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HIGH CHEMICAL ABUNDANCES IN VIRGO SPIRAL GALAXIES?[1]

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ABSTRACT

We present evidence that spiral galaxies in the Virgo Cluster have systematically higher interstellar abundances than comparable field galaxies. This conclusion is based on spectra of H II regions in five Virgo spirals of type Sc. A possible explanation is that abundances in the field spirals are strongly affected by infall of metal-poor gas or by radial inflow of gas from the outer H I disk. These processes are inhibited in the cluster environment, and the Virgo spirals may have evolved more nearly in the manner of the closed box "simple model" of chemical evolution.

Subject headings: galaxies: abundances — galaxies: clustering — galaxies: evolution — galaxies: interstellar matter — nebulae: H II regions

1. INTRODUCTION

Studies of spiral galaxies have shown that radial gradients in $O/H \equiv N(O)/N(H)$ occur across the disks of all spiral galaxies (Pagel & Edmunds 1981). Chemical abundance measurements of spiral galaxies made to date have mostly involved isolated galaxies or galaxies in small groups. Many of these studies have been aimed at looking for empirical relationships between morphological type, luminosity, and gas fraction (e.g., Garnett & Shields 1987, and references therein). Relatively little systematic effort has been devoted to using abundance gradients to examine critically the success of alternative models of galactic evolution. In this paper we will focus on the question of environmental influences by conducting a survey of abundances in H II regions in spirals in the Virgo Cluster of galaxies. These are compared with abundances in comparable field galaxies with the aim of identifying systematic effects of the cluster environment.

The importance of environmental effects on spiral galaxies in rich clusters is well established (e.g., Giovanelli & Haynes 1985; Sarazin 1988; and references therein). Ram pressure stripping is apparently responsible for the truncation of the H I disks of spirals in the Virgo Cluster core (Warmels 1986), with resultant effects on star formation and spiral arm morphology in the outer disks (see photographs in Sandage 1961). Obvious environmental effects relevant to the chemical evolution of cluster spirals include the stripping of gas from the outer disk, possible ablation from the inner disk, and the stripping of a hot corona above the disk (cf. Savage 1987). Of particular interest to the comparison of cluster and field spirals is the possibility of continuing accretion of primordial gas onto the disks of field spirals (cf. Gunn 1983). The chemical implications of infall have been discussed theoretically (e.g., Tinsley & Larson 1978; Tinsley 1981), and they include a decrease in O/H at fixed gas mass fraction ($\mu \equiv N_{\rm H\,I}/M_T$), and a reduction in O/H for a given value of N/O (Serrano & Peimbert 1983). Since cluster spirals will be speeding through a hot intracluster medium, such infall seems unlikely. Recent studies also emphasize the importance of radial gas inflow from the outer H I disk (Lacey & Fall 1985; Clarke 1989), which will clearly be affected by the observed stripping of cluster spirals.

In the next section we present new observations of H II regions in Virgo Cluster spiral galaxies. We then bring together data for both Virgo Cluster spirals and comparable field galaxies, and, analyzing these data in § 3, we find evidence that the Virgo spirals are metal-rich relative to the field galaxies. In § 4 we discuss this result in view of current models of the chemical evolution of galaxies.

2. OBSERVATIONS

In order to compare the abundances in Virgo spirals with field spirals, we have drawn primarily from observations in the literature, and we have added new observations. Edmunds & Pagel (1984) have shown that early-type spirals (Sc and earlier) have a larger dispersion in abundance than late-type spirals (Scd and later) when compared at a given effective radius or mass surface density (possibly reflecting the importance of the contribution of the bulge). We concluded that late-type spirals would provide the best sample for the initial comparison attempted here and put these galaxies at highest priority in our observing programs. However, given the difficulties encountered in observing, we still lack sufficient observations of truly late-type spirals. Our sample of galaxies is listed in Table 1. This sample is not to be considered as definitive or final. As we discuss later, more observations of both field and Virgo Cluster galaxies are needed if firm conclusions are to be reached.

For the field galaxy comparison sample, we have collected all field Sc galaxies (catalogued as Sc in the RSA and $4 \leq T \leq 7$ in the RC2) with published spectrophotometry of [O II] and [O III] in at least six H II regions. We have excluded both barred and interacting systems. Since the average abun-

[1] Observations reported here were obtained, in part, with the Multiple Mirror Telescope, a facility operated jointly by the University of Arizona and the Smithsonian Institute

