Revista Mexicana de Astronomía y Astrofísica, **27**, 21-28 (1993)

SYSTEMATICS OF H II REGION ABUNDANCES IN GALAXIES

R.C. Kennicutt,[1] M.S. Oey
Steward Observatory, University of Arizona
D. Zaritsky[2]
Carnegie Observatories
and
J.P. Huchra
Harvard-Smithsonian Center for Astrophysics

RESUMEN

Estudios previos de abundacias de la fase gaseosa en galaxias de disco han favorecido espirales de campo tardías con regiones H II brillantes. Presentamos resultados preliminares de dos búsquedas para delinear las propiedades de las abundancias en el intervalo completo de tipos, luminosidades y propiedades estructurales de galaxias. Las galaxias de la muestra presentan un amplio intervalo de abundancias medias del disco y de gradientes de abundancia. Las abundancias medias está corrrelacionadas con el tipo, la luminosidad y la velocidad circular de las galaxias a lo largo que lo que es predominantemente una secuencia de un sólo parámetro, aunque es difícil determinar cuál de estas variables está acoplada más fundamentalmente a la abundancia del disco. La relación abundancia–luminosidad de galaxias espirales se traslada casi directamente a la de las galaxias irregulares Magallánicas y elípticas. La pendiente del gradiente de abundancia no está acoplada directamente al tipo de Hubble o a la luminosidad, sino que aparece estar correlacionada con la estructura de barra.

ABSTRACT

Previous studies of gas-phase abundances in disk galaxies have favored late-type field spirals with bright H II regions. Here we report preliminary results from two surveys undertaken to delineate the abundance properties of the full range of galaxy types, luminosities, and structural properties. The galaxies in our sample show a wide range of mean disk abundances and abundance gradients. The mean abundances are correlated with galaxy type, luminosity, and circular velocity along what is predominantly a single-parameter sequence, though it is difficult to determine which of these variables is more fundamentally coupled to the disk abundance. The abundance–luminosity relation for spirals maps almost directly onto those for Magellanic irregular and elliptical galaxies. The slope of the abundance gradient is not closely coupled to Hubble type or luminosity, but appears to be correlated with bar structure.

Key words: **GALAXIES: ABUNDANCES — GALAXIES: ISM — H II REGIONS**

[1] Observations reported in this paper were obtained in part at the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

[2] Hubble Fellow.

1. INTRODUCTION

Most of what is known about the chemical abundances of galactic disks has come from spectrophotometric observations of extragalactic H II regions. Following the initial studies by Searle (1971) and Shields (1974), numerous investigators have measured the oxygen abundance patterns in spiral disks and Magellanic irregular galaxies (see reviews by Pagel & Edmunds 1981, Dinerstein 1990, and Shields 1990). This work shows that most disks exhibit radial O/H abundance gradients and that there is significant variation in characteristic abundance from galaxy to galaxy. The variety in properties may either be tied to local parameters such as disk gas fraction or surface density (cf. Edmunds & Pagel 1984, Vila-Costas & Edmunds 1992) or to global parameters such as galaxy type, mass, or luminosity (e.g., Garnett & Shields 1987).

Limitations in the available data make it difficult to integrate these observations into a comprehensive picture of disk chemical evolution. For most galaxies measurements of only a few H II regions are available, which is barely enough to characterize the overall disk abundance, much less the gradient, and those measurements are biased toward bright, easily measured H II regions in late-type, gas-rich galaxies. There is a particular dearth of information on early-type galaxies (Sb and earlier) because the brightest H II regions in these galaxies are typically 10–100 times less luminous than those in late-type spirals (Kennicutt 1988), and consequently are beyond the reach of most current instrumentation. For these reasons the extant observations probe only a small subset of the range in physical conditions in disks.

