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# Abundances in Spiral and Irregular Galaxies

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**Abstract**

This paper reviews the current data on gas-phase abundances in spiral and irregular galaxies. I discuss the spatial distribution of abundances in galaxies and what we know about the variation of abundance ratios for elements commonly observed in ionized nebulae. Brief comments are made on the astrophysical significance of various observed abundance phenomena.

## 1.1 Introduction

It is certainly appropriate to review gas-phase abundances in galaxies for this symposium, as the study of abundances in galaxies began in large part in Pasadena, with the work of Leonard Searle and Wallace Sargent. Searle (1971) demonstrated, through a relatively simple ionization analysis, that the radial gradients of [O III] emission-line strengths observed in spiral galaxies were most likely explained by radial gradients in the composition of the interstellar gas. At about the same time, Searle & Sargent (1972), as well as Peimbert & Spinrad (1970), showed that oxygen abundances in dwarf irregular galaxies were much lower than in the solar neighborhood, while helium abundances were close to the solar neighborhood values. These results implied that dwarf galaxies were not as evolved as the Milky Way, and that most of the helium in the universe came not from stars, but rather from nucleosynthesis in the Big Bang.

Since then abundance data has accumulated for some fifty spiral galaxies and numerous dwarf galaxies. Here I present an overview of the patterns of metallicity and element abundance ratios observed in spiral and irregular galaxies. I will discuss the results for both types of galaxies rather than separately; many aspects can be discussed for the combined groups, although there are a number of differences that could constitute the topic of an entire conference alone. The observational data to be discussed represent a highly selected sample of abundances, gas masses, and stellar photometry from sources too numerous to mention individually. I will employ abundances derived almost exclusively from H II region spectra, since they contribute the largest set of abundance data for spirals and irregulars in the local universe.

## 1.2 Spatial Abundance Profiles

Most of the data on abundances in external galaxies comes from spectroscopy of H II regions. Accurate abundances depend on high S/N measurements of electron temperature. While this has been relatively easy for metal-poor galaxies, few measurements were

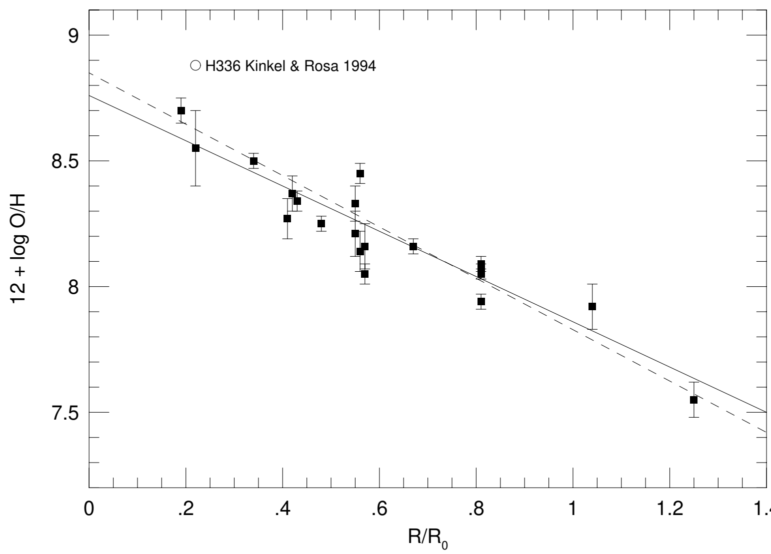


Fig. 1.1. The gradient in O/H across the disk of the spiral galaxy M101 vs. galactocentric radius (Kennicutt, Bresolin, & Garnett 2003).

available for metal-rich regions in spirals. New studies are beginning to crack this barrier, as $T_e$ measurements are being made for solar-metallicity H II regions (Castellanos et al. 2002, Kennicutt, Bresolin, & Garnett 2003). Another happy development is that abundances are being measured for luminous stars in nearby galaxies (e.g., Monteverde et al. 1997, Korn et al. 2002). The stellar abundances appear to be in good general agreement with those derived from H II regions.

The spatial distribution of abundances in galaxies depends coarsely on the Hubble type. Unbarred or weakly barred spiral galaxies typically have a strong radial gradient in metallicity (Figure 1.1), as determined from O/H (Zaritsky, Kennicutt, & Huchra 1994; [ZKH]; Vila-Costas & Edmunds 1992; [VCE]; van Zee et al. 1998; Ferguson et al. 1998). The derived O/H can drop by a factor of 10-50 from the nucleus of a galaxy to the outer disk. In the best-studied spirals, such as M101, the O/H gradients are closely exponential over many disk scale lengths. Irregular galaxies, by contrast, show little spatial variation in abundances, to high levels of precision (Kobulnicky & Skillman 1996), indicating a well-mixed ISM. Strongly barred spiral galaxies show evidence that their O/H gradients are more shallow than in unbarred spirals.

### *1.2.1 Metallicity versus Galaxy Luminosity/Mass*

Detailed examination of this data shows that there are significant correlations between abundances and abundance gradients in spirals and irregulars with galaxy structural properties. One well-established correlation is the relation between metallicity and galaxy