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TABLE 1

A. COMPARISON FIELD GALAXIES

Name	Regions	Type[a]	T^b	L ($10^9 L_\odot$)	i (°)	log $(D_{\rm H\,I}/D_{\rm O})_0$
NGC 300	6	Sc	7	3	45	0.09
NGC 598 (M33)	11	Sc(s)	6	4	54	−0.16
NGC 628 (M74)	7	Sc(s)	5	13	4	0.07
NGC 1566	7	Sc(s)	4	8	30	...
NGC 2403	6	Sc(s)	6	5	60	0.03
NGC 2903	7	Sc(s)	4	20	60	−0.12
NGC 2997	49	Sc(s)	5	14	38	...
NGC 5457 (M101)	8	Sc(s)	6	17	18	−0.13
NGC 6946	7	Sc(s)	6	21	30	0.05

B. H I DEFICIENT VIRGO CLUSTER SPIRAL GALAXIES

Name	$R_{\rm M87}$ (°)	Type[a]	T^b	L ($10^9 L_\odot$)	i (°)	log $(D_{\rm H\,I}/D_{\rm O})_0$
NGC 4254 (M99)	3.7	Sc(s)	5	20	28	−0.12
NGC 4303 (M61)	8.2	Sc(s)	4	21	25	−0.33
NGC 4321 (M100)	4.0	Sc(s)	4	23	30	−0.22
NGC 4571	2.4	Sc(s)	7	5	28	−0.24
NGC 4689	4.6	Sc(s)	4	6	30	−0.35

[a] Sandage & Tammann 1981 (RSA).
[b] de Vaucouleurs, de Vaucouleurs, & Corwin 1976 (RC2).

dance in a galaxy is a strong function of total galaxy luminosity (Garnett & Shields 1987), it is important to note that there is a good overlap for the two samples in galaxy luminosity. The Virgo sample is weighted more heavily toward earlier T types; possible effects of this will be discussed in § 3.

In this paper we will follow the definitions and nomenclature of Warmels (1986). We take H I deficiency as an indicator that a galaxy is suffering environmental modification, and we follow Warmels in adopting the H I radius relative to optical radius, compared to the average for field galaxies of comparable type, as an indication of the degree of stripping. We introduce the following shorthand:

$$(D_{\rm H\,I}/D_{\rm O})_0 \equiv \frac{D_{\rm H\,I}/D_{\rm O}}{\langle D_{\rm H\,I}/D_{\rm O}\rangle_{T,F}} \quad (1)$$

to denote the normalized H I diameter. Warmels found an average of 1.79 ± 0.56 for $D_{\rm H\,I}/D_{\rm O}$ for the field galaxies for types Sc and later.

For the Virgo Cluster, there are two Sc galaxies with published spectrophotometry, NGC 4254 and NGC 4321 (McCall, Rybski, & Shields 1985). We present here new observations of H II regions in NGC 4254, NGC 4303, and NGC 4321 obtained with the Multiple Mirror Telescope (MMT) in 1990 April, and an MMT observation of a single H II region in NGC 4571 obtained in 1989 April. We also add a single H II region in NGC 4689, from an observation made with the 2.7 m telescope at the McDonald Observatory in 1989 March.

For the MMT observations we used the 1024-element Blue Channel intensified Reticon detector. Typically we used a 2″ × 3″ aperture yielding roughly 10 Å spectral resolution with a wavelength coverage of 3600–7200 Å. Typical integration times were 10 minutes per H II region. The 1990 April observations were made through clouds, so only relative line strengths are reported here.

For the McDonald Observatory observations we used the large Cassegrain spectrograph (LCS). The LCS uses a Texas Instruments $(800)^2$ pixel CCD as a detector, and was configured with a 2″ wide long-slit resulting in a resolution of 6 Å (FWHM) and a wavelength coverage of 3650–5100 Å. Because of poor weather, only a single 30 minute integration of one H II region in NGC 4689 was obtained.

Standard stars from Filippenko & Greenstein (1984) and Oke (1974) were observed during the MMT and McDonald observing runs, respectively. The spectra were then calibrated for relative spectral response, using the standard star observations. The Balmer lines were corrected for an assumed 2 Å EW underlying absorption, and then a reddening was determined from the relative Balmer line strengths assuming the values for an electron temperature of 10,000 K and an electron density of 100 as listed in Brocklehurst (1971). All line strengths were then corrected for reddening using the galactic reddening law compiled by Seaton (1979) as parameterized by Howard (1983). The resultant relative line strengths are listed in Table 2, where the H II regions are identified by the numbers assigned by Hodge & Kennicutt (1983).

Oxygen abundance values were derived by using the empirical calibration of the strong line parameter $R_{23} \equiv ([{\rm O\,II}] + [{\rm O\,III}])/{\rm H}\beta \equiv I(\lambda3727 + \lambda4959 + \lambda5007)/I(\lambda4861)$ (Edmunds & Pagel 1984). In the next section, where we have drawn values from the literature, we have used the published line strengths and treated all of the data in a uniform manner.

