galaxy, the diffuse ISM, and molecular clouds. The remainder of the article is devoted to other galaxies, which raise special problems in abundance determination. The various indicators (statistical properties

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of stars, emission nebulae, and integrated light from stellar populations) and their virtues and limitations are discussed in Section 4, while in Section 5 we attempt to summarize what is known about Irregular (and Blue Compact) galaxies, Ellipticals, Dwarf Spheroidals, and Spirals, with special reference to abundance gradients, the nitrogen:oxygen ratio, and overall mass-metallicity relations. We give some brief conclusions and suggestions for future work in Section 6.

2. THE SOLAR NEIGHBORHOOD

We regard the solar neighborhood, somewhat loosely, as the region within which fairly accurate abundances of elements can be determined by stellar spectroscopy, i.e. that within a distance of the order of a kiloparsec. Important topics are (*a*) the standard abundance distribution in stars and the interstellar medium (ISM) and its uniformity (or otherwise); (*b*) the age-metallicity relation; (*c*) the statistical distribution of metallicities in long-lived stars; and (*d*) abundance anomalies of individual elements or isotopes that are considered as population-related, rather than due to processing in the observed stars themselves.

2.1 *Standard Abundance Distribution*

Most of our "standard" abundances come from observations within the Solar System (e.g. Cameron 1980), but a comparison with abundances in the ISM and in hot young stars gives an idea of the degree to which solar abundances are truly "cosmic" and provides some insight into the uncertainties in all three sources of data. Recent abundance determinations for some common elements are compared in Table 1, which shows that there is little difference between the Sun, young stars, and the local present-day ISM. The most disturbing discrepancy is that oxygen and nitrogen seem to be underabundant in Orion (and other nearby galactic H II regions) and in the Cygnus Loop SNR by a factor of 2 or so, which needs to be borne in mind when one tries to put together stellar and nebular data in order to study large-scale trends within and between galaxies. The discrepancy in Orion has been discussed by Meyer (1979), who finds that condensation on grains could account for part (but probably not all) of the discrepancy. [There is evidence for a stronger depletion of iron (Peimbert 1979a) and presumably other refractory elements.] Isotope ratios of C, N, O, Si, and S in the local ISM (Penzias 1980, Wannier 1980) differ from solar-system values by factors that are significant in the first three cases, but always less than 2. The interstellar D/H ratio, while on average consistent with the solar-system value, shows large local

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Table 1 "Cosmic" abundances of some common elements

	12 + log He/H	12 + log O/H	log O/C	log O/N	log O/Ne	log O/S	12 + log Fe/H
Sun							
Photosphere[a]		8.9	0.2	0.9		1.7	7.6
Prominences[b]	10.8						
Corona[c]				0.9	1.1		
B stars	11.0[d]	8.9[e]	0.5:[f]	1.0[e]	0.9[g]		7.5[f]
Orion Nebula	11.0[h]	8.6[i]	0.1[i,j]	0.9[h]	0.7[k]	1.3[l]	6.7[m]
Cygnus Loop[n]		8.5	0.2	0.7		1.8	
Disk planetary nebulae[o]		8.7					

[a] Lambert 1978, Lambert & Luck 1978, Blackwell & Shallis 1979
[b] Hirayama 1971
[c] Walker, Rugge & Weiss 1974
[d] Leckrone 1971
[e] Kane, McKeith & Dufton 1980, Dufton, Kane & McKeith 1981
[f] Hardorp & Scholz 1970, Kodaira and Scholz 1970
[g] Auer & Mihalas 1973
[h] Peimbert & Torres-Peimbert 1977
[i] Torres-Peimbert, Peimbert & Daltabuit 1980
[j] Bohlin et al. 1980
[k] Meyer 1979
[l] Lester, Dinerstein & Rank 1979
[m] Peimbert 1979a
[n] D'Odorico & Dopita 1980
[o] Kaler 1980

variations (Vidal-Madjar et al. 1978 and references therein, Laurent, Vidal-Madjar & York 1979).

2.2 *Age-Metallicity Relation*

Stellar abundances in the solar neighborhood have been reviewed by Pagel (1979a), to which the reader is referred for a brief account of the methods used. Relatively unbiased surveys such as that of Bond (1970) or an inspection of the *Bright Star Catalog* (B.S.C.) indicate that the vast majority of stars have values of "metallicity," i.e. [Fe/H] (where $[X]$ denotes the logarithm of any quantity X in a star minus log X in the Sun), that have a Gaussian distribution with mean $\simeq -0.15$ and standard deviation $\simeq 0.2$, with only 3 stars out of about 10^4 in the B.S.C. forming a separate population (extreme Population II) with $-2.6 \leq [\mathrm{Fe/H}] \leq -1.3$ and extreme kinematic properties, which may be shared by all late-type stars having $[\mathrm{Fe/H}] < -0.6$ (Eggen 1979). A catalogue of spectroscopic [Fe/H] determinations has been published by Cayrel et al. (1980). The existence of "super metal-rich" (SMR) stars (Spinrad & Taylor 1969), with very strong CN, Mg I, and Na I, of which the best-known prototype is the giant μ Leo, has aroused much controversy (Peterson 1976, Bonnell & Branch 1979 and references therein, Deming 1980, Pritchet & Campbell 1980). Our inclination is to believe the concordant results of high-dispersion spectroscopy in the infrared (Branch, Bonnell & Tomkin 1978)

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and photoelectric narrow-band spectrum synthesis studies (Williams 1971, Gustafsson, Kjaergaard & Andersen 1974, Edmunds 1976), which indicate $0.3 \leq [Fe/H] \leq 0.6$ for this star. The existence of SMR stars is also supported by observations in visual binary systems (Deming & Butler 1979). However, they are neither extreme enough (in contrast to the halo stars) nor numerous enough to affect the approximate statistical description given above and they are not present (as was once suspected) in the galactic clusters M67 and NGC 188 (e.g. Pagel 1974 and references therein, Janes 1974, Griffin 1975, 1979, Cohen 1980a,b); their importance lies more in the implications of the inclusion of μ Leo-like stars in stellar population syntheses to account for the integrated spectra of the nuclear regions of large galaxies. The intrinsic metallicity dispersion of the nearby stars, after age effects, abundance gradients, and observational errors have been allowed for, is believed not to exceed 0.15 dex (Mayor 1976).

Eggen, Lynden-Bell & Sandage (1962) studied the kinematics of extremely metal-poor stars and showed that they have large eccentricities and motions perpendicular to the galactic plane, extending over a wide range. On the plausible hypothesis that these are the oldest stars in the solar neighborhood, this suggests that they were born during a phase of rapid collapse in which the galactic halo was formed, followed by a dissipative phase that eventually gave rise to the disk. Age dating of globular clusters (Demarque 1980) gives a nominal range of a few Gyr between the oldest (most metal-deficient) and youngest (least metal-deficient), but in view of various uncertainties about the systematic effects of chemical composition on age estimates, combined with recent doubts about the actual metallicity of the more metal-rich clusters, we cannot regard this result as conclusive (cf. van Albada, de Boer & Dickens 1979).

In contrast to the situation in the halo, star formation in the disk has been an ongoing process over a significant time of the order of 10^{10} years and the simplest ideas on galactic chemical evolution lead one to expect a steady enrichment with time, unless the results of nucleosynthesis are counteracted by some effect like inflow of unprocessed material (e.g. Audouze & Tinsley 1976). The resulting age-metallicity effect has proved difficult to establish because of problems of calibration and observational selection, combined with the facts that the metallicity range of disk stars is fairly small and that the relatively easily dateable galactic clusters cover only the latter half of the age span of the disk. [Ages and metallicities of clusters have been listed by Demarque (1980).] The best data on the age-metallicity relation come from studies of the Strömgren colors of field stars of spectral type F by Mayor (1976) and Twarog (1980), the latter, in particular, including significant corrections for helium abundance and selection effects not included in previous work. The resulting relations

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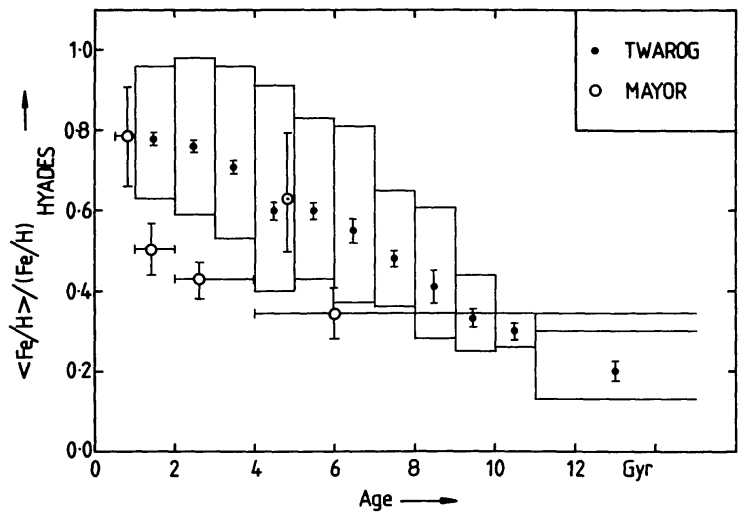

Figure 1 Relation between age and geometric mean metallicity (actual value relative to Hyades), deduced from Strömgren *uvby* β colors of F stars in the solar neighborhood. Filled circles: Twarog, with error bars denoting the standard error of the mean; boxes indicate widths of age bins and sample standard deviation within each bin. (Twarog's youngest age bin is omitted because he gives it little weight.) Open circles: Mayor; vertical error bars denote systematic calibration uncertainties while horizontal error bars denote widths of age bins. The position of the Sun is shown, following the Sun-Hyades calibration by Branch, Lambert & Tomkin (1980).

(Figure 1) differ considerably in detail owing to the use of different stellar evolutionary models, etc., but the general trend appears well established and can be regarded as being more or less linear in actual (not logarithmic) abundances.