The advent of CCD detectors and high efficiency spectrographs on large telescopes makes it possible to obtain spectra for large samples of H II regions, for galaxies which span the full range of physical properties and environments. At Arizona we have begun a broad program aimed at delineating the systematic behavior of H II region abundances and abundance distributions over the full range of spiral and irregular galaxies. Other goals of the program are to test for systematic changes in the stellar content, extinction, and ionization structure of the H II regions with metallicity and galaxy type, to test whether galaxy environment can affect chemical evolution, and to evaluate and refine the diagnostic methods used to interpret the nebular spectra. In this paper we present a progress report on the abundance studies, in particular a survey of early-type spirals (Oey & Kennicutt 1993; hereafter denoted OK) and a broader study of mean abundances and abundance gradients in spiral galaxy disks (Zaritsky, Kennicutt, & Huchra 1993, hereafter denoted ZKH). We also call the reader's attention to a recent parallel study by Vila-Costas & Edmunds (1992; henceforth denoted VE), which presents a detailed analysis of the abundance properties of disks, based on a compilation of data in the literature.

2. OBSERVATIONS

The foundation of our survey is spectrophotometry for 67 H II regions in a sample of 15 Sa–Sb galaxies (OK), and spectra for 156 additional H II regions in 14 galaxies of type Sb–Sd (ZKH). The goal of the OK survey was to extend the available abundance measurements to the earliest type galaxies possible. H II regions become progressively fainter in early-type galaxies (e.g., Kennicutt et al. 1989), and most of the objects in the OK sample have Hβ fluxes of order $10^{-16} - 10^{-14}$ ergs cm^{-2} s^{-1}, which is $\sim$10–10000 times fainter than the brightest H II regions in M33 or M101. In the OK survey spectra were obtained for about 100 candidate H II regions, and 67 were of sufficient quality to derive abundance estimates.

The goal of the ZKH survey was to obtain high quality spectra for 10–15 H II regions per galaxy, over the maximum radial extent available, so that the form of the abundance gradient could be well determined. Galaxies were selected from the target list for the HST Extragalactic Distance Scale Key Project because a primary motivation for the program was to calibrate the abundances of the HST target fields. This sample was augmented with data from the literature (including OK) for H II regions in 26 other spirals which had reliable spectroscopy for at least 5 H II regions. The entire ZKH sample contains 39 galaxies with 575 observed H II regions.

Most of our spectra were obtained with the Red Channel CCD Spectrograph on the MMT, using a grating that provided coverage of the 3650–5100 Å region at 9 Å resolution. A 2" × 180" slit was used, which was often rotated to enable observations of two or more H II regions at a time. Spectra covering the 3600–9500 Å range were obtained for 42 H II regions in the ZKH sample, using the Boller & Chivens Spectrograph on the Steward Observatory 2.3 m telescope. An echellette grating provided a spectral resolution of 2.5–4.8 Å resolution with a 4.5" × 16" aperture. H II regions were selected from the atlas of Hodge & Kennicutt (1983) or from Hα images obtained at the 2.3 m telescope. Accurate offsets were computed and used for the faintest regions.

The number of spectral lines that can be analyzed is limited by the faintness of most of the H II regions in our sample. Integration times of 10 to 90 min provided sufficient S/N in the critical diagnostic lines of Hβ, Hγ,

[OII]$\lambda\lambda$3726,3729, and [OIII]$\lambda\lambda$4959,5007 for the MMT data, and additionally Hα, [NII]λ6583, [SII]$\lambda\lambda$6717,6731, and [SIII]λ9069 for the 2.3 m data. Further observations in the red are being obtained for a subset of the H II regions in this study, but the results presented here are based entirely on the blue spectra. Reddening was determined using the Balmer decrement and an absorption W_λ = 2 Å in the underlying stellar continuum. Oxygen abundances were estimated using the R_{23} parameter of Pagel et al. (1979), where $R_{23} \equiv$ ([OII] + [OIII])/Hβ. In the excitation regime of interest here, the forbidden line strengths *decrease* with increasing metallicity. Although the forbidden lines are very weak in many of the H II regions studied, implying high abundances, they were detected in every H II region studied. This excludes the presence of any extreme metal-rich ($Z \geq 4Z_\odot$) objects in our sample. Details of the actual R_{23} calibrations, which differ slightly between the two papers, are given in OK and ZKH.