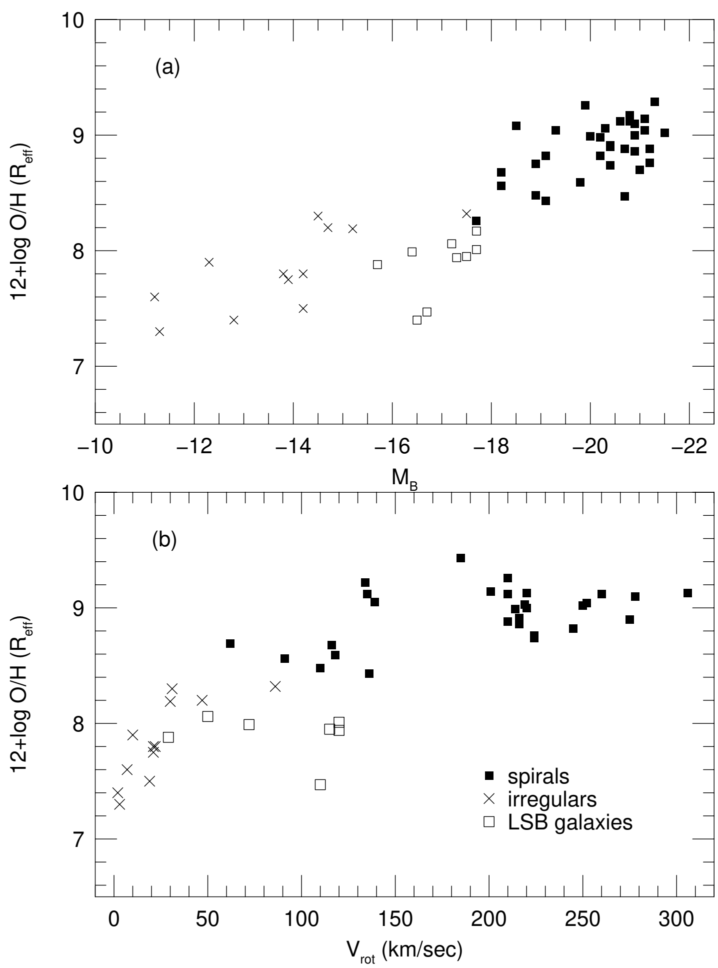


Fig. 1.2. Top: The correlation of spiral galaxy abundance (O/H) at the half-light radius of disk from the galaxy nucleus vs. galaxy blue luminosity. Bottom: abundance versus maximum rotational speed $V_{rot}$.

luminosity or (Lequeux et al. 1979; Garnett & Shields 1987; Skillman et al. 1989). This is shown in the top panel of Figure 1.2, where I plot O/H determined at the half-light radius of the disc ($R_{eff}$) versus B-band magnitude $M_B$. ZKH noted the remarkable uniformity of this correlation over 11 magnitudes in galaxy luminosity, for ellipticals and star-forming spiral and irregular galaxies. The correlation between O/H and rotation speed $V_{rot}$ (bottom panel

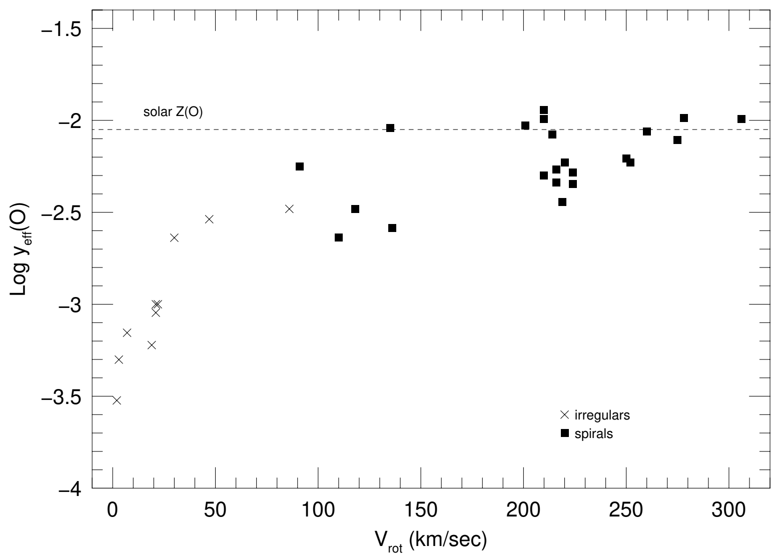


Fig. 1.3. Effective yields $y_{eff}$ for nearby spiral and irregular galaxies versus rotation speed $V_{rot}$ (Garnett 2002). Filled squares represent the data for spirals while the crosses show the data for irregulars.

of Fig. 1.2) looks more interesting, as it suggests that the average metallicity approaches a constant for the most massive galaxies.

To the extent that blue luminosity reflects the mass of a system, the metallicity-luminosity correlation suggests a common mechanism regulating the global metallicity of galaxies. The most commonly invoked mechanism is selective loss of heavy elements in galactic winds (e.g., Dekel & Silk 1986). However, a metallicity-luminosity correlation could also occur if there is a systematic variation in gas fraction across the luminosity sequence. This question of particular interest for understanding the evolution of dwarf galaxies (e.g., Lee et al. 2003).

The question of loss of metals from galaxies is profound because of the existence of metals in low column density Lyman-$\alpha$ forest systems (Ellison et al. 1999), which are probably gas clouds residing outside of galaxies. It is therefore a useful exercise to investigate what kinds of galaxies are potential candidates for ejecting heavy elements into the IGM.

This question can be examined further by studying metallicity as a function of gas fraction. In the context of the simple, closed box, chemical evolution, Edmunds (1990) showed that outflows of gas and inflows of metal-poor gas cause galactic systems to deviate from the closed box model in similar ways. Specifically, defining the effective yield $y_{eff}$

$$y_{eff} = \frac{Z}{ln(\mu^{-1})}, \tag{1.1}$$

outflows of any kind and inflows of metal-poor gas tend to make the effective yield smaller than the true yield of the closed box model. Thus, comparing effective yields for a sample of galaxies can provide information on the relative importance of gas flows from one galaxy to another. Such a comparison is presented in Figure 1.3 (Garnett 2002), which plots the effective yields derived for 22 spiral and 10 irregular galaxies versus $V_{rot}$ using equation 1.1 and published data on abundances, atomic and molecular gas, and photometry. The data show a factor of 10-20 systematic increase in $y_{eff}$ from the least massive irregulars to the most massive spirals.