2.3 *Metallicity Distribution*

The narrow distribution of metallicities in long-lived stars, such as the G dwarfs (van den Bergh 1962, Schmidt 1963) or M dwarfs (Mould 1976), has been extensively discussed as a constraint on galactic enrichment models (e.g. Lynden-Bell 1975, Audouze & Tinsley 1976, Tinsley 1980, Pagel 1981); the G-dwarf data were discussed by Pagel & Patchett (1975), who found that the metallicities in a cylinder at right angles to the galactic plane fitted a Gaussian distribution with a mean $[Fe/H] = -0.3$ relative to the Hyades (for which $[Fe/H] = +0.20 \pm 0.10$ relative to the Sun; Branch, Lambert & Tomkin 1980) and a dispersion in the raw data of about 0.25. After applying somewhat uncertain corrections for observational error and cosmic scatter (due to abundance gradients and perhaps other effects), Pagel & Patchett adopted for the intrinsic distribution due to the age-metallicity relation a truncated Gaussian with an effective dispersion between 0.075 and 0.18. Some implications for the past rate

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of star formation in the solar neighborhood have been discussed by Pagel (1981).

The above figures refer to disk stars, which form the vast majority of stars in the solar neighborhood. The distribution in the halo is relatively much wider (Hartwick 1976, Searle & Zinn 1978) and is closer in form to that predicted by the "simple" model of galactic chemical evolution. According to Bessell (1977) and Carney & Peterson (1980), stars can be found with [Fe/H] < -3, but Bond (1980) finds the number of such stars to be very small, suggesting that a tiny degree of "prompt initial enrichment" may have preceded the formation of any low-mass stars even in the halo.

2.4 *Primordial Variations in Relative Abundances*

Primordial variations in relative abundances of different nuclear species are expected as a consequence of the existence of various nucleosynthesis processes taking place in different sites and, therefore, affecting the interstellar medium at different rates. However, such variations (as opposed to those caused by self enrichment affecting stellar atmospheres in later phases of evolution) have proved quite difficult to establish and for a long time it was possible to say that all the elements from carbon upwards vary in lockstep, within the uncertainties of observation (e.g. Unsöld 1974), and also that for moderate values of [Fe/H], such as found in disk stars, [Fe/H] can still be regarded as a good indication of relative heavy-element abundance although carbon and oxygen are the main individual contributors to this (about 20 and 45 percent, respectively). In the more extreme cases, however, primordial variations in some elements and even isotopes are now well established (cf. Pagel 1979a). In what follows, we briefly summarize the present status of primordial abundance variations in individual elements relative to Fe or other standards when appropriate.

Evolution of the *light* elements (Li, Be, B), which are affected by destruction at stellar surfaces, has been discussed by Reeves & Meyer (1978). *Carbon* shows little or no specific abundance variation in unevolved field stars (Peterson & Sneden 1978 and references therein) whereas *nitrogen* shows a significant tendency to be deficient in weak-metal stars, though with exceptions (Harmer & Pagel 1970, 1973, Tomkin & Bell 1973, Sneden 1974, Clegg 1977, Sneden & Peterson 1977, Pagel 1979a). Variations in N/O in the interstellar medium are discussed below. *Oxygen* in weak-metal stars is usually deficient by smaller factors than iron, with [O/Fe] ≤ 0.6 (Sneden, Lambert & Whitaker 1979), and observations of halo planetary nebulae suggest a similar result for both O and Ne (Peimbert 1978, Kaler 1980). These generalizations do not necessarily apply to the stars in

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globular clusters, where some of the variations in CH, CN, and CO seem to be too drastic—and to extend too far down towards the main sequence—to be explained by mixing effects alone (see Kraft 1979; but cf. Cohen 1980a) and positive [O/Fe] values have not been found in M13 (Pilachowski, Wallerstein & Leep 1980), although they are found, or may be present, in several other clusters such as M92, M15 (Cohen 1979b), M3, M5 (Pilachowski, Wallerstein & Leep 1980), NGC 288 (Pilachowski & Sneden 1980), M71, and ω Cen (Cohen 1980a,b, Mallia & Pagel 1981). The primordial (C + N + O)/Fe ratio is probably not the "second parameter" affecting horizontal-branch types (cf. Kraft 1979, Pilachowski, Wallerstein & Leep 1980, Zinn 1980b) because both M13 and NGC 288 are of the "blue" HB type (Pilachowski & Sneden 1980).

Elements from *sodium* to *silicon* show odd-even effects in some of the most metal-deficient stars, as is predicted by the theory of explosive carbon burning (Arnett 1971; but cf. Arnett & Wefel 1978), superposed on a small enhancement of the "α-particle" elements Mg, Si, Ca, Ti relative to iron (Wallerstein 1962, Peterson 1981 and references therein). Particularly striking is the factor of 4 deficiency of ^{25}Mg and ^{26}Mg relative to ^{24}Mg in the subdwarf Groombridge 1830 (Tomkin & Lambert 1980). When many weak-metal stars are considered together there is a large scatter in Na/Fe and especially Al/Fe (Peterson 1981; cf. also Spite & Spite 1978, 1980). Spite & Spite have suggested that Al/Fe may be influenced by diffusion effects, and this receives some support from the fact that Peterson's Al-deficient stars are confined to a narrow range of effective temperatures, between 5800 and 6300 K. In NGC 6752, Al I features are positively correlated with CN (Norris et al. 1980), while in M13 three stars show large Na/Fe variations which may be correlated with carbon or anti-correlated with oxygen (or both) (Peterson 1980) although both clusters are quite homogeneous in [Fe/H].

The behavior of *calcium* is of some importance because of the use of the spectral-type difference ΔS as an abundance indicator in field and cluster RR Lyrae stars. Various analyses lead to an apparent spread in [Ca/Fe] at given [Fe/H] (Butler, Dickens & Epps 1978), which could be largely spurious (Butler & Deming 1979, Suntzeff 1980); Ca/Fe is then enhanced by factors close to 2 for metal-deficient stars in general, as shown in the diagram by Peterson (1981). The same applies to *titanium*. Variations within the *iron group* are virtually insignificant (Pagel 1979a), a conclusion now extended to *copper* (Peterson 1981).

Elements which (in the Solar System at least) are predominantly due to the *s-process* show a barely significant correlation with [Fe/H] for disk stars (Spite 1968, Huggins & Williams 1974) and a more significant correlation for extreme halo stars (Spite & Spite 1978); yttrium, which

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may be taken as typical of the $N = 50$ magic number peak, varies with about half of the amplitude of barium, on the $N = 82$ peak, and the latter roughly follows the relation

$$[\mathrm{Ba/Fe}] \simeq 0; \qquad [\mathrm{Fe/H}] > -1.3$$
$$[\mathrm{Ba/Fe}] = 0.6([\mathrm{Fe/H}] + 1.3); \qquad [\mathrm{Fe/H}] \leq -1.3.$$

In stating these conclusions, we are assuming that all of the so-called barium stars, with $[\mathrm{Ba/Fe}] > 0$, are self-enriched, which may not be completely true in the light of the recent result that extreme (but not mild) Ba II stars are binary (McClure, Fletcher & Nemec 1980). *Europium*, which is the only readily accessible *r*-process element in stellar spectra, varies in lockstep with iron quite closely (Butcher 1972, Spite & Spite 1978). The variations in *s*- and *r*-process elements, therefore, are *qualitatively* as expected if the latter are primary nucleosynthesis products from supernovae which also make iron and the former are secondary products of red giant evolution with mixing (typified by carbon, S, and Ba II stars), but *quantitatively* the *s*-process variations are far smaller than would be expected in a situation of steady enrichment. Models of galactic chemical evolution have yet to come to grips with this problem (cf. Tinsley 1979, 1980).

3. LARGE-SCALE TRENDS WITHIN THE GALAXY

3.1 *Abundance Gradients in Stars and the Interstellar Medium*

Various investigations of stars, H II regions, and planetary nebulae (Table 2) indicate the existence of a radial gradient in metallicity of the order of -0.05 dex kpc^{-1} in the neighborhood of the Sun (see Peimbert 1979b for a discussion and earlier references). The gradient is fairly similar for oxygen, nitrogen, and metals, except in the case of planetary nebulae, for which nitrogen shows a significantly steeper gradient than oxygen (cf. Danziger et al. 1978), but the situation is complicated by the existence of planetaries of different types involving various degrees of self-enrichment; the relation between N and O abundances will be discussed further below. Most of the gradients are in fair agreement with one another, but there is disagreement on their age-dependence (if any) and on whether the logarithmic gradient is constant or flattens off towards the Galactic center, which would correspond to an approximately linear trend in the actual abundances within a few kpc of the solar galactic radius (cf. Pagel 1979b). Supergiants give larger abundances and larger gradients than do the

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Table 2 Local abundance gradients in the galactic disk

Objects	$\frac{-\partial[\mathrm{Fe/H}]}{\partial R}$	$\frac{-\partial \log(\mathrm{O/H})}{\partial R}$	$\frac{-\partial \log(\mathrm{N/H})}{\partial R}$	Ref.
Young disk stars (dF + dG)	0.10 ± 0.02			
Old disk stars	0.04 ± 0.03			Mayor 1976
All stars	0.05 ± 0.01			
gK and open clusters	0.05 ± 0.01			Janes 1979
Cepheids (from periods)		0.08:		Peimbert 1979b
H II regions (optical spectra)		0.06 ± 0.02	0.08 ± 0.02	Talent & Dufour 1979
		0.13 ± 0.04	0.23 ± 0.06	Peimbert et al. 1978
		0.05 ± 0.03	0.10 ± 0.03	Hawley 1978
H II regions (electron temperature)		0.05:		Mezger et al. 1979
Planetary nebulae (optical spectra)		0.06 ± 0.02	0.18 ± 0.04	Torres-Peimbert & Peimbert 1977

other objects (Luck & Bond 1980) but they have been omitted from the table because of the possibility that their atmospheric compositions are affected by mixing with the interior (Luck & Lambert 1980). A further complication is that Talent & Dufour (1979) deduce significant abundance changes *along* each of the Sagittarius, Local, and Perseus arms, corresponding to a radial gradient of about -0.2 dex kpc^{-1} in any one arm—a result for which it is difficult to think of any theoretical explanation. Grénon (1972) and Janes (1975) have discussed the complications introduced by the radial gradient into the relationship between compositions and kinematic properties of disk population stars. A gradient at right angles to the galactic plane also exists (e.g. Trefzger 1981); it is of the order of -0.6 dex kpc^{-1} near the plane, but it is difficult to sort out age and purely height-dependent effects (Mayor 1976).