3. RESULTS

3.1. Early-Type Spirals (OK)

The H II regions in early-type disks show systematically higher abundances than those in late-type galaxies. This is illustrated in Figure 1, which compares the O/H abundances of H II regions in the OK sample (Sa–Sb) with a comparison sample (types Sc and later) drawn from McCall, Rybski, & Shields (1985). Although there is considerable dispersion and overlap in abundances between the samples, the mean abundance of the OK sample is 12 + (O/H) = 8.97. The error in this result is dominated entirely by the uncertainty in the the R_{23} calibration at high abundance, which may be as large as ±0.3 dex (see discussion below). However differential comparisons of the different H II region samples should be less affected by this uncertainty, providing that a consistent R_{23} calibration is employed. The mean abundance of the OK H II regions is considerably above the solar value ($\simeq$8.9) and 1.5 times larger than the mean of the McCall et al. sample. While it is tempting to associate the higher abundances directly with morphological type, differences in other parameters such as galaxy luminosity may also be important. We discuss this point further in the next section.

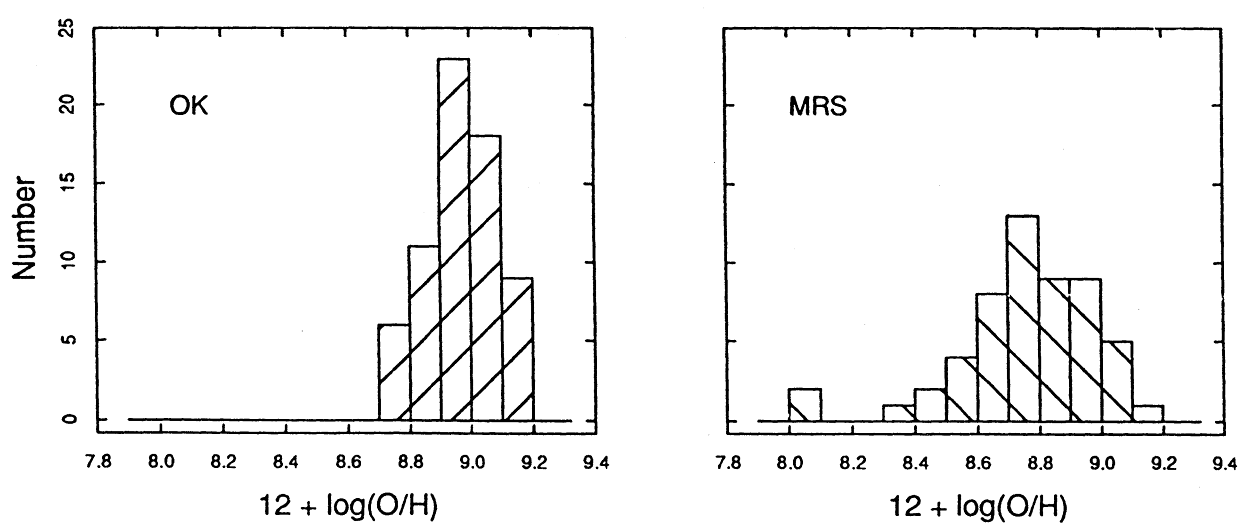

Fig. 1. — Comparison of abundances for Sa–Sb galaxies (left) vs. types Sc and later (right), from OK.

Figure 2 compares the Balmer-derived visual extinctions for the OK sample vs. a late-type galaxy sample compiled by Kennicutt, Keel, & Blaha (1989, KKB). Despite the higher abundances in the early-type disks, the extinction is slightly *lower* in the early-type galaxies. This paradox is easily explained when one recalls that the H II regions in Sa–Sb galaxies are considerably smaller than their counterparts in late-type spirals, and hence the total column density of gas and dust along the line of sight to (and through) these objects is probably lower. The absence of abnormally high extinction indicates that the low luminosities of the H II regions in early-type disks is not caused by dust; the low Hα luminosities must reflect an intrinsic change in the ionizing luminosities of the OB associations and star clusters with Hubble type.

