RevMexAA (Serie de Conferencias), **12**, 189–194 (2002)

CHEMICAL EVOLUTION OF GALAXIES

Gregory A. Shields

Department of Astronomy, University of Texas at Austin

RESUMEN

Las abundancias químicas dan claves importantes sobre la evolución de las galaxias. Las nebulosas ionizadas están entre las fuentes principales de mediciones de abundancias químicas, especialmente en las galaxias externas. Estudios de regiones H II han mostrado que la metalicidad total de las galaxias se incrementa con la luminosidad galáctica, y que las galaxias espirales tienen característicamente gradientes radiales de composición química. Hay indicaciones de influencias ambientales sobre las abundancias químicas. Las nebulosas planetarias proporcionan otra medida de las abundancias en la Vía Láctea y otras galaxias. Instrumentos en el espacio exterior han permitido mediciones para elementos que son inaccesibles en longitudes de onda ópticas. Los grandes telescopios hacen posible el estudio de estrellas individuales en galaxias externas y el estudio de abundancias interestelares en galaxias de corrimiento al rojo intermedio y alto. Estos avances son promesa de una época excitante, mientras los astrofísicos se esfuerzan por completar una teoría de evolución galáctica desde la Gran Explosión hasta el presente.

ABSTRACT

Chemical abundances provide important clues to the evolution of galaxies. Ionized nebulae are one of the main sources of chemical abundance measurements, especially in external galaxies. Studies of H II regions have shown that the overall metallicity of galaxies increases with galactic luminosity, and that spiral galaxies characteristically have radial gradients in chemical composition. There are indications of environmental influences on chemical abundances. Planetary nebulae provide another measure of abundances in the Milky Way and other galaxies. Space facilities have allowed measurements for elements that are inaccessible at optical wavelengths. Large telescopes make possible the study of individual stars in external galaxies and the study of interstellar abundances in galaxies at intermediate and high redshifts. These advances promise exciting times as astrophysicists strive to paint a complete picture of galactic evolution from the Big Bang to the present.

Key Words: **GALAXIES: ABUNDANCES — GALAXIES: EVOLUTION — ISM: ABUNDANCES — STARS: ABUNDANCES**

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

1. INTRODUCTION

Ionized nebulae have played an important role in the measurement of interstellar abundances in our own galaxy and others while also serving as a laboratories for atomic physics. Early nebular studies focused on planetary nebulae and H II regions in our galaxy. These showed abundances roughly similar to those in the sun, but with significant differences depending on the element, location in the Galaxy, and the stellar population involved. The advent of sensitive detectors and the increasing availability of large telescopes made possible the systematic study of giant extragalactic H II regions (GEHRs), planetary nebulae, and supernova remnants in external galaxies. This work revealed patterns of variation of chemical composition with position in a galaxy, and from galaxy to galaxy. Today we know that chemical abundances decrease outward across the disks of galaxies, and that they increase with increasing galactic luminosity. These trends are qualitatively echoed in the abundances of stars in elliptical galaxies. The relative abundances of the elements also show systematic trends. There are indications that the cluster environment affects the chemical evolution of spiral galaxies. Observations of QSO emission lines suggest a metal rich environment in galactic nuclei even at high redshift. Studies of QSO absorption lines probe the interstellar medium of galaxies at early times. These results provide a rich set of constraints for theoretical models. For a detailed discussion of abundances in spiral and elliptical galaxies, the reader is referred to the excellent review by Henry & Worthey (1999, "HW"). Observational results and theoretical foundations are discussed in the classic review by Tinsley (1980).

2. FOUNDATIONS

A useful reference model for chemical evolution theory is the so-called "simple model", involving progressive conversion of gas to stars in a closed box. In this model, stars either live forever or die instantaneously, returning enriched material to the interstellar medium (ISM). The mass of freshly produced metals per unit mass of long lived stars formed is the "yield", p. Then the mass fraction of metals, Z, in the gas increases as the gas fraction, $\mu \equiv M_{\rm gas}/M_{\rm tot}$, decreases, according to $Z = p \ln \mu^{-1}$ (Searle & Sargent 1972). An interesting way to express measured abundances is the "effective yield", defined in terms of the simple model of chemical evolution: $Z({\rm O}) = p_{\rm eff}({\rm O}) \ln \mu^{-1}$, etc.