3.2 *The Diffuse Interstellar Medium and the Galactic Center*

Observations of element abundances in the diffuse interstellar medium and in molecular clouds are subject to depletion and fractionation effects (Spitzer & Jenkins 1975, D. G. York, in preparation), but some evidence on total abundances comes from X-ray absorption measurements (Ryter, Cesarsky & Audouze 1975), which are compatible with (but do not necessarily demand) an abundance gradient reaching an enhancement by a factor of 3 or so at the galactic center. Infrared observations of Sgr A(W) suggest an enhancement of this order in Ne and presumably other heavy

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elements relative to H (Aitken, Griffiths & Jones 1976). Molecular observations imply that the isotopic ratios $^{13}C/^{12}C$, $^{14}N/^{15}N$, $^{17}O/^{16}O$ (which are expected to be enhanced by the CNO cycle) increase by small but significant amounts in the order: Solar System, galactic disk ($R_\odot \pm 4$ kpc where $R_\odot$ is the solar galactocentric radius), galactic center by factors of up to 3 or 4, but without any significant gradient in the galactic disk (Penzias 1980, Wannier 1980).

If, as has been rather naturally supposed in some chemical evolution models (e.g. Talbot & Arnett 1974, Vigroux, Audouze & Lequeux 1976), ^{13}C, ^{14}N, and ^{17}O are secondary nucleosynthesis products from ^{12}C and ^{16}O initially present in the progenitor star, one expects their abundances relative to primary products like ^{12}C and ^{16}O to vary (in first approximation) as the total abundance of primary elements relative to hydrogen, assuming that the efficiency of secondary production is independent of stellar composition. (This assumption actually seems rather doubtful: cf. Sweigart & Mengel 1979, Rocca-Volmerange & Audouze 1979.) The galactic center isotopic abundances conform to this trend (N/O is unknown there), but the isotope and N/O ratios in the disk do not. Taking into account the N/O ratio in other galaxies (see below), several authors (e.g. Smith 1975, Edmunds & Pagel 1978, Alloin et al. 1979) have proposed that a substantial component of nitrogen is a primary product whose yield (relative to oxygen) depends on the age and/or initial mass function of the underlying stellar population and is fairly constant in any one galaxy, but Wannier (1980) argues that a more radical revision of ideas on galactic chemical evolution is needed. We believe that classical secondary production may well be taking place near the centers of our own and some other galaxies (like M81 where evidence for a large N abundance is good; M. Peimbert, in preparation), but that in most other places the evidence favors either a primary process—meaning that ^{13}C, ^{14}N, and ^{17}O come from the CNO cycle in stars that are already self-enriched in carbon by helium burning and mixing—or a form of secondary processing in which the shortage of "seeds" in low-abundance stars is more or less compensated by an increase in the vigor of mixing processes. (This could also have some relevance to the *s*-process abundances discussed in Section 2.4.) The many anomalies encountered in globular cluster red giants (e.g. Kraft 1979) suggest that both of these effects may well be operating.

Several other isotope ratios (Penzias 1980, Wannier 1980) are also of interest. D/H has an abundance gradient decreasing inwards, which agrees with cosmological synthesis and a limited degree of destruction by astration; however, the nonzero value at the galactic center implies a modest inflow of unprocessed material or a separate production source (Audouze 1977). $^{18}O/^{16}O$ is enhanced at the galactic center while $^{15}N/^{14}N$

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is depleted, both by about a factor 2. Sulphur and silicon isotopes are effectively unchanged.

3.3 *The Galactic Halo*

An abundance gradient also exists in the galactic halo, in that relatively metal-rich globular clusters with integrated spectral type G are usually confined to the "inner halo" within 10 kpc of the galactic center (Kinman 1959, Searle & Zinn 1978, Harris & Canterna 1979, Zinn 1980a; but see Cohen et al. 1980 on Pal 12, a metal-rich cluster at 14 kpc), whereas metal-weak clusters of type F are found at all galactocentric distances. The latter have $[Fe/H] \geq -2.3$ (Cohen 1979b), but in the case of the metal-rich clusters the estimated metallicities of two prototypes, M71 and 47 Tuc, have recently been drastically revised downwards from 0.0 and -0.4, respectively (Hesser, Hartwick & McClure 1977), to -1.2 (M71: Cohen 1980a,b; 47 Tuc: Pilachowski, Canterna & Wallerstein 1980), and with this revision of the calibrators carried through, the overall abundance gradient expressed as [Fe/H] virtually disappears (Zinn 1980b). These more recent estimates may well be slightly too low (cf. Zinn 1980b); e.g., for 47 Tuc, Mallia (1978) estimated $[Fe/H] \simeq -1.0$, Dickens, Bell & Gustafsson (1979) suggested -0.8, and E. A. Mallia and B. E. J. Pagel (in preparation) find $[Fe/H] = -0.9$ from a detailed analysis of 11 red giants. Observations of RR Lyrae stars in Baade's window give $\langle[Fe/H]\rangle = -0.65 \pm 0.15$ for field stars in the inner halo (Butler, Carbon & Kraft 1976). However, there is no doubt that the earlier estimates are substantially too high, and that even these "metal-rich" globulars fall below the nearby galactic clusters in metallicity, so that the difference in color-magnitude diagrams commented on by Demarque & McClure (1977) is no longer so surprising (cf. Demarque & McClure 1980). Stars of a single cluster are usually found to have identical metallicities, with the marked exception of ω Cen where they range over an order of magnitude or more (Kraft 1979 and references therein, Rodgers et al. 1979, Cohen 1980a, Mallia & Pagel 1981). M22 may possibly also have some range of metallicities (Hesser & Harris 1979).

Rodgers, Harding & Sadler (1980) have found a population of intermediate-age A-type stars with near-solar abundances up to 8 kpc from the galactic plane which they suggest could be remnants of an encounter between the Galaxy and a third Magellanic-type object some 2 billion years ago. Gas in the galactic halo also exists and produces absorption lines detectable in the ultraviolet (Boksenberg et al. 1978, Savage & de Boer 1979, 1980, Ulrich et al. 1980). Visible interstellar absorption lines from gas far out in the disks or halos of other galaxies are also seen, e.g. Ca^+ (but not Na) in NGC 3067 against the quasar 3C232 (Boksenberg

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& Sargent 1978) and in galaxies of the Klemola 31 group against Pks 2020-370 (Boksenberg et al. 1981); such gas is likely to cause many of the absorption-line systems observed in high redshift quasars in general (Boksenberg 1978, Sargent et al. 1979), but so far little is available in the way of precise quantitative abundance data.

4. OTHER GALAXIES: ABUNDANCE INDICATORS

4.1 *Individual Stars*

Direct spectroscopic analyses of individual stars are available in a few cases only which are confined—to our knowledge—to high-luminosity stars in the Magellanic Clouds and have given rather discrepant results in the past (Przybylski 1968, 1972, Wares, Ross & Aller 1968, Wolf 1972, 1973, Osmer 1973, Fry & Aller 1975, Foy 1977). Low-resolution spectra of giants in the Draco and Ursa Minor dwarf satellite systems resemble those of the most metal-weak galactic clusters (Cowley, Hartwick & Sargent 1978), and scanner measurements by Zinn (1978) of 23 giants in Draco give $\langle[\mathrm{Fe/H}]\rangle = -1.9$ with a range over a factor of 3. Stetson (1980) argued that the presumed range is due to inclusion of stars on the asymptotic branch, but a still bigger range has been found from spectral scans of the Ca^+ K line (Kinman, Kraft & Suntzeff 1981). Other techniques applicable to individual stars in satellite systems of our Galaxy are DDO photometry (e.g. Gascoigne et al. 1976; but cf. Gustafsson, Bell & Hejlesen 1977) and the broader-band (and hence more rapid) Washington photometry (Canterna & Schommer 1978). Of these methods, the scanner technique (Searle & Zinn 1978) seems to be the most precise and reliable, at least for old populations resembling those of the galactic globular clusters, but all methods are in need of recalibration at the high-metallicity end (cf. Zinn 1980b).

Many of the statistical characteristics of stellar populations are abundance-related and can be used (with due precautions) as abundance indicators within (and occasionally beyond) the Local Group. These have been reviewed by van den Bergh (1975) and will not be discussed in detail here, but they include the systematics of color-magnitude diagrams, the period and color distributions of cepheids (cf. Iben & Tuggle 1975) and other variables, and the color distribution of supergiants (cf. Humphries & Davidson 1979), with the numerical ratio B/R increasing with metallicity although in the metal-weak SMC no supergiants are detected with spectral type later than M1 (Humphries 1979). Most of these population characteristics are affected (in principle at least) by age and initial mass function

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as well as composition (the latter in itself possibly involving more than one parameter), but in some cases there is hope that these can eventually be sorted out (cf. Kraft 1979 on the "second parameter" in globular clusters). Thus, the "thick" giant branches in the Sculptor, Fornax, and Ursa Minor dwarf systems have been taken as an indication of a metallicity range similar to that in ω Cen (Norris & Bessell 1978, Demers, Kunkel & Hardy 1979), while the colors of SMC cepheids at a given period indicate a uniform metal deficiency by a factor of about 4 (Gascoigne 1969, Bell & Parsons 1972, 1974). The H-R diagrams of clusters in the Magellanic Clouds (cf. van den Bergh 1975) have been subjected to many conflicting interpretations which we do not have space to review here. The brightest and reddest stars of intermediate age in the Clouds are carbon stars (Feast & Lloyd Evans 1973, Blanco, Blanco & McCarthy 1978, Mould & Aaronson 1979, 1980) with $M_{\rm bol} \simeq -5$, as are those in Fornax (Demers & Kunkel 1979, Aaronson & Mould 1980) and Sculptor (Westerlund 1979). Infrared photometry of these very red stars provides a powerful age indicator based on the systematics of the AGB which implies that these stars are more massive and hence younger than stars of similar metallicity in Galactic globular clusters and that the metallicity spread in Fornax and the Clouds is associated with a significant age spread (cf. Norris & Zinn 1975); this is in agreement with the classification of spectral scans of the integrated light of Magellanic Cloud clusters by Searle, Wilkinson & Bagnuolo (1980) which implies a quite smooth one-to-one correspondence between these two parameters.