3. COMPARING VIRGO AND FIELD SPIRAL ABUNDANCES

In order to compare abundances of Virgo and field spiral galaxies, proper criteria must be chosen. McCall (1982) and Edmunds & Pagel (1984) have shown that oxygen abundances in extragalactic H II regions are closely correlated with normalized galactocentric radius and local mass surface density. In simple evolution schemes, the abundance in a galaxy can be related to the gas mass fraction (see § 4). For comparison of abundances as a function of these parameters, we have compiled the individual properties of H II regions in field and Virgo Cluster spiral galaxies. For those galaxies which have been observed in both H I and CO, and for which the inclination is sufficiently large to yield a reliable rotation curve (≥15°), the data for each of the individual H II regions are listed in Table 3.

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TABLE 2A

SPECTRA AND DERIVED PROPERTIES

λ Identification	NGC 4254 +080−016 HK 20	NGC 4254 +106+019 HK 1	NGC 4254 −117−002 HK 208	NGC 4303 +021−007 HK 95	NGC 4303 −001+045 HK 135	NGC 4303 −013−044 HK 155	NGC 4303 +046+006 HK 49	NGC 4303 −014· +048 HK 157	NGC 4303 +032−040 HK 76	NGC 4303 +022+067 HK 91
3727 [O II]	1.96 ± 0.31	2.06 ± 0.32	1.79 ± 0.28	0.70 ± 0.35	0.93 ± 0.15	1.01 ± 0.16	0.82 ± 0.13	1.02 ± 0.16	1.78 ± 0.29	0.99 ± 0.16
4101 Hδ	0.23 ± 0.07	...	0.27 ± 0.07	...	0.28 ± 0.06	0.27 ± 0.04	...	0.27 ± 0.04	0.28 ± 0.03	...
4340 Hγ	0.52 ± 0.05	0.53 ± 0.05	0.49 ± 0.05	0.64 ± 0.25	0.60 ± 0.06	0.50 ± 0.05	0.36 ± 0.08	0.60 ± 0.06	0.46 ± 0.05	0.47 ± 0.06
4861 Hβ	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10
4959 [O III]	0.16 ± 0.03	0.25 ± 0.04	0.10 ± 0.03	...	...	0.07 ± 0.02	...	0.06 ± 0.03	0.16 ± 0.02	...
5007 [O III]	0.37 ± 0.04	0.74 ± 0.07	0.32 ± 0.03	0.22 ± 0.11	0.07 ± 0.03	1.14 ± 0.02	0.09 ± 0.05	0.17 ± 0.03	0.50 ± 0.05	0.08 ± 0.04
6563 Hα	2.97 ± 0.30	2.97 ± 0.30	2.93 ± 0.29	2.87 ± 0.29	2.86 ± 0.29	2.93 ± 0.29	2.72 ± 0.27	3.09 ± 0.31	2.95 ± 0.30	2.88 ± 0.29
6584 [N II]	0.88 ± 0.09	0.71 ± 0.07	0.78 ± 0.08	1.14 ± 0.23	0.95 ± 0.10	1.01 ± 0.10	0.91 ± 0.09	1.04 ± 0.10	1.20 ± 0.12	0.91 ± 0.09
6717 [S II]	0.25 ± 0.04	0.31 ± 0.04	0.36 ± 0.05	...	0.22 ± 0.04	0.26 ± 0.03	0.25 ± 0.05	0.22 ± 0.04	0.22 ± 0.03	0.32 ± 0.04
6731 [S II]	0.24 ± 0.04	0.23 ± 0.04	0.31 ± 0.05	...	0.15 ± 0.04	0.22 ± 0.03	0.25 ± 0.05	0.20 ± 0.04	0.15 ± 0.03	0.19 ± 0.04
c(Hβ)	0.6 ± 0.2	0.4 ± 0.2	0.4 ± 0.2	0.3 ± 0.2	0.4 ± 0.2	0.2 ± 0.2	0.4 ± 0.2	0.7 ± 0.2	0.3 ± 0.2	0.2 ± 0.2
EW(Hβ) Å	55	18	32	...	33	36	19	160	64	21
(O II + O III)/Hβ	2.45 ± 0.31	3.05 ± 0.03	2.21 ± 0.28	0.99 ± 0.38	1.02 ± 0.16	1.22 ± 0.17	2.94 ± 0.15	1.25 ± 0.17	2.44 ± 0.29	1.10 ± 0.17
$(O/H)_{emp}$ ($\times 10^4$)	11.5	8.3	13.4	22.0	21.7	19.8	22.3	19.6	11.6	20.9