Oxygen, neon, and sulfur, among other elements, are "primary" products of stellar nucleosynthesis, whose yields depend relatively little on the abundances in the progenitor star. On the other hand, nitrogen largely results from secondary production, so that the yield is proportional to the abundance of C and O in the progenitor. This leads to an increase in N/O with increasing O/H, above a minimum N/O that corresponds to the primary contribution to nitrogen production. This is shown by observations of H II regions in spiral and irregular galaxies for O/H above a threshold value ~ 0.2 solar (e.g., Talbot & Arnett 1974; Garnett 1990, 2002). Iron is believed to be produced in part by type Ia supernovae that require time ($\sim 10^9$ yr) to evolve to the point of explosion (see review by Wheeler, Sneden, & Truran 1989). The more massive stars producing elements such as O explode effectively instantaneously, and therefore the O/Fe ratio is an indicator of the timescale on which a population of stars was formed.

The number of main sequence stars as a function of abundance in the solar neighborhood disagrees with the simple model in the sense that there are too few metal poor stars (van den Bergh 1962; Audouze & Tinsley 1976). This "G dwarf problem" is an important constraint on models for chemical evolution of the Galaxy. One solution is that continuing infall of metal poor gas causes the abundances to approach an asymptotic value at which most stars are formed (Larson 1972).

Pagel (2001) gives a succinct discussion of results involving stellar abundances in the halo, "thick disk", and "thin disk" of the Milky Way. The high O/Fe ratio in the halo and thick disk suggests a brief formation period, early in the history of the Galaxy. The thin disk has lower O/Fe and a metallicity distribution consistent with prompt initial enrichment (perhaps from the thick disk) combined with infall of extragalactic gas, with a hiatus in star formation between the thick and thin disk formation of several billion years. See Pagel (2001) and Chiappini, Matteucci, & Gratton (1997) for further discussion and references.

3. RADIAL GRADIENTS

Radial gradients in chemical composition are characteristic of spiral galaxies. Searle (1971) studied the systematic variation of the [N II], [O II], and [O III] emission-line intensities of GEHRs in several spiral galaxies as a function of galactocentric distance. His analysis indicated radial decreases in O/H and N/O. The latter was consistent with the suggestion by Peimbert (1968) that the strong [N II] emission from the nuclei of M51 and M81 reflected a high abundance of nitrogen. Searle's work was followed by other observational studies and by analyses involving computer models of the nebular ionization and thermal structure (e.g., Smith 1975; Shields & Searle 1978). As results for a substantial number of galaxies became available (e.g., McCall, Rybski, & Shields 1985; Zaritsky, Kennicutt, & Huchra 1994, ZKH), analysis of the systematics of abundances became possible. Radial gradients may be fit by an exponential in R/R_0, where R_0 is the isophotal radius. Barred spirals have gradients substantially shallower than normal spirals, but similar overall abundances (Martin & Roy 1994; ZKH). Low surface brightness spirals have relatively low abundances for their mass (McGaugh 1994). Local abundances increase with the local surface surface brightness or surface mass density (McCall 1982; Edmunds & Pagel 1984; Vila-Costas & Edmunds 1992).

The Milky Way has a gradient in O/H of -0.06 dex/kpc (HW, and references therein). This is supported by studies of H II regions and planetary nebulae (Maciel & Köppen 1994). Carraro, Ng, & Portinari (1998) note that a variety of theoretical models for the chemical evolution of the Galaxy match the radial gradient at the present time, but have quite different predictions for the time evolution of the gradient. They conclude from the available stellar data, in particular for open clusters, that the gradient has changed relatively little with time. This conclusion seems in harmony with the fact that nonbarred spirals have similar gradients, which might not be expected if gradients changed greatly during the course of galactic evolution.