4.2 *Emission Nebulae*

Emission-line observations of H II regions (cf. Peimbert 1975) and mature supernova remnants have many advantages over stellar observations as a probe of current abundances in the gas phase of the ISM in remote galaxies, while planetary nebulae serve a similar function for intermediate-age stars for which, however, self-enrichment effects (often of great interest in themselves) need to be taken into account. The advantages are that emission lines due to the abundant elements H, He, N, O, Ne, S, Cl, and Ar (and C in the ultraviolet) are readily detectable at great distances and can be straightforwardly interpreted when a temperature-sensitive line ratio (usually O III $\lambda 4363/\lambda 5007$) can be measured, although for some elements (notably S, Cl, and Ar) there are uncertain ionization corrections. This is usually the case for gas-rich Irregular galaxies and compact extragalactic H II regions, and for the outer parts of Scd spirals, in which the abundances of O, etc. are low (and the ionizing stars hot; see, for example, Shields & Tinsley 1976) leading to high electron temperatures

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that can be measured. For H II regions in earlier-type spirals and in the inner parts of Scd spirals, however, the abundances are larger and the ionizing stars cooler and more blanketed, and then some form of model fitting is required which involves serious uncertainties because of a shortage of critical data. However, Searle (1971) suggested that the large-scale trends shown by H II regions in the Scd galaxies M33 and M101 ([O III]/Hβ and Hα/[N II] increase by very large factors as one goes outwards from the nucleus; cf. Aller 1942, 1956) are due to a large-scale radial abundance gradient, with O and N abundances having low values at the periphery and increasing towards the center, and this has been confirmed by Smith (1975), who measured electron temperatures in the outer regions of these galaxies, and (in the case of M101) by Shields & Searle (1978) who were able to fit a fairly unique model to the inner H II region S5 by including the [S III] lines near λ9000 and found $12 + \log(\mathrm{O/H}) = 9.1 \pm 0.2$ for this object, contrasted with a value of 8.13 ± 0.09 for the outermost H II region they observed. This result, together with confirmatory model calculations (e.g. Collin-Souffrin & Joly 1976, Stasinska 1978), has inspired a number of authors to use various strong-line ratios (for a list of data and correlation diagrams see Alloin, Collin-Souffrin & Joly 1979) as a direct indicator of electron temperatures and/or oxygen abundances (one implying the other), e.g. [O III]/Hβ (Jensen, Strom & Strom 1976), [O, III]/[N II] (Alloin et al. 1979), and ([O III] + [O II])/Hβ (Pagel et al. 1979), and a tentative calibration of all three line ratios has been given by Pagel, Edmunds & Smith (1980). The uncertainties in such methods are important. For example, the calibration of the high-abundance end (based on model calculations extrapolated from S5 by Dufour et al. 1980) would be lowered in the presence of internal dust (Sarazin 1976, 1977); scatter can be introduced by nonuniform geometry (Stasinska 1980) and by departures from the underlying assumption that, for giant H II regions at least, the ionizing radiation field is uniquely related to the oxygen abundance. The uncertainties in these "guessing" methods have been discussed by Stasinska et al. (1981); we estimate a standard error for them of about ± 0.2 dex, over and above the systematic uncertainty at oxygen abundances exceeding that of S5.

The application of modern, detailed shock models to spectra of mature supernova remnants (Dopita 1976, Dopita, Mathewson & Ford 1977, Dopita, D'Odorico & Benvenuti 1980) provides a valuable alternative source of data for abundant elements in the ISM because the uncertainties in the shock parameters, while significant, are entirely different from those arising in the analysis of H II regions; in particular, the [N II]/Hα ratio is quite insensitive to shock conditions and it is easy to recognise the few cases affected by self-enrichment. In Figure 2 we compare oxygen and

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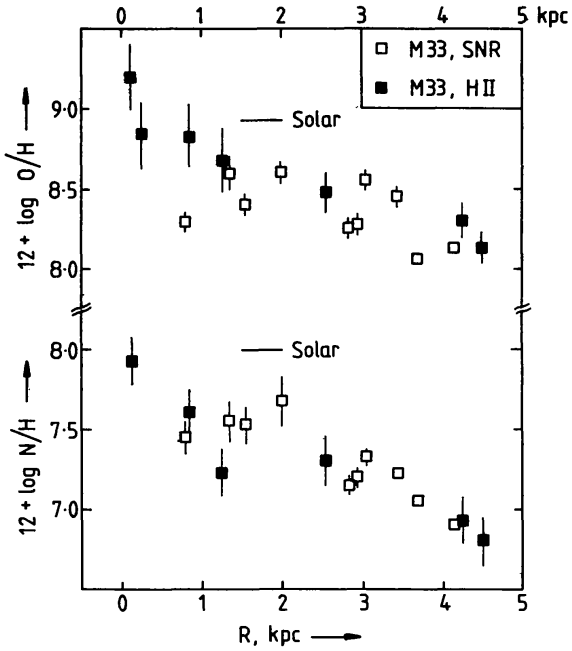

Figure 2 Oxygen and nitrogen abundances in H II regions (filled squares) and supernova remnants (open squares) as a function of radial distance from the center of M33. The H II region data are those of Smith (1975), analyzed using his electron-temperature data (for the outer H II regions) and the ([O II] + [O III])/Hβ calibration of Pagel, Edmunds & Smith (1980); error bars represent either the discrepancy between the two or the estimated error of the calibration. The SNR data are from Dopita, D'Odorico & Benvenuti (1980) with error bars corresponding to the range of results deduced from various shock models.

nitrogen abundances deduced for H II regions and SNRs as a function of radial distance in M33; the agreement for N/H is remarkably good.

Planetary nebulae have been observed in several galaxies of the Local Group (see Webster 1978, Ford 1978, Dufour & Talent 1980) and are usually hot enough that the electron temperature can be measured, apart from technical difficulties caused by their smallness at great distances. Peimbert (1978) has classified galactic planetaries into four types: I, massive with He, N enhanced; II, intermediate Population I with N slightly enhanced (but cf. Kaler 1978); III, high velocity with composition similar to II; and IV, halo objects with O and Ne deficient by an order of magnitude. Carbon exceeds oxygen in many planetaries (see, for example, Aitken et al. 1979 and references therein), so that He, C, and N are all likely to have been affected by self-enrichment to varying degrees, although there is no reason to believe that O and Ne are affected (see, for example, Kaler 1978, 1980). Magellanic Cloud planetaries have been discussed by Webster (1978) and Aller et al. (1980), among others, and show enhancements of N and perhaps He relative to H II regions; their usually normal oxygen abundances suggest that the majority of observed systems are

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quite young. In some cases the nitrogen enhancement is extreme, and a similar object in NGC 6822 has nitrogen enhanced by a factor approaching 200 implying primary production (Dufour & Talent 1980). We feel that planetary nebulae are not suitable objects for the study of abundance gradients in nitrogen.

4.3 *Integrated Light from Stellar Populations*

The absence of H II regions from elliptical or S0 galaxies, except in some of their nuclei where excitation mechanisms may be uncertain, means that abundance determinations must be based on color or absorption-line-strength measurements. Since individual stars can be resolved only for the nearest extragalactic systems, these measurements are inevitably of an integrated stellar population, so that theoretical population models and/or some form of empirical calibration against galactic globular clusters must be employed in their interpretation. Integrated colors and line strengths have also been measured in and around the nuclei of spiral galaxies (particularly M31), although interpretation becomes even more difficult in the presence of young blue stars.

The variation of color indices with metallicity results from a combination of effects: (*a*) the *U* band is strongly influenced by metallic line blanketing in the stellar atmospheres; (*b*) as the metallicity of the stars increases, so does the envelope opacity, causing a drop in their effective temperatures and a shift of flux towards the infrared; (*c*) the relative number of stars on the blue horizontal branch decreases as metallicity increases. All three effects cause a reddening of color with increasing metallicity. The $(U-V)$ index is far more sensitive to metallicity changes than is $(B-V)$, but the *U* band is also particularly sensitive to the presence of young blue main-sequence stars and theoretical population models have difficulty in accurately reproducing the ultraviolet fluxes observed. Indices including an infrared or red color such as $(V-K)$ or $(U-R)$ benefit from effect (*b*) above. The infrared colors are more sensitive to the presence of a dwarf-enriched population, but such a population seems to be observationally excluded (see section on luminosity indicators below) so this is probably not important.

Line strengths have been measured mainly by intermediate-band photometry on various systems, particularly those of Spinrad & Taylor (1969), DDO (McClure & van den Bergh 1968), and Faber (1973), important features being CN around $\lambda 4200$, the sodium D lines, the magnesium b triplet and MgH band head around $\lambda 5175$, various groups of iron lines, and the infrared luminosity-sensitive features discussed later. The presence of young blue stars can be detected by the addition of a hydrogen line (Heckman 1980) or by noting discrepancies between line strengths and

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colors (Burstein 1979). Even when uncalibrated, spatial variations of line groups can provide evidence that at least *something* is varying between or across galaxies.

4.3.1 CALIBRATION OF COLORS AND LINE STRENGTHS For calibration an initial mass spectrum of the form $N(m)\,dm \propto m^{-(1+x)}\,dm$ is assumed where $N(m)\,dm$ is the number of stars formed between masses m and $m + dm$; $x = 1.35$ would correspond to the usual Salpeter function. A single age and metallicity are also usually assumed for the population, both rather dubious assumptions, using theoretical stellar evolutionary tracks to predict the fraction and parameters of the giant stars present. Color calibrations made in this way have been given by Strom et al. (1976) suggesting $\frac{\Delta(U-V)}{\Delta \log Z} \simeq 0.85$ and $\frac{\Delta(U-R)}{\Delta \log Z} \simeq 1.18$ (Strom & Strom 1978), by Tinsley (1978, revising Larson & Tinsley 1974) suggesting $\frac{\Delta(B-V)}{\Delta \log Z} \simeq 0.42$, and particularly by Aaronson et al. (1978) who tabulate model $(U-V)$, $(V-K)$, and $(J-K)$ values for several metal abundances. For abundances near solar, Aaronson et al.'s results suggest $\frac{\Delta(U-V)}{\Delta \log Z} \simeq 1.13$ and $\frac{\Delta(V-K)}{\Delta \log Z} \simeq 0.62$. These calibrations have been revised somewhat by Frogel et al. (1980), but without altering the overall trends. Although these calibrations give a reasonable estimate of relative abundance changes, the fixing of an absolute scale is difficult. The major problem [which also applies for semi-empirical calibration of indices, like that of $(U-R)$ by Hartwick (1980), which rely on globular cluster colors] is the uncertainty in the true metal abundance of the few so-called "metal-rich" globular clusters (cf. Section 3.3 above), since most of the galaxies are more metal-rich than the majority of globulars. These revisions, even if we assume a fairly conservative -0.8 for [Fe/H] in both M71 and 47 Tuc, greatly affect the metal-rich end of the color calibration, with the galaxies lying on an *extrapolation* of color-metallicity relations for globulars. Reliable metallicity determinations in metal-rich globular clusters are thus of prime importance.