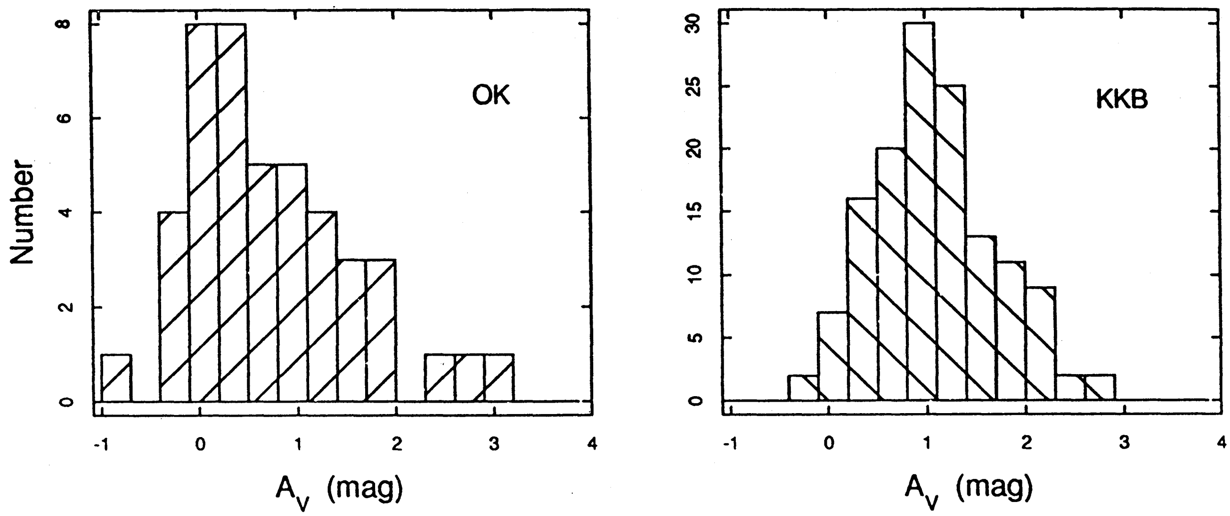

Fig. 2. — Comparison of visual extinctions in Sa–Sb galaxies (left) with late-type galaxies (right), from OK.

The most metal-rich H II regions in the OK sample are roughly twice solar (cf. Figure 1), similar to the most metal-rich regions observed in certain late-type galaxies such as M51 or M83. How reliable are these abundances? Unfortunately there are no solid observational calibrations of the R_{23} index for these low-excitation H II regions, and so the inferred abundances are highly model dependent. This dependence was investigated quantitatively by OK, who computed photoionization models for metal-rich H II regions over a wide range of physical conditions, using a program kindly provided by G. Shields. OK found that for abundances above solar the nebular temperature (and hence its excitation) is very sensitive to the gas density, exclusive of any effects due to varying abundance, ionizing spectrum, or ionization parameter. This sensitivity is due to competition between collisional and radiative de-excitation of the fine-structure cooling lines (particularly those of O^{++}), which dominate the nebular cooling at these metallicities. A similar density dependence at high metallicity can be seen in the H II region models by Stasińska (1990). In a similar vein Henry (1993) has shown that variations in grain depletion of refractory species can substantially alter the excitation vs. abundance calibration at high metallicity. Based on these results OK concluded that the abundances of the metal-rich H II regions are uncertain by roughly a factor of two, but that it is highly unlikely that O/H in the most metal-rich H II regions is much lower than twice solar. The abundances shown in Fig. 1 are based on a conservative calibration, which if anything probably underestimates the actual values at the metal-rich extreme.

3.2. General Abundance Patterns in Disk Galaxies (ZKH, VE)

Figure 3 presents the abundance distributions for the 39 spiral galaxies in the ZKH sample. This includes 14 galaxies observed by ZKH and 6 galaxies from OK (NGC 1068, 3351, 4258, 4736, 6384, 7331), with the remainder of the data coming from the literature. Even a casual inspection of Fig. 3 reveals a large range in both mean disk abundances and the strength of the abundance gradient. Much of the analysis in ZKH and VE is devoted to exploring the systematic behavior of these variations.