Space observatories have made possible the measurement of carbon emission lines in H II regions. Results for spiral and irregular galaxies have revealed an unexpected trend in which C/O increases substantially with increasing O/H (Garnett et al. 1999;

Garnett 2002, and references therein). This may be explained in terms of the effect of stellar winds on the evolution of massive stars. The winds carry off more mass at higher abundances, causing the evolution of the stellar core to be arrested and the yield of oxygen to be decreased, relative to that of carbon (e.g., Carigi 1996, 2002).

4. ABUNDANCE FLUCTUATIONS

Chemical enrichment involves supernova explosions, stellar winds, and planetary nebula ejections. Events involving massive stars are concentrated in young star clusters, leading to the potential for localized enrichment. Infall of primordial (or not so primordial) gas from the environment of a galaxy may involve accretion of gas clouds or dwarf galaxies, possibly leading to localized depressions of heavy element abundances. Heavy elements are dispersed by flows propelled by supernova explosions and stellar winds, as well as differential rotation, large scale flows induced by bars, etc.

Local abundance fluctuations in spiral galaxies have a smaller amplitude than the overall radial gradients. There is, however, evidence for significant fluctuations in the Milky Way. The solar oxygen abundance [O/H] = 8.87 (Grevesse & Noels 1993) significantly exceeds the Orion nebula value 8.58 (Baldwin et al. 1991; Esteban et al. 1998) as well as HW's "composite" H II region value 8.68 ± 0.05 at the solar circle. (One uncertainty is the nagging question of temperature fluctuations in the nebular gas, Peimbert 1967). Abundances in B stars in the vicinity of the Orion complex agree with the nebular value, although there is evidence that abundances increased as star formation progressed through the region (Cunha & Lambert 1992). The sun is 0.17 dex more metal rich than the average nearby star (Wielen, Fuchs, & Dettbarn 1996). Wielen et al. propose that the sun was born ~ 2 kpc closer to the Galactic center than its current orbital radius, where abundances were higher. Dispersions among open clusters presumably are less affected by this process, if indeed it is important (Garnett & Kobulnicky 2000).

Edvardsson et al. (1993) found a large spread in [Fe/H] in G stars at the solar circle, but little trend in metallicity with age. Friel & Boesgaard (1992) studied C and Fe abundances in F stars in open clusters in the Galactic disk. They found no significant dispersion in abundance among the stars in a single cluster at the level of 0.05 dex but significant differences from cluster to cluster at a level of ~ 0.1 dex. They found little dependence on age from 50 million to 5 billion years. The open clusters studied by Carraro et al. (1998) show a range in [Fe/H] of 0.6 dex, suggesting a dispersion $\sigma \approx 0.15$. In contrast, interstellar oxygen measurements by Meyer, Jura, & Cardelli (1998) show a dispersion of only ± 0.05 dex on a number of sightlines. In a recent study of the Galactic H II regions by Deharveng et al. (2000), the scatter of the best measurements around the mean gradient in O/H is small. Garnett & Kobulnicky (2000) examine evidence for abundance fluctuations in H II regions, stars, and the interstellar medium. They argue that selection effects in the star sample of Edvardsson et al. complicate the interpretation of the abundance scatter, and that the true dispersion for field stars is less than 0.15 dex.

Results for external spirals are inconclusive, because of the lack of precise measurements of the electron temperature in a sufficient sample of GEHRs. In a study of H II regions in M101, Kennicutt & Garnett (1996) suggest, on the basis of line ratio correlations, that the true dispersion around the mean gradient is less than the observed scatter of 0.1 to 0.2 dex.

These results suggest that, in the disks of spiral galaxies, abundance fluctuations with $\sigma \approx 0.1$ dex occur on a scale larger than the clouds that form a typical open cluster, but smaller than the distance between open clusters. The dominant cause of the fluctuations remains unclear. Several processes have been discussed, including local enrichment by supernovae and accretion of clouds of metal poor gas (e.g., Carraro et al. 1998, and references therein). Franco et al. (1988) discuss the possibility that the Orion molecular cloud complex, with its relatively low metallicity, results from the impact of a metal poor gas cloud.