Since the early work of Spinrad & Taylor (1969), theoretical line-strength calibrations have been attempted by Faber (1973), Larson & Tinsley (1974), Mould (1978) for the Mg λ5175 index, and Cohen (1979a) for several groups of lines.

4.3.2 POPULATION MODELS AND LUMINOSITY INDICATORS Population modeling involves the fitting of colors and line strengths by mixtures of stars of various types, ages, and metallicity, usually with imposed astrophysically reasonable constraints (such as smooth variation of the main-

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sequence mass function) on the model. It has been attempted with varying degrees of sophistication for both ellipticals and the nuclear regions of spirals (Joly 1973, 1974, Turnrose 1976, Williams 1976, Prichet 1977, Prichet & Campbell 1980, O'Connell 1976, 1980, Heckman 1980). Separation of age and metallicity effects is not simple, and the assumption of a uniformly old population for elliptical galaxies is seriously questioned by O'Connell's claim that star formation in M32 continued up until 5×10^9 yr ago. But at least the mass function can be constrained by luminosity-sensitive line strengths. The early suggestions (Spinrad & Taylor 1971, Joly 1973) were of a dwarf-enriched population in the nuclei of spiral galaxies, i.e. $x \gtrsim 3.5$. Measurement of infrared features sensitive to the luminosity of stars, i.e. H_2O 2.1μ, CO 2.3μ (Baldwin et al. 1973, Frogel et al. 1975, 1978, Aaronson, Frogel & Persson 1978), the NaI doublet near λ8185 and CaII triplet near λ8500 (Cohen 1978), the Wing-Ford band λ9910 (Whitford 1977, Cohen 1978) identified as due to Fe H (Wing, Cohen & Brault 1977), all indicate that in elliptical galaxies and the nuclei of spirals the late-type giant stars are the dominant contributors to the observed light, and that $x \lesssim 2$. Cohen (1978) also investigated infrared TiO bands, but concluded that they were not sufficiently sensitive to luminosity to be a useful population discriminant.

5. OTHER GALAXIES: RESULTS

5.1 *Irregular and Blue Compact Galaxies*

The gas-rich Irregular galaxies and blue compact galaxies or extragalactic H II regions (Searle & Sargent 1972) are in many ways the simplest and most satisfying systems to study because they usually contain bright H II regions of high excitation in which abundances can be determined by standard methods. Abundance gradients are small or absent (Pagel et al. 1978, Pagel, Edmunds & Smith 1980) and the average abundances in the various systems mostly conform to simple concepts of galactic evolution, so that interesting parameters like the heavy-element "yield" and the primordial helium abundance can be deduced with a relatively high degree of confidence. Data are now available for about 35 of these systems (Lequeux et al. 1979, French 1980, Talent 1980, Kinman & Davidson 1981, Tully et al. 1981) ranging in oxygen abundance (12 + log O/H) from 7.14 (Mk 116 = I Zw 18) to 8.44 (IC 3258) if temperature fluctuations are taken to be zero.

A correlation between helium and oxygen abundances is found in some of these investigations but not in others, which is hardly surprising because the whole effect is only 25 percent and this is easily swamped in errors of observation and ionization corrections, particularly with regions of

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differing ionization superposed on the spectrograph slit. The latter effect is least likely to arise in Local Group galaxies, where individual H II regions are well resolved, and we would therefore recommend the numbers given by Lequeux et al., i.e. $Y_0 = 0.23$ for the primordial helium mass fraction and $dY/dZ \simeq 2$, except that these numbers change to 0.22 and 3 respectively if temperature fluctuations are equated to zero, which is close to the results found by French, and this value of Y_0 (for which we estimate that the error does not exceed ± 0.01) is in good agreement with less precise values deduced from the luminosities of subdwarfs (Carney 1979) and from the relative populations of the RGB and HB in globular clusters (Iben 1968, Renzini 1977, Caputo, Castellani & Wood 1978). Such a low value imposes severe constraints on big-bang cosmology and elementary particle physics (Tayler 1980). The existence of a dY/dZ effect is in agreement with that of a He/H gradient found in our Galaxy, for example, by Thum, Mezger & Pankonin (1980).

The "simple" one-zone model of galactic chemical evolution predicts the relationship

$$Z = p \ln(m/g)$$

(Searle & Sargent 1972) between the heavy-element abundance Z (by mass) and the masses m and g of the entire system and of residual gas, respectively, where p is a constant known as the "yield" and is the ratio of mass of heavy elements newly synthesized and ejected to mass locked up in compact remnants and long-lived stars, in each stellar generation. Oxygen abundances in the vast majority of Irregular and blue compact galaxies studied conform to this relationship (but not quite all: Kinman & Davidson 1981) and give a yield of 0.003 ± 0.001 which places constraints on the initial mass function, while the large dY/dZ favors evolutionary models of massive stars with substantial mass loss in the hydrogen and helium-burning phases (Lequeux et al. 1979, Serrano & Peimbert 1981).

Both $Z\,[\simeq 25\,(\mathrm{O/H})]$ and m/g increase with the total mass of the system, the data of Lequeux et al., Talent, and Kinman & Davidson being roughly represented by the relationship (assuming zero temperature fluctuations)

$$Z \simeq 0.0025 \log M_8; \qquad 0.0 < \log M_8 \leq 2.6$$

where M_8 is the mass in units of 10^8 solar masses. (Lequeux et al., who include a temperature fluctuation correction, derive a coefficient of 0.004.) A composite mass-abundance diagram is shown in Figure 7.

The Ne/O ratio $\simeq 0.2$ in all H II regions and Ar/O is probably between 5×10^{-3} (Meyer 1979) and 10^{-2} (Pagel et al. 1978, Pagel, Edmunds & Smith 1980); S/O has been found to *decrease* with increasing O/H (French 1980, cf. Talent & Dufour 1979), but French's result is affected by the use of an incorrect ionization correction scheme (cf. Pagel 1978, Natta,

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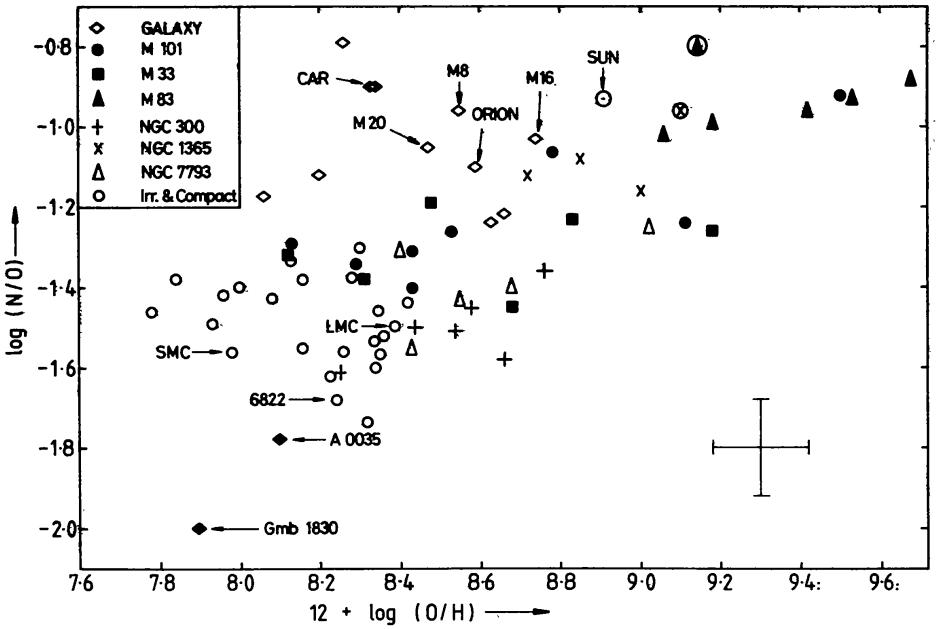

Figure 3 Relation between log(N/O) and log(O/H) in galactic and extragalactic H II regions. The following sources of data are used: Galaxy, Talent & Dufour (1979); M101 and M33, Smith (1975) reanalyzed using the ([O II] + [O III])/Hβ calibration of Pagel, Edmunds & Smith (1980); M83, Dufour et al. (1980) using electron temperatures consistent with their oxygen abundances; NGC 300 and 1365, Pagel et al. (1979), M. G. Edmunds and B. E. J. Pagel (in preparation); NGC 7793, M. G. Edmunds and B. E. J. Pagel (in preparation); Irregular and compact galaxies, Lequeux et al. (1979), Pagel, Edmunds & Smith (1980), Talent (1980), French (1980); A0035, Fosbury & Hawarden (1977); Groombridge 1830, Tomkin & Bell (1973), Sneden, Lambert & Whitaker (1979). Galactic nuclear regions are marked by circles round the corresponding symbols. The error bars are schematic overall average estimates.

Panagia & Preite-Martinez 1980) and the true state of affairs is still uncertain. C/O may have about the same (or slightly lower) value in the SMC as in the Sun or Orion (Gilra et. al. 1980). Thus, observed elements attributed to helium, carbon, and oxygen burning apparently vary in lockstep, with the *possible* exception of sulphur.

The fact that nitrogen is over-deficient in the oxygen-deficient Magellanic Clouds, compared to the solar neighborhood, appeared some years ago to support the classification of N as a secondary nucleosynthesis product with (roughly) N/O $\propto$ O/H (Talbot & Arnett 1974), but a comparison of N/O with O/H in different objects in different galaxies leads to a much more complicated picture (Pagel et al. 1978, Edmunds & Pagel 1978, Alloin et al. 1979). Figure 3 shows the data as they are at present.[1]

[1] We have not included I Zw 18 as only an upper limit is available, log N/O < -1.3 (French 1980), CG 1116+51 for which the temperature is uncertain (French 1980), and V11 Zw 403 for which only photographic spectrophotometry is available (Tully et al. 1981), but we do include data for Spirals in which it may or may not be relevant that the Simple galactic chemical evolution model does not apply.