TABLE 2B

SPECTRA AND DERIVED PROPERTIES

λ Identification	NGC 4303 +005−073 HK 124	NGC 4303 −049−094 HK 205	NGC 4303 −110+075 HK 278	NGC 4321 −001−066 HK 160	NGC 4321 +013+102 HK 143	NGC 4321 −032+147 HK 201	NGC 4321 −131−027 HK 284	NGC 4321 +029+146 HK 128	NGC 4571 −010+050 HK 22	NGC 4689 −033−011 HK 62
3727 [O II]	1.25 ± 0.20	2.82 ± 0.45	2.69 ± 0.43	1.06 ± 0.21	1.03 ± 0.17	2.60 ± 0.42	1.87 ± 0.30	1.87 ± 0.30	0.69 ± 0.11	1.81 ± 0.45
3868 [Ne III]	...	0.16 ± 0.03	...	...	...	...	0.16 ± 0.03	...	...	...
4101 Hδ	...	0.28 ± 0.03	0.28 ± 0.03	...	0.32 ± 0.05	...	0.27 ± 0.03	0.25 ± 0.05	...	...
4340 Hγ	0.50 ± 0.06	0.50 ± 0.05	0.51 ± 0.05	0.43 ± 0.08	0.57 ± 0.06	0.77 ± 0.10	0.50 ± 0.05	0.56 ± 0.06	0.48 ± 0.05	0.53 ± 0.10
4861 Hβ	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10
4959 [O III]	0.17 ± 0.04	0.47 ± 0.05	0.80 ± 0.08	...	...	0.28 ± 0.12	0.14 ± 0.03	0.07 ± 0.03	...	...
5007 [O III]	0.28 ± 0.04	1.46 ± 0.15	2.29 ± 0.23	0.16 ± 0.06	0.27 ± 0.06	0.57 ± 0.12	0.48 ± 0.05	0.32 ± 0.03	0.15 ± 0.15	0.16 ± 0.10
6563 Hα	3.07 ± 0.31	2.82 ± 0.28	3.12 ± 0.31	2.74 ± 0.27	3.02 ± 0.31	3.02 ± 0.30	3.02 ± 0.30	2.92 ± 0.29	2.89 ± 0.29	...
6584 [N II]	1.40 ± 0.14	0.62 ± 0.06	0.69 ± 0.07	0.85 ± 0.08	0.74 ± 0.07	0.90 ± 0.09	1.02 ± 0.10	0.89 ± 0.09	0.56 ± 0.06	...
6717 [S II]	0.45 ± 0.07	0.28 ± 0.04	0.18 ± 0.05	0.48 ± 0.08	0.26 ± 0.04	0.47 ± 0.09	0.27 ± 0.04	0.34 ± 0.04	0.26 ± 0.06	...
6731 [S II]	0.42 ± 0.07	0.16 ± 0.04	0.16 ± 0.05	0.48 ± 0.08	0.25 ± 0.04	0.31 ± 0.09	0.18 ± 0.04	0.13 ± 0.03	0.26 ± 0.06	...
c(Hβ)	0.4 ± 0.2	0.2 ± 0.2	0.0 ± 0.2	0.7 ± 0.2	0.4 ± 0.2	0.6 ± 0.2	0.3 ± 0.2	0.5 ± 0.2	0.4 ± 0.2	0.0 ± 0.2
EW(Hβ) Å	46	207	117	39	62	33	137	68	41	...
(O II + O III)/Hβ	1.70 ± 0.21	4.75 ± 0.48	5.78 ± 0.49	1.27 ± 0.22	1.39 ± 0.19	3.45 ± 0.45	2.49 ± 0.31	2.26 ± 0.31	0.89 ± 0.19	2.02 ± 0.47
$(O/H)_{emp}$ ($\times 10^4$)	16.8	4.3	3.2	19.4	18.6	6.9	11.2	13.0	22.7	15.3

NOTE.—Columns in order by galaxy (NGC), region, and HK number.