This result is striking verification that the yields derived for dwarf irregulars are significantly lower than in spiral galaxies. The trend toward small $y_{eff}$ in the least massive galaxies suggests that it is the loss of metals in galactic winds that drives the correlation, although other factors such tidal stripping may also be important. The plot suggets that galaxies with $V_{rot} <$ 100-150 km s$^{-1}$ lose significant quantities of metals, while more massive ones retain essentially all their metals; this transition is consistent with estimates of Martin (1999).

### *1.2.2 Abundance Gradient Variations*

Figure 1.4 shows that the steepness of abundance gradients (expressed in dex/kpc) decreases with galaxy luminosity. However, more luminous galaxies have larger disk scale lengths, and so if one looks at the gradient per disk scale length (Figure 1.4, bottom panel), the correlation goes away. Considering the errors in the computed gradients (typically 25%), then the scatter in gradients per scale length slopes may be consistent with purely observational scatter. This is related to the exponential abundance gradients noted previously. It has been suggested (Combes 1998) that purely exponential gradients may be explained by so-called "viscous disk" models (Lin & Pringle 1987; Clarke 1989) for disk evolution; if the timescale for viscous transport of angular momentum is comparable to the star formation timescale (with the two timescales connected through the gravitational instability perhaps), such models naturally produce an exponential stellar disk. Another interesting possibility (Prantzos & Boissier 2000) is that the variation in gradients is a result of evolution of disks that follow the scaling relations for galaxies in the cold dark matter model for galaxy formation (Mo, Mao, & White 1998). In the chemical evolution models of Prantzos & Boissier, average metallicity correlates with galaxy mass, while the angular momentum parameter determines the gradient slope; galaxies with larger angular momentum have longer scale lengths and shallower abundance gradients. This would be remarkable since it is not obvious that the present day composition of galaxies should have any memory of the initial conditions for galaxy formation. for the Milky Way.

### *1.2.3 Barred Spirals*

Bars are interesting because the gravitational potential of a bar is expected to induce a large-scale radial gas flow, through radiative shocking and subsequent loss of angular momentum as the gas passes through the bar (Barnes 1991). The radial flow could significantly alter the metallicity distribution by mixing in gas from outer radii, thus weakening composition gradients. The evidence so far accumulated indicates that barred spirals generally have shallower composition gradients than weakly-/non-barred spirals (ZKH; Martin & Roy 1994). Martin & Roy (1994) have argued that the slope of the composition gradient correlates with both bar length and bar strength (the ratio of bar length to width). This is illustrated in Figure 1.5, which shows the O/H gradient per kpc versus bar length $a$ relative to the photometric radius (*top panel*) and versus bar strength $E_B = 10(1-b/a)$, where b is the bar width (*bottom*. The plots show that (1) the non-barred spirals show a wide range of

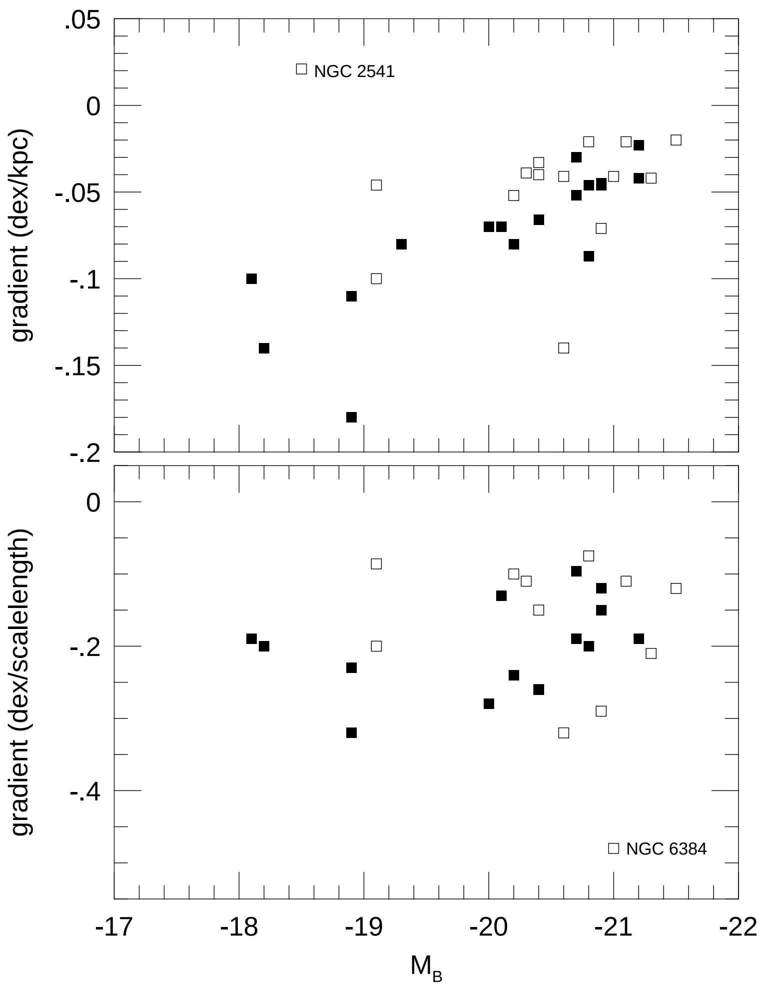


Fig. 1.4. The correlation of abundance gradient vs. $M_B$, from Garnett et al. (1997a). The upper panel shows abundance gradients per kpc, while the lower panel shows gradients per unit disk scale length.

values for gradient slopes, although on average they are steeper than those for barred spirals; and (2) the O/H gradients for the barred spirals tend to get shallower with increasing bar length and bar strength.