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Overall, some correlation exists, with a 45° line forming a lower envelope to a good fraction of the data; but the scatter is large and is unlikely to be purely observational since, for example, the Magellanic Clouds and NGC 6822 are among the best-studied objects available (Peimbert & Torres-Peimbert 1974, 1976, Dufour 1975, Pagel et al. 1978, Aller, Keyes & Czyzak 1979, Lequeux et al. 1979, Pagel, Edmunds & Smith 1980, Talent 1980) and neither the Irregulars (taken as a group) nor the H II regions of our Galaxy show a significant trend. We believe that varying amounts of primary nitrogen are needed to account for the data, as discussed in Section 3.2.

5.2 *Elliptical and S0 Galaxies*

5.2.1 METALLICITY AND ABSOLUTE MAGNITUDE It is convenient to discuss elliptical and S0 galaxies together, since they appear to have almost identical color and line-strength properties—somewhat surprisingly, perhaps, in view of the distinctive disc structure of S0's. We must distinguish two (possibly separate) effects: (*a*) the variation of color or line strength across a given system, and (*b*) the variation of some kind of mean color or line strength between systems, as a function of absolute magnitude or other property. The color-absolute magnitude effect is the more thoroughly investigated of the two. Since radial variations within galaxies exist, corrections are needed in order to compare colors of galaxies at some particular intrinsic photometric radius. These may be uncertain, particularly if elliptical galaxies are prolate objects for which we do not know the orientation, but nevertheless a strong correlation of $(U-V)$, $(V-K)$, and $(U-R)$ colors with M_v is observed, in the sense that the brighter galaxies are redder (Baum 1959, de Vaucouleurs 1961, de Vaucouleurs & de Vaucouleurs 1972, Lasker 1970, Sandage 1972, Sandage & Visvanathan 1978a,b, Visvanathan & Sandage 1977, Frogel et al. 1978, Strom & Strom 1978). Sandage and Visvanathan find no evidence for any difference in the color-magnitude relations of E or S0 galaxies, and no evidence for a difference between galaxies in the field and in clusters. Their relation implies $\Delta(U-V)/\Delta M_v \simeq 0.10$ (see Figure 4). Interpreted as a metallicity change this is equivalent to nearly an order-of-magnitude change in metals between $M_v = -23$ and $M_v = -15$, and a metallicity change is supported by Faber's (1973) observation of line-strength correlations with absolute magnitude. Tinsley (1978) suggests a metallicity-mass relation $Z \propto M^{0.25}$. Larson, Tinsley & Caldwell (1980) suggest that there may be a significant difference in the scatter of the color-magnitude diagram for field and cluster galaxies, which could be due to residual star formation in field galaxies.

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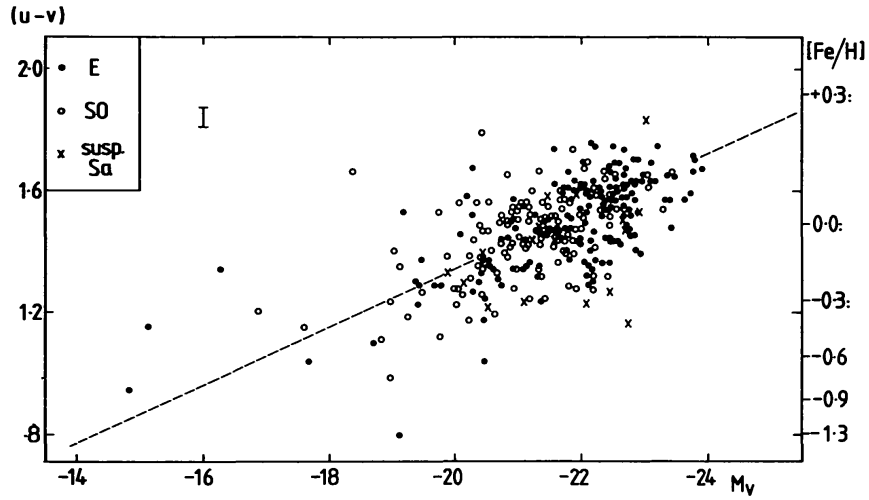

Figure 4 Color-magnitude relation for field and cluster elliptical and S0 galaxies. Data are from Sandage & Visvanathan (1978b, Table 1). Colors are corrected to an apparent aperture of half the de Vaucouleurs diameter, uncertain values have been omitted, and where the E or S0 classification is uncertain the point has been plotted as S0. The error bar is a rough estimate of photometric uncertainty in the colors. The color scale is transformed from $(u-V)$ to $(U-V)$ using Sandage & Visvanathan (1978a), and the metallicity scale from the calibration of Aaronson et al. (1978). The dashed line is Visvanathan & Sandage's (1977) mean relation, their assumed distance modulus to the Virgo cluster and H_0 being 31.70 and 50 km s^{-1} Mpc^{-1} respectively.

There is some uncertainty whether the color-magnitude relation flattens off for very luminous galaxies. Baum's relation, which flattened at both luminosity extremes, was based on a small sample of $(B-V)$ colors—which do not have nearly as strong a correlation with M_v as do $(U-V)$ colors. De Vaucouleurs (1961) and de Vaucouleurs & de Vaucouleurs (1972) claim a flattening, although it is not immediately evident in their later data. Lasker (1970) and Frogel et al. (1978) both suspect a flattening, but it is not apparent in the extensive data of Sandage & Visvanathan (1978a,b) or Strom & Strom (1978).

In all the color–absolute magnitude relations there is considerable scatter about the mean relationship, and Terlevich et al. (1981) have shown a correlation between the line strengths at a given absolute magnitude and the velocity dispersion in the galaxy. Since the ellipticity also varies with velocity dispersion, the result implies that flatter ellipticals have lower metallicities than more spherical systems at a given luminosity. This effect had also been noted from Sandage & Visvanathan's colors by van den Bergh (1979). The implied differences in metal abundance depend on uncertain projection effects, but must be at least a factor of two.

5.2.2 RADIAL GRADIENTS Radial variations in the metal content of stars between the central and outer parts of elliptical and S0 galaxies

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are evident in both line-strength and color gradients. Colors redden (or are flat within experimental error) towards the center, although sometimes the nucleus may be somewhat bluer than its surrounding region—through the presence of emission lines or the ultraviolet contribution of a small population of young blue stars or from a nonthermal central source. Variations may be measured either by using apertures of different sizes, centered on the nucleus, or by using a small aperture at different positions. The color-aperture relation has been extensively discussed by de Vaucouleurs (1961), de Vaucouleurs & de Vaucouleurs (1972), de Vaucouleurs & Corwin (1977), Tifft (1963, 1969), and Frogel et al. (1978); and more data have recently been published by Persson, Frogel & Aaronson (1979). Although variable-aperture photometry gives a broad idea of the color trends, the small moveable aperture method (also effectively the method used in photographic photometry) probably gives a more accurate measurement of gradients. Miller & Prendergast (1962) used the rather insensitive $(B-V)$, but later investigations (Burkhead & Kalinowski 1974, Strom et al. 1976, 1977, 1978, and particularly Strom & Strom 1978), use either $(U-V)$ or $(U-R)$. The number of galaxies studied individually in detail is still small, but Figure 5 shows the gradients observed by Strom et al. (1977) along both the major and minor axes of the S0 galaxy NGC 3115. Not all ellipticals show large gradients $\left(\text{i.e. } \frac{\Delta \log Z}{\Delta R} \geq 0.04 \text{ dex kpc}^{-1}\right)$, although projection effects from the uncertain shapes (particularly as the colors observed centrally must be an

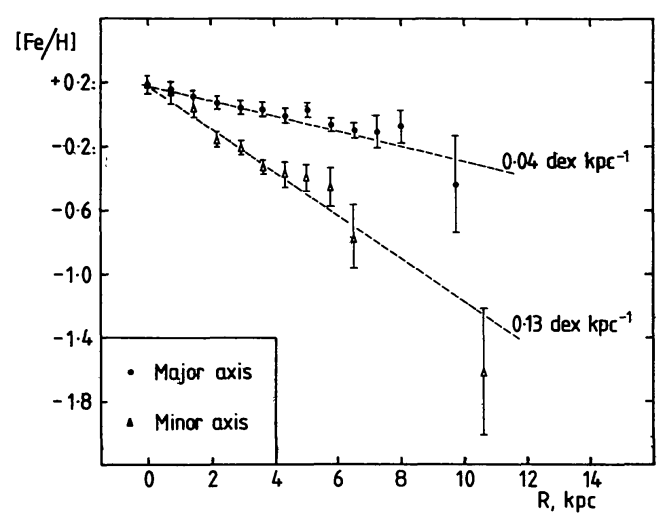

Figure 5 Radial gradients in the S0 galaxy NGC 3115. The "mean" metallicity of the stellar population has been derived from the $(U-V)$ photometry of Strom et al. (1977) using the calibration of Aaronson et al. (1978). Note that error bars represent photometric errors only. Radial distances are computed assuming $H_0 = 50$ km s^{-1} Mpc^{-1}.

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integration along the line of sight through outer parts as well) make general statements difficult. In their extensive ($U-R$) photometry of Coma cluster galaxies, Strom & Strom (1978) suggest that only systems with $M_v < -21$ ($H_0 = 55$ km s^{-1} Mpc^{-1}) show particularly large color changes with radius, and then only in 20 percent of systems of this brightness. In systems with an obvious gradient such as NGC 4816 (Strom & Strom 1978) the continuous ($U-R$) change of about 1.2 magnitudes out to 70 kpc implies an order-of-magnitude variation in metal content. Color changes are undoubtedly present in systems of lower luminosity, although Strom & Strom suggest that these may often be small outside 2 kpc from the nucleus. The Stroms and their collaborators have also noted a tendency for the contours of constant color to be significantly flatter than the isophotes in systems with large color changes.