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TABLE 3

INDIVIDUAL H II REGION PARAMETERS

A. THE FIELD GALAXIES

Region Name (1)	log (R_{23}) (2)	12 + log (O/H) (3)	ρ/ρ_E (4)	σ_D (5)	$\sigma_{H I}$ (6)	σ_{H_2} (7)	ln μ (8)	Source (9)
				NGC 598				
CC 93	0.28	9.20	0.07	501	6.7	7.7	−3.3	1, 2, 3
+034−037	0.44	8.98	0.11	468	6.5	7.7	−3.2	1, 3
IC 142	0.52	8.87	0.55	224	7.3	1.5	−3.0	1, 2, 3
−185+163	0.60	8.74	0.56	219	7.6	1.5	−2.9	1, 3
MA 2	0.61	8.73	0.69	178	8.9	1.5	−2.6	1, 2, 3
NGC 595	0.62	8.72	0.97	110	7.8	0.7	−2.3	1, 2, 3
−499−054	0.58	8.77	1.09	89	6.7	0.7	−2.3	1, 3
NGC 604	0.70	8.60	1.39	55	9.4	0.0	−1.6	1, 2, 3
IC 131	0.86	8.36	1.69	33	8.8	0.0	−1.3	1, 2, 3
NGC 588	0.89	8.31	2.22	14	7.9	0.0	−0.8	1, 2, 3
−606−1708	0.80	8.45	2.50	9	4.2	0.0	−0.9	1, 2, 3
				NGC 2403				
+010+032	0.63	8.70	0.39	371	7.2	3.8	−3.2	1, 3
−045+055	0.58	8.78	0.45	339	7.2	3.5	−3.2	1, 3, 4
+063−049	0.48	8.92	0.49	316	7.3	3.1	−3.1	1, 3
+045+069	0.71	8.58	1.00	135	8.4	1.9	−2.3	1, 3
−096+035	0.79	8.46	1.06	123	8.4	1.5	−2.3	1, 3, 4
−186+045	0.69	8.61	1.48	60	8.1	0.0	−1.8	1, 3, 4
−133−146	0.85	8.37	2.36	14	5.8	0.0	−1.0	1, 3
+165+136	0.92	8.26	2.55	10	5.5	0.0	−0.5	1, 3
−494+137	0.86	8.36	3.66	1.5	3.7	0.0	−0.3	1, 3
				NGC 2903				
+024+047	−0.36	9.46	0.64	851	6.0	40	−2.7	1, 5
−003−070	0.13	9.28	1.41	234	6.0	25	−1.9	1, 5
−003+069	−0.14	9.39	1.55	186	5.6	22	−1.8	1, 5
−021+105	0.53	8.85	2.84	21	2.6	0.0	−1.9	1, 5
+039−078	0.52	8.87	2.85	21	2.6	0.0	−1.9	1, 5
+047−072	0.25	9.22	2.99	17	2.5	0.0	−1.8	1, 5
+174+197	0.78	8.48	3.91	4	2.9	0.0	−0.6	1, 5
				NGC 5457				
+223−127	0.86	8.62	1.37	214	7.7	4.6	−2.6	1, 6
+252−107	0.84	8.39	1.45	186	7.8	4.4	−2.5	1, 6
+098+272	0.67	8.65	1.47	182	7.8	4.2	−2.5	1, 6
−243+163	0.70	8.59	1.56	154	7.6	3.8	−2.4	1, 6
−376−063	0.66	8.66	1.98	78	6.5	3.1	−1.9	1, 6
+666+172	1.08	8.03	3.55	5.5	5.5	0.0	−0.5	1, 6
				NGC 6946				
−008+066	0.24	9.22	0.35	708	8.1	54.0	−2.2	1, 7
−034−080	0.22	9.23	0.43	631	8.6	41.5	−2.3	1, 7
+144−003	0.31	9.18	0.69	407	9.4	19.2	−2.4	1, 7
+182+103	0.74	8.54	0.96	257	8.7	10.8	−2.3	1, 7
−128+146	0.52	8.78	1.03	229	8.5	7.7	−2.4	1, 7
−245+055	0.48	8.92	1.23	162	7.1	7.4	−2.2	1, 7
−099−261	0.62	8.71	1.38	126	6.4	6.2	−2.1	1, 7

The entries in Table 3 are as follows. The first column identifies the region following the nomenclature of McCall et al. (1985). The second column lists values of R_{23}, which is converted to an oxygen abundance in column (3) following the calibration of Edmunds & Pagel (1984). Columns (4) and (5) give the galactocentric radius normalized to the effective radius (ρ/ρ_E) and disk surface mass density (σ_D) as calculated by McCall (1982). We had to derive appropriate values for ρ_E and σ_D for the three Virgo galaxies which are not listed in the compilation from McCall. For this we assumed a Virgo Cluster distance (12 Mpc) consistent with that of McCall (1982). For NGC 4571 we used the surface photometry and rotation curve from van der Hulst et al. (1987). For NGC 4303, we used the optical parameters from the RC2 and the rotation curve from Guhathakurta et al. (1988). For NGC 4689, we used a value of $\rho_E = 0.4\, D_O = 0\overset{'}{.}82$, and the rotation curve data from Guhathakurta et al. (1988).

Column (6) gives the average H I mass surface density at the appropriate radius for the H II region. Column (7) gives the estimated average H_2 mass surface density which has been