The mean disk abundance, whether defined at a fixed physical radius (kpc) or in terms of a fixed fractional isophotal radius (ρ_0) or scale length, is strongly correlated with the global physical properties of the parent galaxy. This is illustrated in Figure 4, which shows the dependence of the mean abundance at 0.4 ρ_0 on absolute magnitude, circular velocity, and the de Vaucouleurs T-type of the parent galaxy. Because luminosity and rotation velocity are strongly correlated with each other (and on average with type) it is not evident from Fig. 4 whether the correlations represent a physical dependence on one or more parameters. Simple chemical evolution theory lead us to expect a correlation between gas-phase abundance and galaxy type, because gas content (and hence mean disk gas fraction) is known to change systematically with Hubble type (e.g., Young 1990) However mean abundance and gas fraction are only weakly correlated (not shown), which suggests that other parameters influence the global chemical evolution.

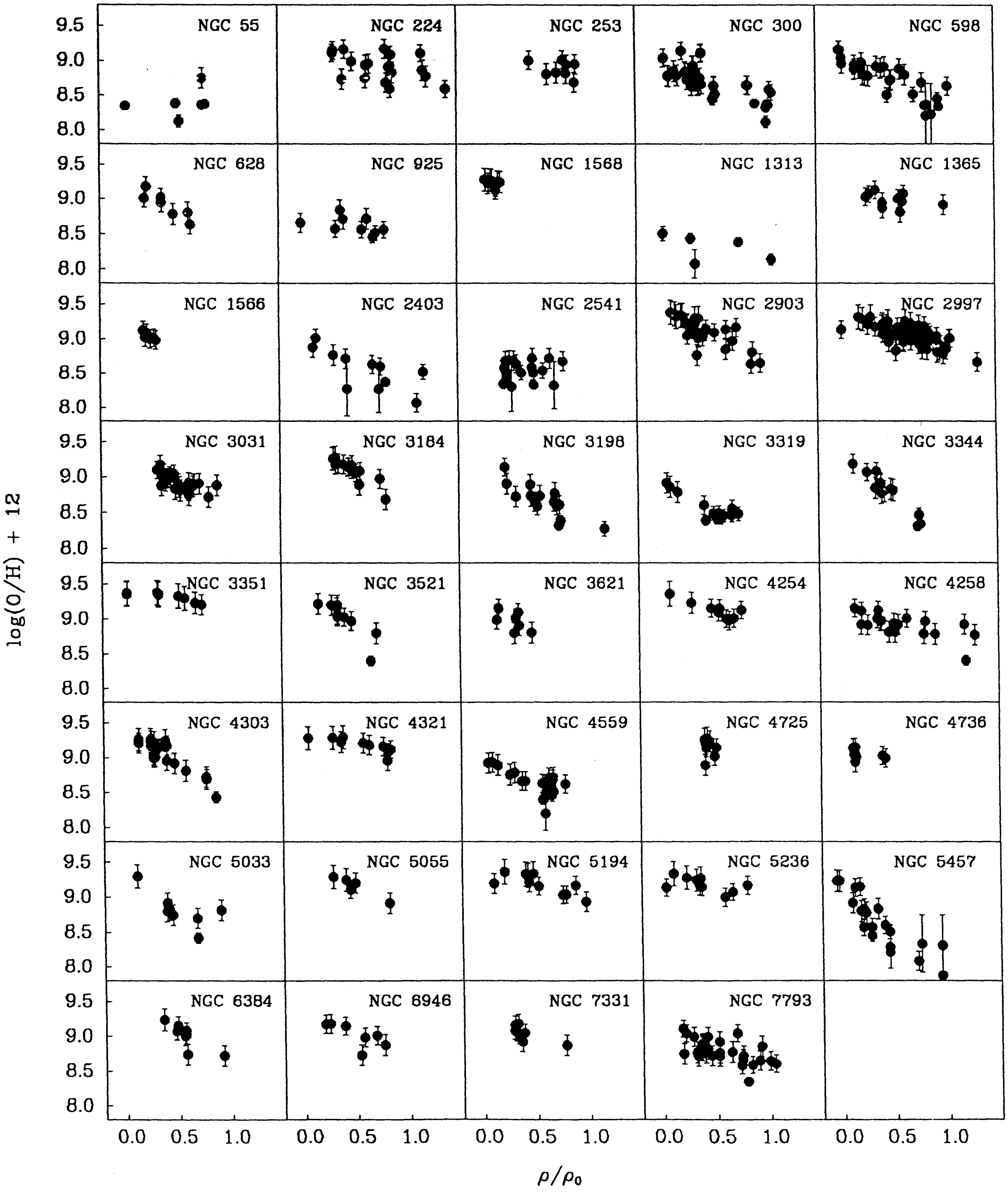

Fig. 3. — Abundance distributions of 39 spirals from ZKH.