Curiously, some barred spirals (e.g., NGC 1365; Roy & Walsh 1997) show an O/H gradient within the bar, with flattening only outside the bar. One way to explain this is if strong

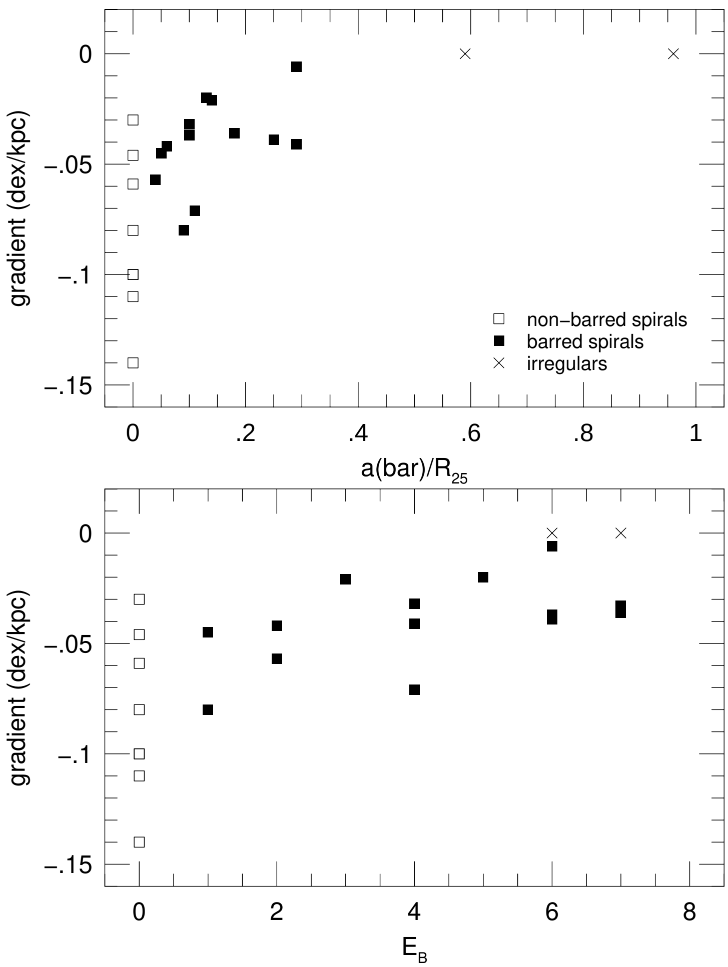


Fig. 1.5. *Top:* O/H gradient per kpc vs. bar length $a$ relative to the photometric radius $R_{25}$. Filled squares are barred spirals, unfilled squares non-barred spirals, and crosses are irregular galaxies. Bottom: O/H gradient vs. bar strength $E_B = 10(1{-}b/a)$, where $b/a$ is the ratio of bar minor and major axes. Plot adapted from Martin & Roy 1994.

star formation occurs in the bar, building up abundances faster than the radial flow can homogenize them (Friedli, Benz, & Kennicutt 1994).

### *1.2.4 Cluster Spirals and Environment*

Environment and interactions appear to play a significant role in the evolution of galaxies, particularly in dense environments. Interactions with satellites may be responsible for the significant fraction of lopsided spiral galaxies (Rudnick & Rix 1998). Disk asymmetry may affect the inferred spatial distribution of metals in the interstellar gas. For example, Kennicutt & Garnett (1996) noted an asymmetry in O/H between the NW and SE sides of M101, which may be related to the asymmetry in the structure of the disk. Zaritsky (1995) found a possible correlation between disk $B-V$ and the slope of the O/H gradient such that bluer galaxies tended to have steeper gradients. He suggested that accretion of metal-poor, gas-rich dwarf galaxies in the outer disk could steepen abundance gradients and make the colors bluer through increased star formation.

Rich clusters offer a variety of galaxy-galaxy and galaxy-ICM interactions. The cluster environment affects the morphology of galaxies (Dressler 1980). It is also known that spirals near the center of rich clusters, for example, the Virgo cluster, show evidence for stripping of H I (Warmels 1988; Cayatte et al. 1994). Such stripping is inferred to result from interaction of the galaxy ISM with the hot X-ray intracluster gas. The degree of H I stripping correlates with projected distance from the cluster core.

If field galaxies evolve through continuing infall of gas (Gunn & Gott 1972), then the truncation of H I disks in cluster spirals should have an effect on the chemical evolution. Infall of metal-poor gas reduces the metallicity of the gas at a given gas fraction. Truncation of such infall should then cause the chemical evolution of cluster spirals to behave more like the simple closed box model, and thus should have higher metallicities than comparable field spirals. This idea has led to several studies of abundances in Virgo spirals (Skillman et al. 1996; Henry et al. 1994, 1996). The results indicate that cluster spirals with the largest H I deficiencies have higher O/H abundances than field spirals with comparable $M_B$, rotation speeds, and Hubble types, while spirals with only modest or little H I stripping have abundances comparable to those of similar field spirals. The samples studied so far have been small, and one must worry about possible systematic errors in abundances. This is an area that could benefit from further study with larger galaxy samples and more secure abundance measurements.

## 1.3 Element Abundance Ratios in Spiral and Irregular Galaxies

The abundance ratios of heavy elements are sensitive to the initial mass function (IMF), the star formation history, and variations in stellar nucleosynthesis with, e.g., metallicity. In particular, comparison of abundances of elements produced in stars with relatively long lifetimes (such as C, N, Fe, and the s-process elements) with those produced in short-lived stars (such as O) probe the star formation history. Below, I review the accumulated data on C, N, S, and Ar abundances (relative to O) in spiral and irregular galaxies, covering two orders of magnitude in metallicity (as measured by O/H). The data are taken from a variety of sources on abundances for H II regions in the literature.