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TABLE 3—*Continued*

B. THE VIRGO CLUSTER GALAXIES

Region Name (1)	log (R_{23}) (2)	12 + log (O/H) (3)	ρ/ρ_E (4)	σ_D (5)	σ_{HI} (6)	σ_{H_2} (7)	ln μ (8)	Source (9)
				NGC 4254				
+013+006	−0.33	9.45	0.22	1047	7.8	57.0	−2.5	1, 8, 9
−005+042	0.09	9.30	0.74	437	7.5	25.2	−2.4	1, 8, 9
+055−042	0.30	9.19	1.22	195	7.5	14.2	−2.0	1, 8, 9
+080−016	0.39	9.06	1.36	154	7.9	13.7	−1.8	1, 8, 9, 10
−047−075	0.30	9.19	1.43	138	7.9	11.5	−1.8	1, 8, 9
+093+039	0.49	8.91	1.59	105	8.5	11.0	−1.6	1, 8, 9
+102+015	0.52	8.87	1.65	96	8.8	9.9	−1.5	1, 8, 9
+106+019	0.48	8.92	1.72	84	8.2	8.2	−1.5	1, 8, 9, 10
−117−002	0.34	9.13	1.90	62	7.8	7.1	−1.4	1, 8, 9, 10
				NGC 4303				
+021−007	0.00	9.34	0.36	584	4.5	50	−2.2	8, 9, 10, 11
−001+045	0.01	9.34	0.67	347	6.1	31	−2.0	8, 9, 10, 11
−013−044	0.09	9.30	0.68	341	6.1	31	−2.0	8, 9, 10, 11
+046+006	−0.03	9.35	0.76	299	6.6	27	−2.0	8, 9, 10, 11
−014+048	0.10	9.29	0.76	299	6.6	27	−2.0	8, 9, 10, 11
+032−040	0.39	9.06	0.80	279	6.7	25	−2.0	8, 9, 10, 11
+022+067	0.04	9.32	1.05	183	7.3	18	−1.8	8, 9, 10, 11
+005−073	0.23	9.22	1.09	172	7.3	17	−1.8	8, 9, 10, 11
−049−094	0.68	8.63	1.59	74	7.1	8.4	−1.5	8, 9, 10, 11
−110+075	0.76	8.50	2.14	29	5.7	4.5	−1.1	8, 9, 10, 11
				NGC 4321				
+008−004	−0.06	9.36	0.10	776	4.2	65.6	−2.2	1, 8, 9
−051+009	−0.08	9.37	0.60	331	4.3	22.4	−2.3	1, 8, 9
−001−066	0.10	9.29	0.69	286	4.2	17.1	−2.4	1, 8, 9, 10
+032−074	−0.11	9.38	0.81	234	4.2	13.3	−2.4	1, 8, 9
+013+102	0.14	9.27	1.09	146	4.8	8.0	−2.2	1, 8, 9, 10
−114+010	0.21	9.23	1.35	93	5.5	5.3	−2.0	1, 8, 9
−032+147	0.54	8.84	1.53	70	5.6	3.7	−1.9	1, 8, 9, 10
−131−027	0.40	9.05	1.54	69	5.6	3.7	−1.9	1, 8, 9, 10
+029+146	0.35	9.11	1.59	63	5.0	3.2	−1.9	1, 8, 9, 10
+034+145	0.27	9.20	1.64	58	4.3	2.7	−1.9	1, 8, 9
				NGC 4571				
−010+050	−0.05	9.36	1.53	107	3.0	3.0	−2.5	8, 9, 10, 12
				NGC 4889				
−031−013	0.31	9.19	0.77	447	2.0	11.7	−3.2	8, 9, 10, 11

REFERENCES.—(1) McCall 1982; (2) Vilchez et al. 1988; (3) Young 1987; (4) Fierro, Torres-Peimbert, & Peimbert 1986; (5) Jackson et al. 1989; (6) Solomon et al. 1983; (7) Tacconi & Young 1986; (8) Warmels 1986; (9) Kenney & Young 1988; (10) this paper; (11) Guhathakurta et al. 1988; (12) van der Hulst et al. 1987.

calculated from CO measurements using the conversion of Young & Scoville (1982); $N(H_2)/I_{CO} = 4 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$. Column (8) shows the average local gas mass fraction (μ) which is simply the sum of columns (6) and (7), multiplied by 1.4 to correct for helium, and then divided by column (5). Column (9) lists the sources for the data.

Four galaxies from the field sample have not been included in Table 3. For NGC 300, which lacks CO observations, we have taken H II region spectroscopy from Pagel et al. (1979) and Edmunds & Pagel (1984), and other galaxy properties from McCall (1982). For NGC 628, which has a very small inclination resulting in a very uncertain corrected rotation curve, we have taken all data from McCall (1982). NGC 1566 and NGC 2997 lack both CO and H I data. We have used the H II region spectroscopy of Hawley & Phillips (1980) for NGC 1566 and of Walsh & Roy (1989) for NGC 2997; other galaxy properties are taken from McCall (1982).

An important feature to note is the dominance of σ_{H_2} in some cases in the gas surface density. Unfortunately, the conversion from CO to H_2 is uncertain and controversial (Israel 1988; Maloney & Black 1988). Nonetheless, using the most commonly used conversion factor shows the potential importance of including the H_2 in calculating the total gas surface density. By using the metallicity independent conversion of Young & Scoville, we may be overestimating the H_2 content in the inner parts of the galaxies and underestimating the H_2 content in the outer parts. However, since the molecular gas content of Virgo and field spiral galaxies appear to be quite similar (Stark et al. 1986; Kenney & Young 1989), uncertainty in the H_2/CO conversion should not have a strong effect on the comparison between Virgo and field spirals.