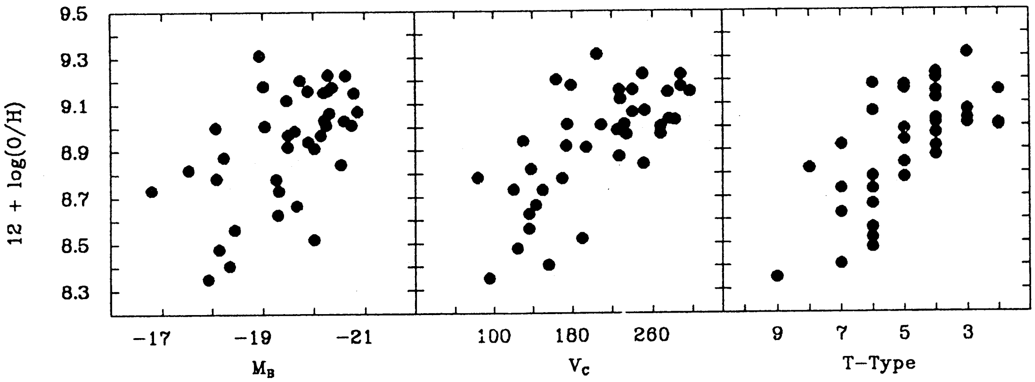

Fig. 4. — Disk abundance vs. absolute magnitude, rotation velocity, and galaxy type, from ZKH.

The loose abundance-luminosity correlation shown in Fig. 4 becomes even more interesting when one adds Magellanic irregular galaxies to the comparison, as presented in Figure 5. The data for irregulars was taken from Skillman, Kennicutt, & Hodge (1989). The two correlations map onto a single abundance–luminosity relation, which also closely parallels the abundance–luminosity relation for elliptical and dwarf spheroidal galaxies shown as a dashed line in Figure 5 (Brodie & Huchra 1991, Bender, Burstein, and Faber 1993, ZKH). One hypothesis is that the latter relationship arises from mass-dependent variations in galactic mass loss (e.g., Franx & Illingworth 1990), and possibly a similar dependence on escape velocity drives the abundances of the irregulars and spirals. However the presence of other factors (e.g., gas fraction, IMF) complicates the interpretation of the relation for gas-rich systems. Various scenarios are discussed in ZKH.

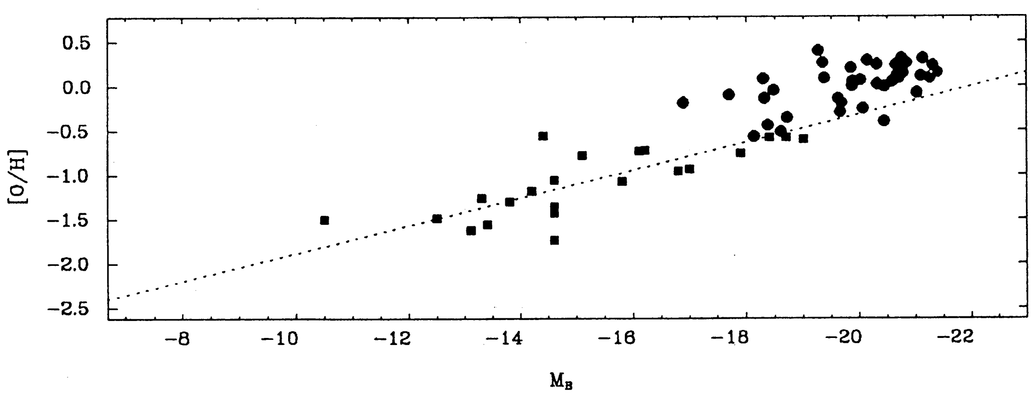

Fig. 5. — Abundance–luminosity relation for irregular (squares) and spiral galaxies (points), from ZKH.