### *1.3.1 Helium*

Helium, the second most abundant element, has significance for cosmology and stellar structure. Most $^4$He was produced in the Big Bang, and the primordial mass fraction $Y_p$ is a constraint on the photon/baryon ratio and thus on the cosmological model. The He mass fraction also affects stellar structure. Helium abundances are difficult to determine in

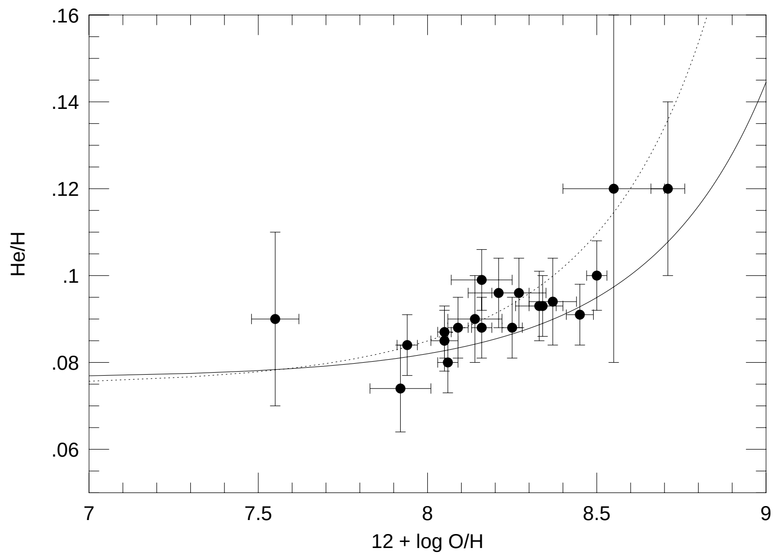


Fig. 1.6. I(He vs. O/H for H II regions in M101 (Kennicutt et al. 2003). The curves show two fits to the $\Delta Y/\Delta(O/H)$ relation for dwarf galaxies from Olive et al. 1998).

any star but OB stars, and in these stars the surface abundance of He may be affected by evolution. On the other hand, He I recombination lines are relatively easy to measure in ionized nebulae, and so a large amount of data is available on He/H in the ISM.

A great deal of effort has been spent discussing the determination of helium abundances and $Y_p$ in metal-poor dwarf galaxies (e.g., Steigman 2003), so I will be brief on this aspect. Peimbert & Torres-Peimbert (1974) made early estimates of $Y_p$ by assuming that the He mass fraction varies linearly with metallicity (or O/H), and thus one could extrapolate He abundances in nebulae with a wide range of O/H to the pre-galactic He abundance at O/H = 0. Today there is very high signal/noise data for He in approximately 40 metal-poor dwarf irregulars, so the extrapolation to O/H = 0 can be estimated to high statistical precision.

The good news is that the best current estimates of $Y_p$ agree to within 5%. This is amazing agreement for measurements derived from spectroscopy of distant galaxies. Nevertheless, the differences in $Y_p$ estimates are still significant for big bang nucleosynthesis theory, as the two largest studies obtain values for $Y_p$ which disagree at the 4-5$\sigma$ significance level (Olive, Skillman & Steigman 1997 vs. Izotov & Thuan 1998). Depending on which estimate is considered most reliable, $Y_p$ either agrees with the best current estimate of D/H, or it does not. At present the battleground for $Y_p$ is focused on sources of systematic error, and these are likely to yield the greatest improvements in He measurements, rather than measuring more data points.

Helium abundances in spiral galaxies are less well-determined, because of more uncertain electron temperatures. The He abundance does have an effect on ionization structure, so it is of interest to know how He/H varies with metallicity in the inner disks of spirals. Figure 1.6 shows He abundances in M101 H II regions, along with extrapolations of fits to the He/H – O/H correlation in metal-poor dwarf galaxies (Olive et al. 1998). The results suggest that $\Delta Y/\Delta(O/H)$ can be fit by a single linear relation up to at least solar abundances.

### *1.3.2 Carbon and Nitrogen*

Carbon abundances in H II regions have been difficult to determine because the important ionization states ($C^+$, $C^{+2}$) have no strong forbidden lines in the optical spectrum. Only the UV spectrum shows collisionally excited lines from both C II and C III. A number of studies of carbon abundances in extragalactic H II regions were made with *IUE* (e.g., Dufour, Shields, & Talbot 1982; Peimbert, Peña, & Torres-Peimbert 1986; Dufour, Garnett & Shields 1988), but for the most part the *IUE* observations suffered from low signal/noise.

The higher UV sensitivity of *HST* offered greatly improved measurements of UV emission lines from [C II] and C III]. Figure 1.7 shows data for C/O as a function of O/H in dwarf irregular and spiral galaxies from *HST* measurements (Garnett et al. 1995a, 1999; Kobulnicky & Skillman 1998). Note that some C (and O) is expected to be depleted onto interstellar dust grains. It is likely that the C/O values should all be increased by 0.1-0.2 dex, but a systematic variation in the fractional depletions with metallicity is not expected.