Two other uncertainties should be noted. Walsh & Roy (1989) observed large variations in R_{23} at a given radius in NGC 2997. If this is generally true in spiral galaxies, then characterizing the abundance gradient in a galaxy based on fewer than 10 H II regions is dangerous. Furthermore, we have

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used azimuthally averaged gas surface densities, which may differ from the values at the location of a particular H II region. All of these spirals show large variations in gas surface density at a given radius.

The data from Table 3 are plotted in Figure 1. Oxygen abundance is plotted versus ρ/ρ_E, σ_D, and μ. These plots resemble Figures 1–3 of Edmunds & Pagel (1984). In each plot, the Virgo spirals form a well-defined locus. The field galaxies show a considerably larger dispersion in O/H, with an average oxygen abundance lower by roughly a factor of 2.

This perceived offset in abundance between the Virgo galaxies and the field galaxies is the main result of the comparison. We will refer to this relative overabundance in the Virgo spirals as the abundance differential, ΔZ_V. Perhaps most surprising is the difference as a function of μ; the Virgo galaxies overlap the same range in μ with the field galaxies, but have higher O/H.

It is possible that the observed abundance differential is a spurious effect of our sample selection. Zaritsky, Elston, & Hill (1990) have proposed that all late-type spiral galaxies can be divided into two distinct groups: i.e., high-excitation (low-abundance) galaxies and low-excitation (high-abundance) galaxies. The separation into distinct groups in the data of Zaritsky et al. is blurred when abundances are plotted versus gas fraction, but a range in excitation remains. If we have observed only low-excitation galaxies in Virgo and, by chance, have assembled a field sample dominated by high-excitation galaxies, then the observed abundance differential may be artificial. Discovery of an H I stripped, high-excitation Sc galaxy in the Virgo Cluster would weaken the case for ΔZ_V.