The abundance gradients in the ZKH and OK samples show a similar range in magnitude. We present in Figure 6 the type dependence of the abundance gradients in the VE (top) and ZKH (bottom) samples. Gradients are defined both in terms of an absolute scale length (left) and as scaled to the isophotal radius (right). Barred galaxies (SB) are denoted by open triangles, normal (SA) spirals by solid points, and mixed types (SAB) by crosses. In some instances there is evidence of a weak type dependence (also see OK), but the trends are much weaker than those seen in the mean disk abundances (cf. Fig. 4). We find that the magnitude of the gradient and the interpretation of any type dependence depends strongly on the manner in which the gradient is defined. For example, gradients scaled to the effective radius (r_e) of the galaxy show a strong type dependence, which is due almost entirely to the influence of bulge light on the measurement of r_e, not on the actual abundance properties of the disk (OK). Similarly part of the difference in abundance trends with physical and isophotal radius (left vs. right in Fig. 6) is attributable to the fact that, on average, late-type spirals are smaller than early-type galaxies, and hence will exhibit steeper gradients from that effect alone. The most interesting resul n Fig. 6 is the marked dependence of the gradient on bar type. This difference could be caused by radial gas lows in the barred systems (e.g., Martin 1992) or by differences in the induced spiral patterns in the galaxies Edmunds & Roy 1993).

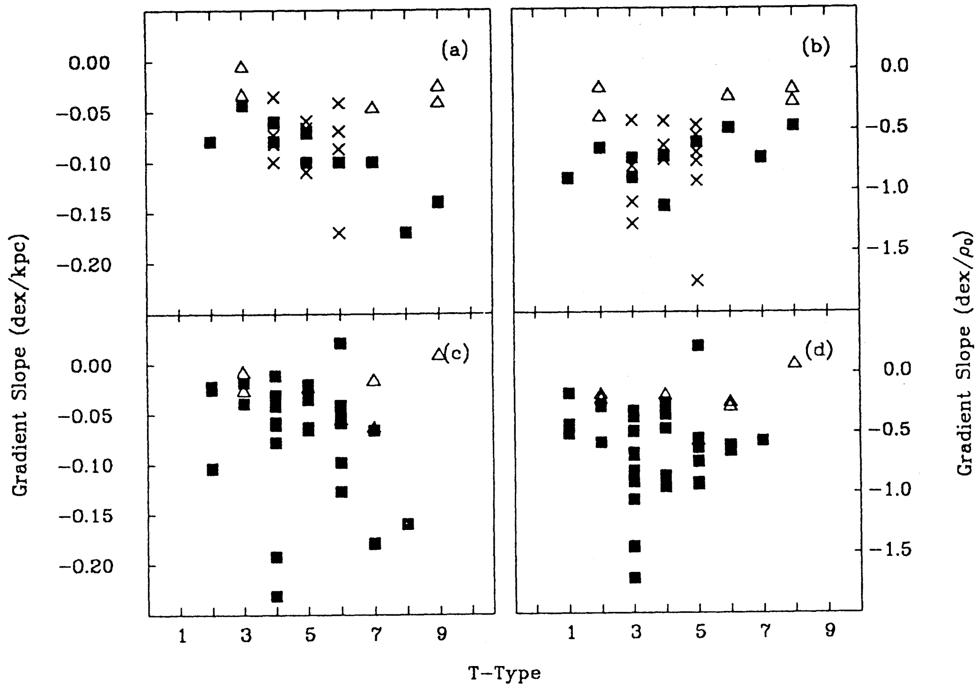

Fig. 6. — Abundance gradient vs. galaxy type and bar type for VE (top) and ZKH (bottom) samples.

4. DISCUSSION

The general picture revealed by these studies varies from that expected from traditional closed-box chemical volution models, in which abundances are primarily determined by local conditions such as the local gas raction. These new data suggest that the abundance properties of disks may be heavily influenced by large cale gas transport processes — outflows, infall, radial transport by bars and/or spiral structure — which are isually ignored in simple chemical evolution models.