Figure 1.7 shows a trend of steeply increasing C/O for log O/H $> -4$, while C/O is roughly constant for lower O/H. This is in agreement with observations of C/O in disk stars in the Galaxy (Gustafsson et al. 1999). The notable trend in Figure 1.7 is the apparent 'secondary' behavior of C with respect to O, despite the fact that C (i.e., $^{12}$C) is primary. Tinsley (1979) demonstrated that such variations can be understood as the result of finite stellar lifetimes and delays in the ejection of elements from low- and intermediate-mass stars. If C is produced mainly in intermediate-mass stars, then the enrichment of C in the ISM is delayed with respect to O, which is produced in high-mass stars. On the other hand, C may also have a metallicity-dependent yield in massive stars which results from the effects of stellar mass loss (Maeder 1992). It is not yet certain which effect dominates to produce the rise in C/O. The biggest uncertainties revolve around the theoretical yields, primarily due to the unresolved uncertainties in the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate (Hale 1998), and the effects of convective mixing during helium burning (Arnett 1996).

### *1.3.3 Nitrogen*

The lower panel of Figure 1.7 shows the variation of N/O with O/H in spiral and irregular galaxies. The trend is very similar to that for C/O; N/O is roughly constant at log N/O $\approx$ -1.5 log O/H $< -3.7$, and increases proportionally with O/H in more metal-rich galaxies. The second component is produced via the classical CNO cycle during hydrogen burning in stars and requires the presence of C and O in the star from birth ("secondary N"), while the first component is postulated to come from the CN cycle on freshly-synthesized C (from He-burning) which has been convectively "dredged-up" into a hot H-burning zone at the base of the convective envelope, and does not require an initial seed of C or O ("primary" N). The latter process is most commonly thought to occur in the asymptotic giant branch (AGB) stage of intermediate mass stars (Iben & Truran 1978), but has been found to occur in models of massive stars with increased convective overshooting or rotationally-induced

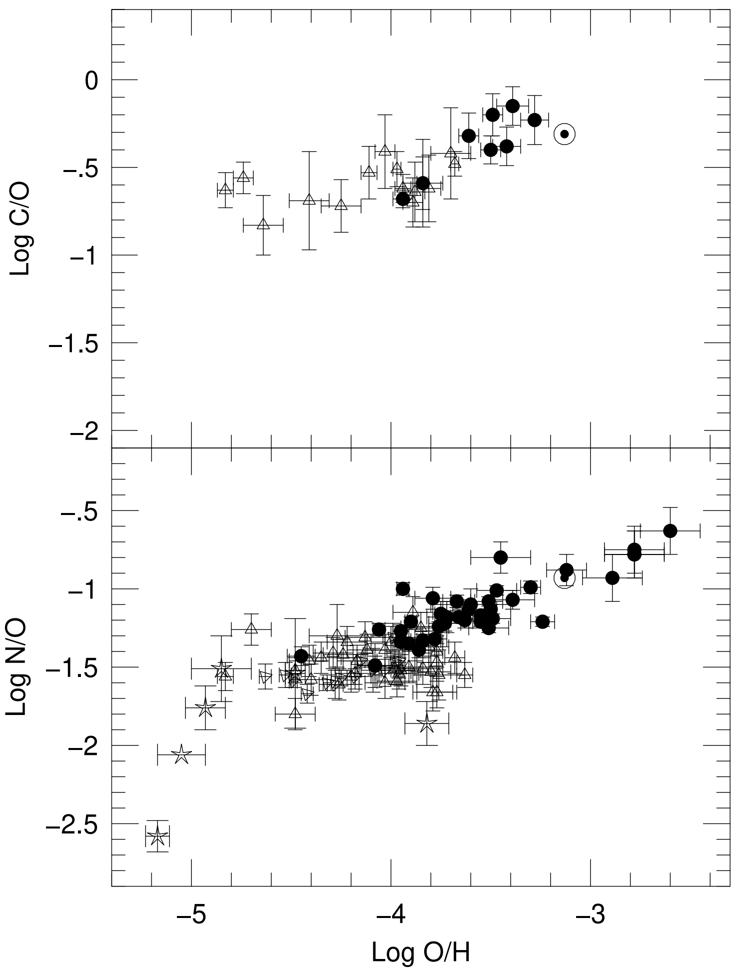


Fig. 1.7. *Top:* C/O abundance ratios from spectroscopy of H II regions in spiral and irregular galaxies. *Open symbols*: irregular galaxies; *filled symbols*: spiral galaxy H II regions. *Bottom:* N/O vs. O/H in spiral and irregular galaxies. *Open circles*: Garnett 1990; *open diamonds*: Thuan et al. 1995; *filled circles*: Garnett et al. 1997; Kennicutt et al. 2003; Díaz et al. 1991; *stars*: high-redshift absorption line systems.

mixing (e.g. Langer et al. 1997). Some scatter is seen in N/O for dwarf galaxies (Kobulnicky & Skillman 1998). This may be the result of localized enrichment by Wolf-Rayet stars.

Recent studies of high-redshift Lyman-alpha absorption systems (plotted as stars in Figure 1.7) have found objects with N/S, N/Si, and N/O ratios much lower than in the dwarf galaxies (Pettini, Lipman & Hunstead 1995; Lu, Sargent, and Barlow 1998; Prochaska et al. 2002).

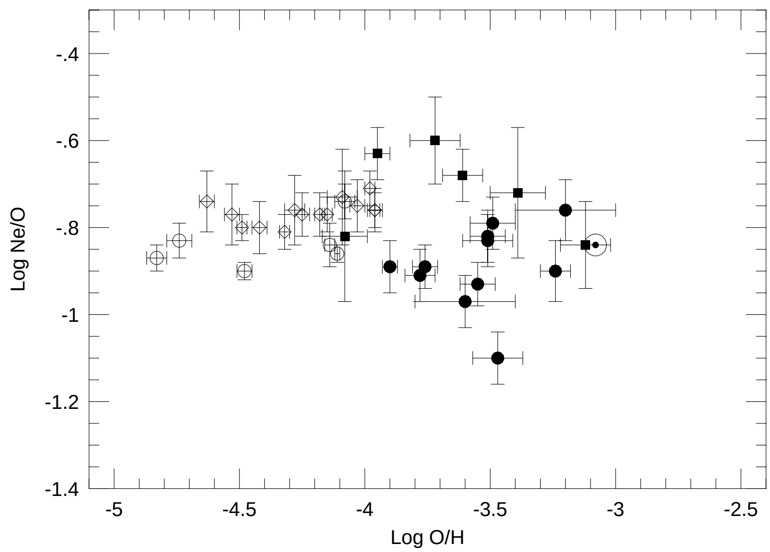


Fig. 1.8. Ne/O abundance ratios in spiral and irregular galaxies. Symbols are the same as in Figure 18.