Line-strength variations have been investigated by Spinrad et al. (1971), Spinrad, Smith & Taylor (1972), Spinrad & Stone (1975), Faber (1977), Cohen (1979a), and Burstein (1979). The general trend is for line strengths to decrease outwards, confirming the decreasing metallicity suggested by the colors, but both observation (limiting to central regions) and calibration are difficult. An exception to the general decrease may be the E0 galaxy NGC 1399 for which CN photometry (Spinrad & Stone 1975) shows little fall off, but the observations are uncertain. Cohen's investigation gives encouraging agreement of metallicity changes in NGC 3115 compared with Strom et al.'s (1977) color photometry, and she also demonstrates observational variation of lines sensitive to abundance while other line groups that are insensitive remain fairly constant. Burstein's observations on the Faber system suggest metallicity gradients ≤ 0.1 dex kpc^{-1} in the six galaxies he examined.

It is not yet possible to decide the actual form of the variation of metallicity with radius in an early-type galaxy until the galaxian shapes can be disentangled, although as Figure 5 shows, a steady trend (steeper along the minor axis) is apparent. Strom et al. (1976) and Faber (1977) suggest that data are consistent with a linear log Z–log R plot although this relation must, of course, break down close to the nucleus. As mentioned in Section 4.3 above, the absolute scale of abundances is uncertain. But assuming a reasonably low metallicity for M71 and 47 Tuc, it seems likely that the central regions of the most luminous ellipticals exhibit colors characteristic of a population with probably twice or at most three times solar. For the center of the nearby elliptical M32 ($M_v = -16.3$) recent discussions (Cohen 1978, 1979a, O'Connell 1980, Prichet & Campbell 1980, Heckman 1980) imply solar or somewhat less metallicity. At this absolute magnitude a lower metallicity might well be expected, although M32 does not conform well to color-magnitude relations, so

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that the tidal influence of M31 and evidence of comparatively young stars (O'Connell 1980) make such predictions uncertain.

5.3 *Dwarf Spheroidal Systems*

The dwarf spheroidial systems are probably satellites of the Galaxy, but represent small elliptical galaxies ($-13 \leq M_v < -8$) in their own right since the spheroidals are morphologically distinct, being much less concentrated than Galactic globular clusters, and the Fornax system has its own globular clusters—all of which are metal poor (van den Bergh 1969, Danziger 1973). The proximity of these galaxies allows resolution of individual stars, and Demers, Kunkel & Hardy (1979) deduce [Fe/H] ~ -0.5 for Fornax from the mean height of the giant branch, although recalibration of metal-rich globulars may lower this to perhaps -1.0. A planetary nebula found in Fornax (Danziger et al. 1978) yields [O/H] $= -0.6$, [N/H] $= -0.7$ [assuming uniform temperature and using solar values of Lambert (1978)], which may be consistent with an overall metallicity near -1.0 since O generally varies less than metals and N may be affected by self-enrichment. Other results for dwarf spheroidal systems are listed in Table 3.

In summary these are all metal-poor systems, as might be expected from the general abundance versus absolute magnitude relationship for elliptical galaxies (cf. Figure 7), and indeed the most massive (Fornax) is also the least metal poor.

Table 3 Metallicities in dwarf spheroidal systems

System	M_v[a]	[Fe/H]	Method	Ref.
Draco	-8.6:	-1.8	DDO	Hartwick & McClure 1974[b]
		-2.3 ± 0.4	CMT_1T_2	Canterna & Schommer 1978
		-1.7 to -2.1	Scanner	Zinn 1978
		-1.8 to -2.8	Spectra	Kinman & Kraft 1980[c], Kinman et al. 1981
U Mi	-8.8	-2.1 ± 0.3	CMT_1T_2	Canterna & Schommer 1978
Sculptor	-11.7	-1.9	H-R diagram	Kunkel & Demers 1977
		-1.5 to -2.2	Spectra	Norris & Bessell 1978
Fornax	-13.6	-0.5[d]	H-R diagram	Demers et al. 1979

[a] van den Bergh (1980).
[b] Using calibration by Bell & Gustafsson (1975).
[c] Evidence for nuclear processing in red giants.
[d] See text.

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5.4 *Spiral Galaxies*

5.4.1 COLOR AND ABSORPTION LINE STRENGTHS Color indices are a much less useful metallicity indicator for spirals and irregulars than for ellipticals because of the overwhelming effect of the young stellar population. The color-aperture effect (de Vaucouleurs 1961, Tifft 1963, Griersmith 1980) indicates a significant reddening towards the nucleus, but this may more obviously be interpreted as an indication of the blue light contribution of young stars in the disk than as necessarily implying an abundance gradient. The spheroidal bulge dominates enough in the nuclear regions of early spirals (S0/a, Sa, Sab) to show a definite color-magnitude relation (Visvanathan & Griersmith 1977) analogous to ellipticals, with $\Delta(U-V)/\Delta M_v^s \simeq 0.13$ where M_v^s is the absolute magnitude of the spheroidal component. This color-magnitude relation may well be a metallicity effect. Indeed, line-strength gradients have been found in the inner regions ($\leq$ 130 pc) of the bulge component of M31 (McClure & van den Bergh 1968, Oke & Schwarzschild 1975, Morton & Andereck 1976, Faber 1977), although the magnitude of the metallicity change is small (less than a factor of two) over such short distances. There is apparent continuity between the spheroidal component and the nucleus itself (Spinrad & Liebert 1975, Thuan & Oke 1976).

Line strengths in the inner disks of M31 and M81 (McClure 1969, Spinrad & Taylor 1971, Joly & Andrillat 1973, Joly 1973, 1974, Cohen 1978, 1979a) all indicate a decrease in metallicity away from the nucleus, with Cohen's calibration suggesting as much as a factor of four from the nucleus to 300 pc. The absolute mean metallicity of the stars in the nuclear region of M31 remains uncertain due to the calibration difficulties already discussed, but almost certainly lies between one and three times solar (O'Connell 1976, Cohen 1978, 1979a, Heckman 1980, Prichet & Campbell 1980).

Globular clusters in external spirals have been reviewed by Harris & Racine (1979) and we will not discuss them further except to note that Faber, Gaskell & Burstein (1980) find distinct spectral differences between the globular clusters of M31 and those of our own Galaxy.

5.4.2 H II REGIONS Data for galaxies in which the abundances have been reasonably well determined are assembled in Table 4 and some of these are plotted in Figure 6 as a function of radius (normalized to the de Vaucouleurs 25 mag arcsec^{-2} isophote, face-on radius R_0). The abundances quoted are those derived with electron temperature from weak lines (assuming zero temperature fluctuation), from H II region models,

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Table 4 Abundances in H II regions of spiral galaxies

Galaxy, NGC, etc.	Type	log $M^a/M_\odot$	Ref.[d]	12 + log(O/H) Max[b] (near centre)	Min[b] (outer)	Ref.[d]
1365	SBbc (Sy)	11.8	1	≥9.1	8.7	1, 9
1566	Sbc (Sy)	11.5:	2	9.6	8.8	10
5457 (M101)	SABcd I	11.4	3	9.5:	8.1	11, 12, 1, 9
6946	SABcd I	11.3	4	9.1	8.5	13
224 (M31)	Sb I–II	11.3	3	9.1	8.5[c]	14
5194 (M51)	Sbcp I	11.3	3	9.6:	9.0	15
				(9.6:		16
Galaxy	Sbc	>11.1	5	(9.0	8.3	17
				(	8.0	18
2997	SABc	11.0:	2	9.1	8.7	9
5236 (M83)	SABcd I–II	10.9	3	9.7:	9.1	15
1313	SBd	10.3	6	8.25	8.25	19
300	Scd	10.3	7	8.8	8.2	1, 9
598 (M33)	Scd II–III	10.2	3	9.2	8.1	11, 1, 9, 20
7793	Sd	9.5	8	9.0	8.4	9

[a] $H_0 = 50$ km s^{-1} Mpc^{-1} assumed in mass estimates.
[b] The Min and Max of columns 5 and 6 refer only to H II regions so far measured, and do not imply absolute limits for the galaxies.
[c] Large scatter.
[d] References:

1. Pagel et al. 1979
2. From BGC blue magnitude with mean mass-luminosity relation of type from Faber & Gallagher (1979).
3. Faber & Gallagher 1979
4. Rogstad, Shostak & Rots 1973
5. From $V_0 = 220$ km s^{-1} assuming spherical distribution. Total mass may be much greater (see reference 3).
6. Carranza & Agüero 1974
7. de Vaucouleurs & Page 1962
8. Agüero 1979
9. M. G. Edmunds and B. E. J. Pagel (in preparation)
10. From ([O II] + [O III])/Hβ measured by Hawley & Phillips (1980).
11. Smith 1975
12. Shields & Searle 1978
13. McCall, Rybski & Shields 1980
14. From [O III]/[N II] measured by Rubin, Kumar & Ford (1972)
15. Dufour et al. 1980
16. Shaver, McGee & Pottasch 1979
17. Mezger et al. 1979
18. Peimbert, Torres-Peimbert & Rayo 1978
19. Pagel, Edmunds & Smith 1980
20. Stasinska et al. 1981

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or by the semiempirical line-strength methods of Pagel et al. (1979, 1980), which give reasonable agreement with SNR abundances in M33, especially for N/H, see Figure 2. The considerable data of Jensen, Strom & Strom (1976) have not been included owing to their lower precision.