The simplest conclusion that may be drawn from these data is that the products of galaxy formation and volution, regardless of the complexity of the process, are surprisingly regular. The most striking example s the uniformity in the abundance–luminosity relations of different galaxy types (Fig. 5). Although the nechanism that produces this uniformity is not understood, there are other well established lines of evidence hat support this contention, such as the small scatter in the Tully-Fisher and Faber-Jackson relationships and he fundamental plane of elliptical galaxies. The data discussed here may hint at basic similarities between the actors driving the chemical evolution of elliptical and spiral galaxies.

The primary limitation of the analysis to date, and a major weakness in the conjectures offered above, is that t is based entirely on the first two moments of the overall abundance distributions. By limiting our attention o the mean abundances and abundance gradients we are neglecting much of the spatially resolved information on local abundances and their dependence on the local conditions in the disk (gas fraction, disk surface density, ocal escape velocity, etc.). Unfortunately attempts to extend the interpretation of local abundance variations (e.g., Edmunds & Pagel 1984, VE) are severely hampered by the lack of a homogeneous data set on the HI and H_2 gas distributions, rotation curves, and stellar distributions. We are compiling such a database, and we hope that this may lead to a deeper physical understanding of the results presented here.

Acknowledgements: RCK and MSO acknowledges financial support from NSF through grant AST-9019150. DZ acknowledges support from NASA through grant HF-1027.01-91A from STScI, which is operated by AURA, Inc., under NASA contract NAS5-26555.

REFERENCES

Bender, R., Burstein, D., & Faber, S. M. 1993, in press
Brodie, J., & Huchra, J. 1991, ApJ, 379, 157
Dinerstein, H. 1990, in *The Interstellar Medium in Galaxies*, H. Thronson & J.M. Shull, eds., Kluwer, p257
Edmunds, M., & Pagel, B. 1984, MNRAS, 211, 507
Edmunds, M., & Roy, J.R. 1993, MNRAS, 261, L17
Franx, M., & Illingworth, G. 1990, ApJ, 359, L41
Garnett, D., & Shields, G. 1987, ApJ, 317, 82
Henry, R. 1993, MNRAS, 261, 306
Hodge, P., & Kennicutt, R. 1983, AJ, 88, 296
Kennicutt, R. 1988, ApJ, 334, 144
Kennicutt, R., Edgar, B., & Hodge, P. 1989, ApJ, 337, 761
Kennicutt, R., Keel, W., & Blaha, C. 1989, AJ, 97, 1022 (KKB)
Martin, P. 1992, Ph.D. thesis, Univ. Laval
McCall, M., Rybski, P., & Shields, G. 1985, ApJS, 57, 1
Oey, M.S., & Kennicutt, R. 1993, ApJ, 411, 137 (OK)
Pagel, B., & Edmunds M. 1981, ARAA, 19, 77
Pagel, B., Edmunds, M., Blackwell, D., Chun, M., & Smith, G. 1979, MNRAS, 189, 95
Searle, L. 1971, ApJ, 168, 327
Shields, G. 1974, ApJ, 193, 335
Shields, G. 1990, NRAA, 28, 525
Skillman, E., Kennicutt, R., & Hodge, P. 1989, ApJ, 347, 875
Stasińska, G. 1990, A&AS, 83, 501
Vila-Costas, M., & Edmunds, M. 1992, MNRAS, 259, 121 (VE)
Young, J. 1990, in *The Interstellar Medium in Galaxies*, H. Thronson & J.M. Shull, eds., Kluwer, p67
Zaritsky, D., Kennicutt, R., & Huchra, J. 1993, in preparation (ZKH)

John P. Huchra: Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, U.S.A.
Robert C. Kennicutt and M.S. Oey: University of Arizona, Steward Observatory, Tucson, AZ 85721, U.S.A.
Dennis F. Zaritsky: Carnegie Observatories, 813 Santa Barbara Street, Pasadena, CA 91101-1292, U.S.A.