A wide range in inferred N/O is seen in the DLAs, but the lowest values are as much as a factor 10 smaller than the average for irregular galaxies. The results are consistent with the idea that the DLAs represent lines of sight through very young galaxies, with an age spread of a few hundred Myr, the timescale for enrichment of N from AGB stars.

### *1.3.4 Neon, Sulfur and Argon*

Neon, sulfur, and argon are products of the late stages of massive star evolution. $^{20}$Ne results from carbon burning, while S and Ar are products of O burning. As they are all considered part of the $\alpha$-element group, their abundances are expected to track O/H closely. Deviations from this may point to unsuspected variations in the stellar IMF or nucleosynthesis.

Neon abundances in extragalactic H II regions are derived primarily from optical measurements of [Ne III], although spacecraft measurements of the IR [Ne II] and [Ne III] fine-structure lines are becoming available. Few measurements of Ne are available for metal-rich objects. The data that are available show that Ne tracks O quite closely (Figure 1.8), in agreement with results from planetary nebulae (Henry 1989).

Figure 1.9 shows data for sulfur and argon. For log O/H $< -3.5$, S/O and Ar/O are essentially constant with O/H, and fall within the range predicted by Weaver & Woosley (1993; WW93). For log O/H $> -3.5$, however, there is evidence for declining S/O and Ar/O as O/H increases. The cause of the decline is not clear. It is possible that the ionization corrections for unseen $S^{+3}$ have been underestimated in the more metal-rich H II regions.

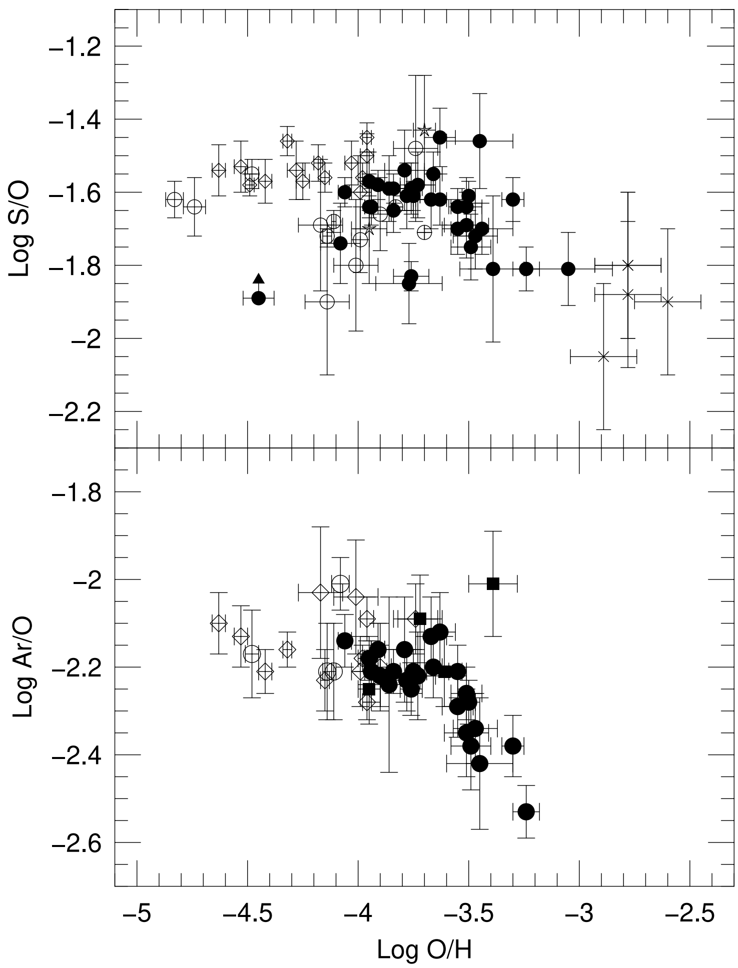


Fig. 1.9. *Top:* S/O abundance ratios in spiral and irregular galaxies. *Bottom:* Ar/O abundance ratios in spiral and irregular galaxies. Symbols are the same as in Figure 1.7.

More observational study, especially IR spectroscopy, of metal-rich H II regions is needed, to rule out ionization or excitation effects.

Because S and Ar are produced close to the stellar core, the yields of S and Ar may be sensitive to conditions immediately prior to and during the supernova explosion, such as explosive processing or fall-back onto the compact remnant (WW93). If real, however, the declining S/O and Ar/O cannot be accounted for by simple variations in the stellar mass function and hydrostatic nucleosynthesis (Garnett 1989); some variation in massive star