The prevailing level of abundance fluctuations in the ISM depends on the competition between localized enrichment and mixing. Roy & Kunth (1995) considered mixing on different scales in the Galactic disk. On scales of 1 to 10 kpc, local abundance fluctuations are smoothed in less that 10^9 yr by turbulent diffusion of clouds together with differential rotation. On scales 100 to 1000 pc, cloud collisions, star-formation driven flows, and differential rotation mix the gas in 10^8 yr. On scales 1 to 100 pc, turbulence in ionized regions mixes the gas in $10^{6.3}$ yr or less.

Abundances in irregular galaxies generally are quite uniform. Kobulnicky & Skillman's (1997) results for NGC 1569 show a dispersion of ± 0.05 dex in O/H and N/O in the well measured regions. They argue that, at the low metallicity of this object, pollution by the ejecta of only a few massive stars should

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

give measurable enrichment. They suggest that the supernova ejecta form a hot wind that escapes the galaxy, disperses the ejecta, and later reaccretes, avoiding local enrichment at the site of the stars' deaths. There are, however, rare cases of local enrichment, in particular an H II region with high N/O in NGC 5253 (Kobulnicky et al. 1997).

5. LUMINOSITY DEPENDENCE

Characteristic abundances increase with galactic luminosity, and this trend embraces irregulars as well as spirals (Skillman et al. 1989; Garnett 1999; ZKH). This trend may involve the escape of nucleosynthesis products in winds from galaxies with low escape velocities (Matteucci & Chiosi 1983). Garnett (2001) plots the dependence of effective yield on luminosity; effective yields for low surface brightness galaxies (LSBs) as a class fall below those for normal galaxies. Stellar abundances in elliptical galaxies also increase with galactic luminosity (HW and references therein).

6. EFFECT OF ENVIRONMENT

Modern ideas about the evolution of galaxies emphasize the role of accretion and mergers. What is the influence of environment on the chemical evolution of galaxies? Skillman et al. (1996) studied the abundances in spirals in the Virgo cluster, based on spectra of GEHRs. They found that galaxies in the cluster core, with marked H I deficiencies, were more metal rich than spirals with normal H I content located in the periphery of the cluster and in the field. They suggested that this results from the curtailment of metal-poor infall onto galaxies in the cluster core, where they are immersed in the hot cluster medium. In contrast, infall continues onto spirals in the cluster periphery and in the field, restraining the increase in abundances with time.

The question of infall onto the Milky Way relates to the proposal by Blitz et al. (1999) that some of the Galactic high velocity clouds (HVCs) observed in H I, and sometimes seen in heavy element absorption lines, are actually a population of dwarf galaxies or gas clouds belonging to the Local Group. The inferred accretion rate of these clouds onto the Milky Way is interesting in the context of chemical evolution. The Blitz model draws together a number of aspects, including cosmological predictions of dwarf galaxy counts and the dynamical evolution of the Local Group. However, the massive H I clouds involved in this model have not been found in other groups of galaxies (e.g., Zabludoff 2001; Zwaan 2001).

Also of interest is chemical evolution in low density environments. Peimbert & Torres-Peimbert (1992) obtained spectra of emission-line galaxies in the Boötes void. Most appear to be irregular galaxies with H II regions ionized by OB stars. Several of the objects have rather low N/O values, compared to a small sample of nearby H II regions with similar O/H, including the LMC. As noted by Garnett (1990), a low N/O value may occur in a young galaxy or in one whose oxygen has been enriched by a recent starburst, because N comes largely from lower mass stars with longer lifetimes than stars producing O. Thus Peimbert & Torres-Peimbert suggest that the Boötes objects with low N/O may be young galaxies; and they note that late collapse of density clumps to form galaxies may be a natural occurrence in a low density environment. However, the range of N/O values shown by Garnett (1990) encompasses the Boötes values, albeit for slightly lower O/H.