All galaxies showing abundance gradients have lower abundances in their outer parts than in the center, but the best functional representation is not clear. Although some galaxies (e.g. NGC 300, NGC 1365) are reasonably represented by straight lines in Figure 6, others (e.g. M101) appear to show a steeper variation in their inner parts (M101 has the biggest range of any of the galaxies studied). Dufour et al. (1980) suggest that the linear relationship between log (O/H) and R may be more uniform between large galaxies than that defined by R/R_0. The radial gradients extrapolate to nuclear gas abundances of order, or greater than, solar. It is not yet clear if there is a definite trend of steepness of gradient with morphological type. Although NGC 1365, M31, and M51 appear to show

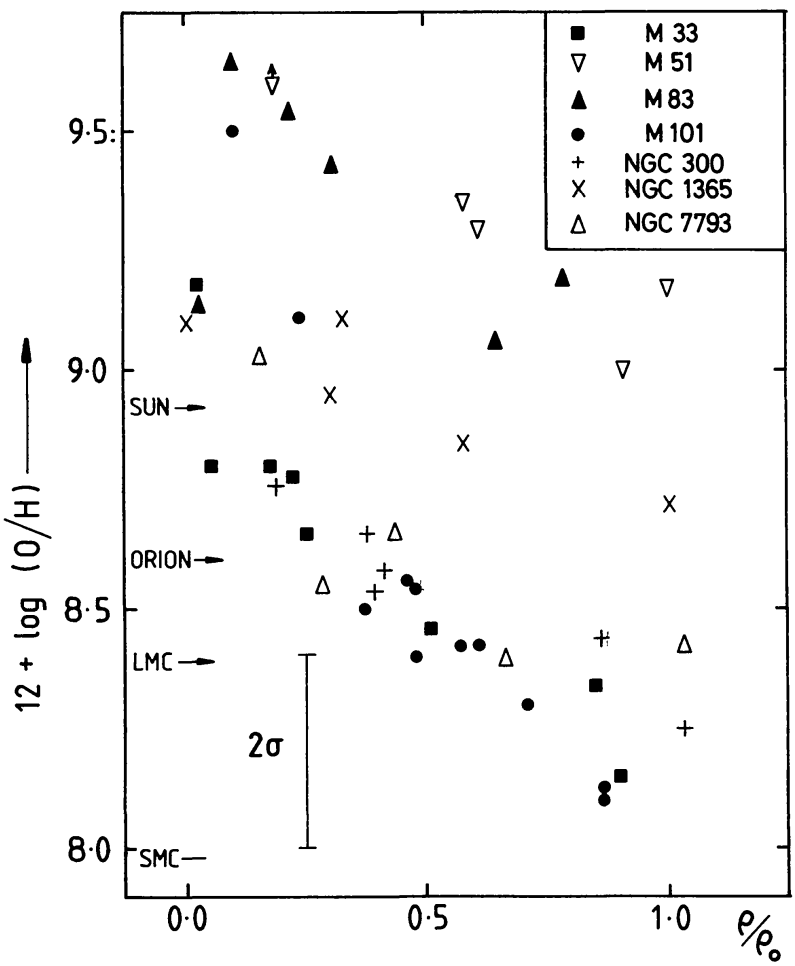

Figure 6 Oxygen gradients in Spiral galaxies. References for abundance are given in Table 4. Abscissa is distance of H II region from center, normalized to the de Vaucouleurs radius.

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somewhat shallower gradients (~ 0.04 dex kpc^{-1}) than the later Sc or Scd types (~ 0.1 dex kpc^{-1}), the gradient is rather uncertain for M31 while in NGC 1365 and M51 the presence of noncircular gas motions induced by bar or companion could have influenced the chemical evolution and make general statements about the influence of morphological type unwise until more good data on earlier types is available. The importance of noncircular motions as a homogenizer of composition is demonstrated for the Magellanic Clouds (Pagel et al. 1978), and particularly for the late barred spiral NGC 1313 (Pagel, Edmund & Smith 1980), which shows a delightfully complex velocity field (Marcellin 1979, Blackman 1981). However, giant H II regions of high excitation, i.e. low abundance of oxygen, etc., are more usually seen in Irregulars, late barred spirals, and the outer parts of late-type normal spirals (Scd and Sd).

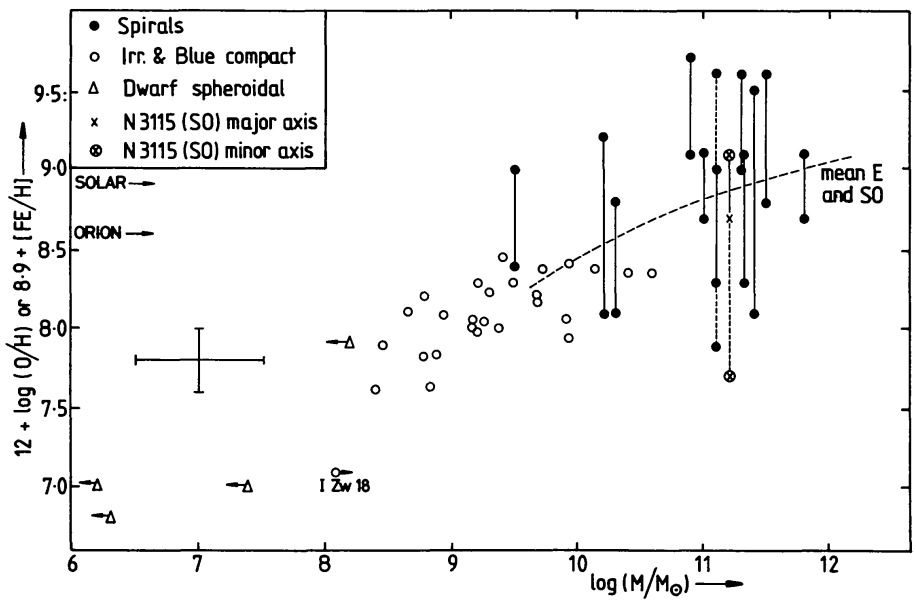

Figure 7 Oxygen (or metal) abundance as a function of mass. The mean elliptical relation was derived from Visvanathan & Sandage's (1977) color-magnitude relation, transformed to $(U-V)$ as in Sandage & Visvanathan (1978a) and calibrated from Aaronson et al. (1978), the masses being implied from M_v assuming $M/L_v = 6.5$ (Schechter & Gunn 1979). The masses of the dwarf spheroidals are calculated in the same manner and probably represent upper limits; metallicities are from Table 3. For the ellipticals, S0, and spheroids the log (O/H) values plotted are simply those implied by the [Fe/H] values and the solar oxygen abundance; it is possible (see Section 2.4) that these should be increased in metal-poor systems by an amount $[O/Fe] \leq 0.6$. The metallicity of NGC 3115 is taken from Figure 5, and its mass deduced by extrapolating a flat rotation curve (Rubin, Peterson & Ford 1980) to the de Vaucouleurs radius. Masses and oxygen abundances in Irregular and blue compact galaxies are from Lequeux et al. (1979), Kinman & Davidson (1981), and Talent (1980).

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There is no obvious dependence of either gradient steepness or absolute abundance at a given radius as a function of mass of the spiral (see Figure 7). The gaseous abundances in nuclei of spirals remain somewhat uncertain. Although higher excitation in the nuclear regions than in the surrounding spiral arms might indicate somewhat decreased abundances (e.g. M83, Dufour et al. 1980; NGC 1365, Pagel et al. 1979), the interference of high excitation caused by a nonthermal nuclear source has been demonstrated for the latter case and H II regions near to the nucleus show the higher abundances expected from extrapolation of the disk gradient (M. G. Edmunds and B. E. J. Pagel, in preparation). Thus, care must be exercised in the derivation of abundances from nuclear spectra; the problem is an important one. For example, Heckman (1980) claims evidence from nuclear spectra that metal abundance and absolute luminosity correlate for late-type galaxies. Tests to distinguish conventional H II region spectra from those due to other forms of excitation have been devised by Heckman and by Baldwin, Phillips & Terlevich (1981).

There is little evidence (see Figure 3) for marked N/O gradients across spirals, except that N/O may increase somewhat in the inner regions of M101 (a factor of 2 overall).

5.5 *Quasars and Active Galaxies*

Although interpretation of the spectra of quasars and active galaxies is necessarily uncertain, there is little evidence of any major departures from either an approximately solar overall metal abundance or from approximately solar relative atomic abundances, including helium (Davidson & Netzer 1979). The emission spectrum from the extreme radio galaxy Cyg A, for example, shows a solar composition (Osterbrock & Miller 1975). The only major anomaly so far found is the quasar Q0353 − 383 (Osmer 1980), which shows evidence of a marked carbon deficiency.

6. CONCLUSION

In the foregoing discussion we have reported many facts and not a few speculations. What are the main conclusions that one can draw from these? Broadly speaking, a number of expectations from stellar evolution and nucleosynthesis theory are confirmed: the abundance of heavy elements in the ISM and in the corresponding stellar populations increases with time at a given place (the solar neighborhood) and with the degree of conversion of gas into stars at different places at a given time (the present), though with a "prompt initial enrichment" in our own

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neighborhood that can be accounted for by taking into account the slow formation of the galactic disk (Lynden-Bell 1975, Larson 1976, Tinsley & Larson 1978, Chiosi & Matteucci 1980). The differential behavior of elements and isotopes is qualitatively in accordance with this trend, and some of the quantitative details—e.g. those concerning helium and C,N,O isotopes—permit interesting constraints to be placed on cosmology, initial mass functions, and the end products of stellar evolution, although many of the details are still not satisfactorily explained.

The existence of differences in heavy-element composition between and across galaxies is now well established, although the absolute scale of the variations remains somewhat uncertain. Whether the mechanism causing differences between galaxies is the same as that which causes gradients across galaxies is unknown. The most obvious candidate for the first effect is mass-dependent gas loss (e.g. Hartwick 1980), but accretion and/or inward gas flows may be important for the gradient effects (e.g. Tinsley 1980, Mayor & Vigroux 1981).

The influence of gas loss is certainly evident in clusters of galaxies, since elliptical galaxies probably contribute a significant amount of heavy-element–rich gas to the intracluster medium (Larson & Dinerstein 1975) where it is visible in X rays (Culhane 1978). The correlation with shape and velocity dispersion (Terlevich et al. 1980) suggests that such processes may be influenced by the local gravitational potential.

More data on a wide range of Hubble types are undoubtedly required. More accurate photometric colors for ellipticals and S0's, and the correlation of color gradients with other properties, would be useful—particularly to find out if a significant fraction of ellipticals shows no color gradient. Further H II region analysis of spirals, particularly of early types, is needed. This should be quite possible using direct imaging techniques if the methods of analysis using only strong-line intensities can be unambiguously established as good abundance indicators. With the advent of the Space Telescope (e.g. Pagel 1979c) examination of the population metallicity structure of some nearby systems will become feasible and population synthesis placed on a broader base.

Perhaps the most surprising fact about abundances in galaxies is not their dissimilarities, but the considerable similarities of abundance distribution as a function of mass of the system, and the observation of gradients in both spirals and ellipticals. The differences between galaxies of different types, masses, or environments undoubtedly have much to tell us about galaxy formation and evolution. The similarities (including QSO abundances) argue that all galactic systems share the same basic nucleosynthetic processes.

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