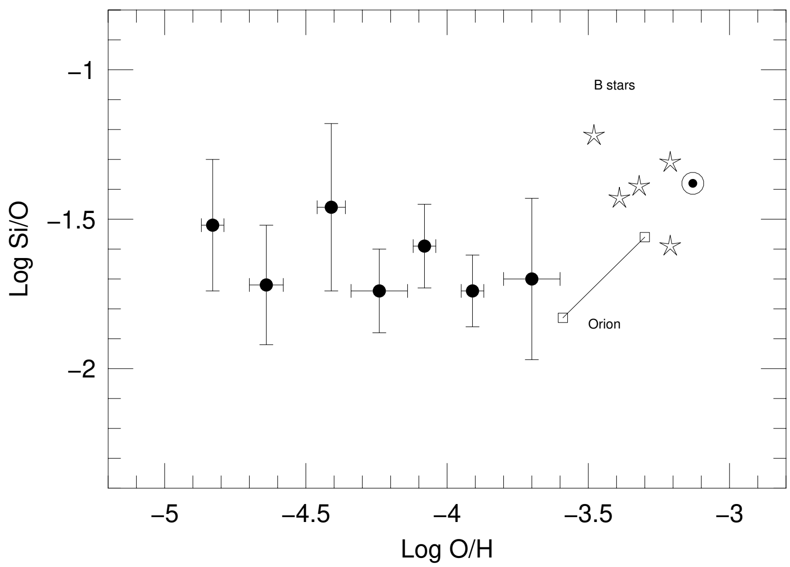


Fig. 1.10. Si/O abundance ratios in irregular galaxies, from Garnett et al. 1995b (filled circles). The open squares represent two different measurements for the Orion nebula, while the stars show averages for four samples of Galactic B stars.

and/or supernova nucleosynthesis at high metallicities (perhaps due to strong stellar mass loss) may be needed.

### *1.3.5 Other Elements*

Few other elements have been measured systematically in extragalactic H II regions, over a wide range of O/H. Emission from [Fe II] and [Fe III] has been detected in a number of H II regions (Rodriguez 2002), but iron is severely depleted onto grains. Silicon can be measured in H II regions through the UV Si III] doublet at 1883, 1892 Å. Figure 1.10 shows Si/O measurements from Garnett et al. (1995b) for a small sample of metal-poor galaxies, along with data for several samples of B stars and the Orion nebula. Si/O appears to be roughly constant but smaller than the average for the Sun and the solar neighborhood B stars. Silicon is certainly depleted onto grains in the ISM, and the results in Figure 1.10 are consistent with a Si depletion of about –0.2 to –0.4 dex in the H II region sample. This is probably appropriate for low density ionized gas (Sofia, Cardelli, & Savage 1994).

Iron has a variety of emission lines from [Fe II] and [Fe III] in the optical spectrum. The [Fe III] 4658 Å is often observed in extragalactic H II regions. Izotov & Thuan (1999) measured [Fe III] in several metal-poor emission-line galaxies and derived Fe abundances. They obtained Fe/O ratios that were similar to the values found for metal-poor stars in the Galactic halo, and used this to argue that the their emission-line galaxies were very young. However, Fe is greatly depleted onto grains in the ISM, so it is improbable that O/Fe ratios in H II regions can be used to interpret the enrichment history of the ISM without better understanding of the depletion factors.

## 1.4 Open Questions and Concluding Remarks

In conclusion, I'd like to enumerate a few questions regarding the chemical evolution of galaxies that seem to need further investigation.

- What are the primary mechanisms determining the shape and slope of abundance gradients in spiral galaxies? We have seen that chemical evolution models tend to predict that composition gradients should get shallower in the inner disks spirals, but this has not been observed in real galaxies. Does viscous evolution play a role in maintaining an exponential gradient, by transferring new gas into the inner disk? This is essentially a hydrodynamical problem.
- How homogeneous are abundances in galaxies at a given place and time? Conflicting studies have argued for significant ($\pm$0.2-0.3 dex) variations in abundances on small scales, or for a very homogeneous composition ($<$ 0.1 dex variations). The question is relevant to the time scales for cooling and mixing of stellar ejecta with the ambient ISM. Most chemical evolution models assume instantaneous mixing, but is this a good approximation?
- Is infall of gas presently occuring in galaxies, and how does the rate evolve with time? This is a big unknown, since most chemical evolution models use relatively slow, ongoing infall of metal-poor gas to suppress the fraction of metal-poor G dwarfs. Observational evidence for classical infall is sketchy. The high-velocity clouds seen at high latitudes may represent infall, or may be part of a Galactic fountain flow, or may be associated with interaction between the Galaxy and its satellite galaxies.
- What galaxies may be losing metals to the IGM, and how much do they contribute? Is there a threshold mass above which galaxies retain metals?
- Does galaxy environment influence composition? The Virgo cluster studies need to be followed up by larger samples in a wider variety of cluster environments. The spiral-rich Ursa Major cluster and the Coma cluster are two obvious choices for continued study.
- Is there zero metallicity gas (or stars for that matter) in galaxies? Pre-enrichment by an initial stellar Population III also provides a solution to the G-dwarf problem and to the origin of metals seen in Ly$\alpha$ forest clouds. What is the composition of the huge gas reservoirs in the outer parts of spirals and irregulars?

We are seeing great improvements in the study of abundances in nearby galaxies, particularly with the new space-based UV and IR observatories, which are greatly improving the data for elements besides oxygen. With these new data, we are in a better position to connect the present-day abundance patterns in galaxies with those observed in high-redshift gas clouds. Eventually, emission-line spectroscopy of distant galaxies should greatly expand our information on heavy element abundances at early times, and allow us to trace the evolution of metallicity in the universe in greater detail. This will be an important complement to the absorption line work on DLAs, as the connection between the emission-line gas and the stellar component is much more clear, and the disk component can be sampled more completely than with absorption studies.

Many of the questions mentioned reference hydrodynamics. Star formation, the evolution of galaxies, and stellar nucleosynthesis all involve hydrodynamics at fundamental levels, so improved hydrodynamical modeling of all of these phenomena should ultimately lead to a better understanding of galaxy evolution. Determining the mechanisms which connect abundances to galaxy structure should provide a continuing challenge to galaxy evolution theorists.

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