The study of abundances in galaxies in low and high density environments deserves more attention. These studies will require spectra of adequate sensitivity and wavelength resolution together with measurements of the gross properties of the galaxies, so that comparisons can be made in a way that isolates the effect of environment.

7. ABUNDANCES IN THE EARLY UNIVERSE

Abundances at high redshift can now be measured in a variety of ways involving emission and absorption lines, thanks to large telescopes and sensitive light detectors. Once the high redshifts of quasars were recognized, the potential to use these remarkable objects as probes of the early universe was clear. Derivation of abundances from the emission lines of AGN is difficult, however. The width of the broad lines impedes measurement of weak lines, and the high electron density in the broad line region (BLR) and the large optical depths of some of the lines makes analysis difficult. This is true in particular for the measurement of the electron temperature, necessary to calculate the line emissivity. Shields (1976) noted that relative abundances of C, N, and O could be derived with less sensitivity to the uncertainty in the electron temperature. The N/O and N/C ratio might in turn be an indicator of the overall metallicity, given the secondary nature of nitrogen production. He found high N/C in two QSOs and suggested a parallel to high nitrogen abundances in nearby normal galactic nuclei and AGN. Hamann & Ferland (1993) studied QSO abundances as a function of redshift by bringing together chemical evolution models and photoionization models. They concluded that most luminous, high redshift QSOs ($z \approx 2$ to 4) have abundances higher than solar. Hamann & Ferland also noted that iron abundances in QSOs at high redshift might constrain cosmological models.

Abundances are also measured in absorbing gas clouds on the line of sight to a QSO. This includes the high column density "damped Lyα" systems (DLAs) and the Lyα forest. An example of the study of heavy element abundances in DLAs is the work of Pettini et al. (1999). They find [Zn/H] ≈ -1.2 in the redshift range $z = 1$ to 3, with rather little systematic dependence on redshift. The relative abundances of the heavy elements are consistent with a mild degree of depletion onto grains, and [Si/Zn] is essentially solar. (The ratio Si/Zn is a useful surrogate for O/Fe.) Thus, these absorbers do not appear to share the [O/Fe] enhancement of metal poor stars in the Galactic halo. Evidently, even at redshifts of 2 or so, past star formation in the DLA systems had proceeded gradually enough that iron production kept pace with oxygen and other SN II products.

Lyα forest clouds often show C IV $\lambda\lambda$ 1548, 1550 absorption lines when observed with sufficient resolution. Songaila & Cowie (1996) measured O VI as well and found that ionization ratios and line widths pointed to photoionization rather than collisional ionization. Mean abundances ratios appear to be [C/H] ≈ -1.5 and [O/C] $\approx$ [Si/C] $\approx +0.5$, with a spread of order a factor 3 in C/H (Songaila & Cowie 1996; Davé et al. 1998; Ellison et al. 2000). These authors note that the high O/C resembles old halo stars; but as discussed above, O/C is also high in metal poor H II regions.

Abundances in DLAs resemble those measured in GEHRS in the more metal poor dwarf irregulars and in the outermost disks of spirals, that is, [O/H] ≈ -1.5. Silk, Wyse, & Shields (1987) suggested that this widespread minimum may result from reaccretion of enriched gas lost from an early population of dwarf galaxies. The more metal poor stars in the Galactic halo might then represent the cannibalized remains of the primordial dwarf galaxies. The very metal poor clouds of the Lyα forest must then largely have escaped the reaccretion process, at least at the epoch at which they are observed.

Observations of abundances in ionized gas in galaxies at high redshifts are also becoming available. Kobulnicky & Zaritsky (1999) observed a sample of emission-line galaxies at redshifts $z = 0.1$ to 0.5 and found them to be only marginally more metal poor than the metallicity-luminosity relation observed for low redshift galaxies. In contrast, Kobulnicky & Koo (2000) obtained near infrared observations of two Lyα emitting galaxies at $z = 2.3$ and 2.9, finding $12 + \log \mathrm{O/H} = 8.2$ to 8.8. From these and other data, they find that emission-line galaxies at these redshifts have abundances substantially below the present day metallicity-luminosity relation. They note that these low abundances resemble those of metal rich globular clusters and raise the possibility that these objects may resemble the formation of galaxies like the Milky Way at $z \approx 3$. The emission-line galaxies at high redshift have abundances higher than the DLAs, indicating that they represent different environments.

8. DISCUSSION

Progress in understanding the chemical evolution of the Milky Way and other galaxies has relied on an increasing wealth of observations and a variety of theoretical inputs. Modern ideas depart from the concept of a monolithic collapse of the protogalaxy (Eggen, Lynden-Bell, & Sandage 1962), embracing mergers, cannibalism, infall, and radial flows in the disk. This complicated set of processes must be constrained by a commensurate set of observations. For the Milky Way, stellar abundances as a function of age and kinematics are increasingly available. Evidence for mergers in the history of the Galaxy can be found in the kinematics of "star streams" (Majewski 1999). Abundance measurements of individual stars in external galaxies are made possible by large telescopes and modern spectrographs (e.g., Venn et al. 2001, 2002).

Ionized nebulae remain the best way to measure the abundances of many elements in the interstellar gas of galaxies. With sensitive detectors on large telescopes, this work will increasingly involve objects at significant redshifts and in a variety of environments, and precise measurements of local abundance fluctuations on various length scales. Ionized nebulae will continue to play an important role in the description of the chemical evolution of the universe from its youth to the present.

I am indebted to Don Garnett, Chip Kobulnicky, Bernard Pagel, Evan Skillman, and Chris Sneden for helpful discussions.

REFERENCES

Audouze, J., & Tinsley, B. M. 1976, ARA&A, 14, 43
Baldwin, J. A., et al. 1991, ApJ, 374, 580
Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, ApJ, 514, 818.
Carigi, L. 1996, RevMexAA, 32, 179
__________. 2002, RevMexAA(SC), 12, 234 (this volume)

Carraro, G., Ng, Y. K., & Portinari, L. 1998, MNRAS, 296, 1045
Chiappini, C., Matteucci, F., & Gratton, R. 1997, ApJ, 477, 765
Cunha, K., & Lambert, D. L. 1992, ApJ, 399, 586
Davé, R., Hellsten, U., Hernquist, L., Katz, N., & Weinberg, D. H. 1998, ApJ, 509, 661
Deharveng, L., Peña, M., Caplan, J., & Costero, R. 2000 MNRAS, 311, 329
Edmunds, M. G., & Pagel, B. E. J. 1984, MNRAS, 211, 507
Edvardsson, B., et al. 1993, A&A, 275, 101
Eggen, O. J., Lynden-Bell, D. & Sandage, A. R. 1962 ApJ, 136, 748
Ellison, S., L., Songaila, A., Schaye, J., & Pettini, M. 2000, AJ, 120, 1175
Esteban, C., Peimbert, M., Torres-Peimbert, S., & Escalante, V. 1998, MNRAS, 295, 401
Franco, J., Tenorio-Tagle, G., Bodenheimer, P., Różyczka, M., Mirabel, I. F. 1988, ApJ, 333, 826
Friel, E., & Boesgaard, A. 1992, ApJ, 387, 170
Garnett, D. R. 1990, ApJ, 363, 142
__________. 1999, in Chemical Evolution from Zero to High Redshift, ed. J. R. Walsh and M. R. Rosa (Berlin: Springer-Verlag), 139
__________. 2001, in ASP Conf. Ser. 230, Galaxy Disks and Disk Galaxies, eds. J. Funes & E. Corsini (San Francisco: ASP), 353
__________. 2002, RevMexAA(SC), 12, 183 (this volume)
Garnett, D. R., et al. 1999, ApJ, 513, 168
Garnett, D. R., & Kobulnicky, H. A. 2000, ApJ, 532, 1192
Grevesse, N. & Noels, A. 1993, in Origin and Evolution of the Elements, ed. N Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge Univ. Press), 15
Hamann, F., & Ferland, G. J. 1993, ApJ, 418, 11
Henry, R. B. C., & Worthey, G. 1999, PASP, 111, 919 (HW)
Kennicutt, R. C., Jr., & Garnett, D. R. 1996, ApJ, 456, 504
Kobulnicky, H. A., & Koo, D. C. 2000, ApJ, 545, 712
Kobulnicky, H. A. & Skillman, E. D. 1997, ApJ, 489, 636
Kobulnicky, H. A., Skillman, E. D., Roy, J.-R., Walsh, J. R., & Rosa, M. R. 1997, ApJ, 477, 679
Kobulnicky, H. A., & Zaritsky, D. 1999, ApJ, 511, 118
Larson, R. B. 1972, Nature Phys. Sci., 236, 7
Maciel, W. J., & Köppen, J. 1994, A&A, 282, 436
Majewski, S. R. 1999, In ASP Conf. Ser. 165, The Third Stromlo Symposium: The Galactic Halo, eds. Gibson, B. K., Axelrod, T. S. & Putman, M. E. (San Francisco: ASP), 76
Martin, P.,& Roy, J.-R. 1994, ApJ, 424, 599
Matteucci, F., & Chiosi, C. 1983, A&A, 132, 121
McCall, M. L. 1982, PhD thesis, University of Texas at Austin
McCall, M. L., Rybski, P. M., & Shields, G. A. 1985, ApJS, 57, 1
McGaugh, S. 1994, ApJ, 426, 135
Meyer, D. M., Jura, M., & Cardelli, J. A. 1998, ApJ, 493, 222
Pagel, B. E. J. 2002, in Cosmic Evolution, A Conference Honoring Jean Audouze and Jim Truran (World Scientific), in press (astro-ph/0101376)
Peimbert, M. 1967, ApJ, 150, 825
__________. 1968, ApJ, 154, 33
Peimbert, M., & Torres-Peimbert, S. 1992, A&A, 253, 349 (PTP92)
Pettini, M., Ellison, S. L., Steidel, C. C., & Bowen, D. V. 1999, ApJ, 510, 576
Roy, J.-R., & Kunth, D. 1995, A&A, 294, 432
Searle, L. 1971, ApJ, 168, 327
Searle, L., & Sargent, W. L. W. 1972, ApJ, 173, 25
Shields, G. A. 1976, ApJ, 204, 330
Shields, G. A., & Searle, L. 1978, ApJ, 222, 821
Silk, J., Wyse, R. F. G. & Shields, G. A. 1987, ApJ, 322, L59
Skillman, E. D., Kennicutt, R. C., & Hodge, P. W. 1989, ApJ, 347, 875
Skillman, E. D., Kennicutt, R. C., Jr., Shields, G. A., & Zaritsky, D. 1996, ApJ, 462, 147
Smith, H. E. 1975, ApJ, 199, 591
Songaila, A., & Cowie, L. L. 1996, AJ, 112, 335
Talbot, R. J., Jr., & Arnett, D. W. 1974, ApJ, 190, 605
Tinsley, B. M. 1980, Fund. Cosmic Phys., 5. 287
van den Bergh, S. 1962, AJ, 67, 486
Venn, K. et al. 2001, ApJ, 547, 765
__________. 2002, RevMexAA(SC), 12, 230 (this volume)
Vila-Costas, M. B., & Edmunds, M. G. 1992, MNRAS, 259, 121
Wheeler, J. C., Sneden, C., & Truran, J. W., Jr., 1989, ARA&A, 279, 349
Wielen, R., Fuchs, B., & Dettbarn, C. 1996, A&A, 314, 438.
Zabludoff, A. I. 2001, ASP Conf. Ser. 240, Gas and Galaxy Evolution, eds. J. E. Hibbard, M. Rupen, & J. H. van Gorkom (San Francisco: ASP), 547
Zaritsky, D., Kennicutt, R. C., & Huchra, J. P. 1994, ApJ, 420, 87 (ZKH)
Zwaan, M. A. 2001, MNRAS, 325, 1142

G. A. Shields: Department of Astronomy, University of Texas, Austin, Texas 78712, USA (shields@astro.as.-utexas.edu).