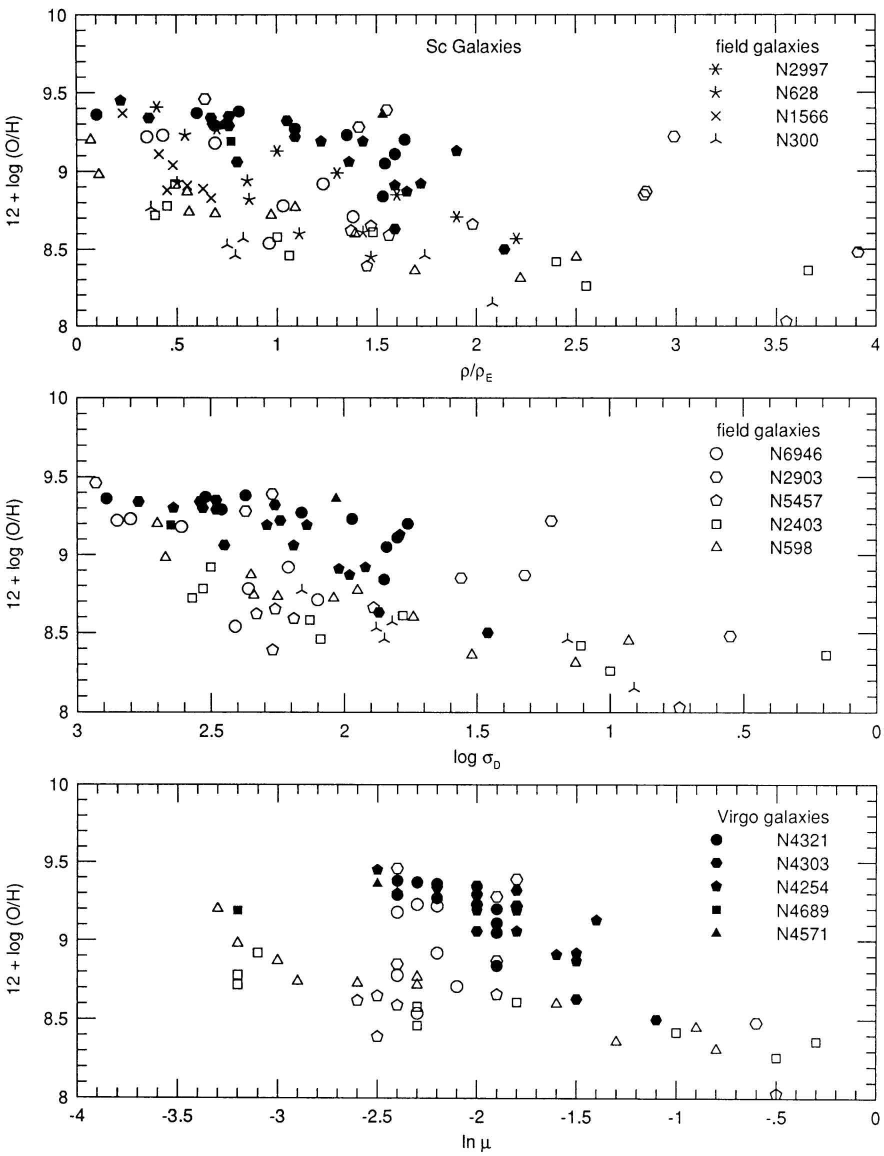

FIG. 1.—A comparison of the oxygen abundances for field and Virgo Cluster Sc galaxies. *Top:* oxygen abundances plotted vs. the galactocentric radius normalized by the effective radius of the disk. *Middle:* oxygen abundances plotted vs. the surface mass density of the disk. *Bottom:* oxygen abundances plotted vs. the radially averaged gas mass fraction. Filled symbols represent Virgo galaxies; open symbols represent field galaxies with H I and CO observations and reliable rotation curves; skeletal symbols represent other field galaxies. The galaxies are ranked in total luminosity by the number of vertices in the symbols. For NGC 2997, seven points are used to represent the mean relationship for the 49 observed H II regions.

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If mean abundance is a function of morphological type, then the difference in distribution in RC2 T types could produce the abundance differential. Such a trend is suggested since a field galaxy with the earliest T type (NGC 2903, $T = 4$) shows uniformally high values of O/H. On the other hand, the latest T-type Virgo spiral (NGC 4571, $T = 7$) shows a high abundance (although here we have only one measured H II region). Also, Garnett & Shields (1987) found abundances in the Sab ($T = 2$) spiral galaxy M81 to resemble those in later type spirals, contradicting any rigid correlation of O/H with morphological type.

The derived magnitude of ΔZ_V could be affected by errors in the slope of the calibration of R_{23} in terms of O/H, which relies on photoionization models in the high-abundance regime. In particular, the relationship between R_{23} and abundance, while reasonably insensitive to stellar temperatures, is strongly sensitive to electron density at solar and higher abundances (B. E. J. Pagel, private communication). However, the qualitative difference in O/H between the Virgo and field galaxies follows directly from the observed [O II] and [O III] line intensities.

Could the empirical relation between O/H and R_{23}, developed for field galaxies, fail in Virgo? McCall et al. (1985) and others have noted that the giant extragalactic H II regions form a one-parameter sequence in which line intensities, nebular ionization parameter, ionizing star temperatures, and O/H vary together. Figure 2 shows that the Virgo and field H II regions conform to a single trend of [O II] versus [O III]. Observations of [O I], [Ne III], and [S III] could help to resolve this question. Of course, direct measurements of electron temperatures would be best. Warmels (1986), Stark et al. (1986), and Kenney & Young (1989) find normal H I and CO emission from the Virgo galaxies inside the H I stripping radius. Furthermore, Kennicutt (1983) finds a normal ratio of Hα to H I emission, indicating a normal rate of ionizing star formation per unit gas mass. All of these facts together support the use of the normal calibration for Virgo H II regions.

4. CHEMICAL ABUNDANCE EVOLUTION MODELS

We have found that, although the Virgo spirals have normal gas contents inside the truncation radius, they have abnormally high interstellar abundances. Thus environmental effects are not restricted to the stripping of the outer disk.

The familiar "simple" model of chemical evolution (Schmidt 1963; Talbot & Arnett 1971) consists of a closed box with instantaneous recycling. The interstellar abundance of a primary element, such as O, is

$$Z = y \ln \mu^{-1} \qquad (2)$$

where μ is the gas mass fraction, and y is the yield (mass of element produced per unit mass of gas permanently consumed). One explanation of ΔZ_V might be that the Virgo galaxies have undergone more complete conversion of stars to gas. Figure 1 shows, however, that the Virgo and field galaxies have similar gas fractions and do not obey the same Z–$\ln \mu$ relation. Another explanation would be a higher yield of oxygen in Virgo. However, the agreement of Virgo and field spirals in Figure 2 suggests that the normal relationship between ionizing star temperature and abundance applies, so that a systematic difference in the proportion of oxygen-producing massive stars seems unlikely. Ionizing photons and oxygen are produced by stars in the same mass range (Woosley & Weaver 1986).

The failure of the simple model to explain the metallicity distribution of stars in the solar neighborhood has led to various modifications (see the review by Tinsley 1980). One possibility is prolonged infall of metal-poor gas onto the disk. For a constant gas mass (star formation equals infall), Z rises from zero, and asymptotically approaches the yield, y, as the gas fraction approaches zero (Larson 1972). Gunn (1981) argues that prolonged infall onto field galaxies is likely to occur in dark-matter cosmologies. However, in Virgo the galaxies are moving at high speeds through hot gas, as evidenced

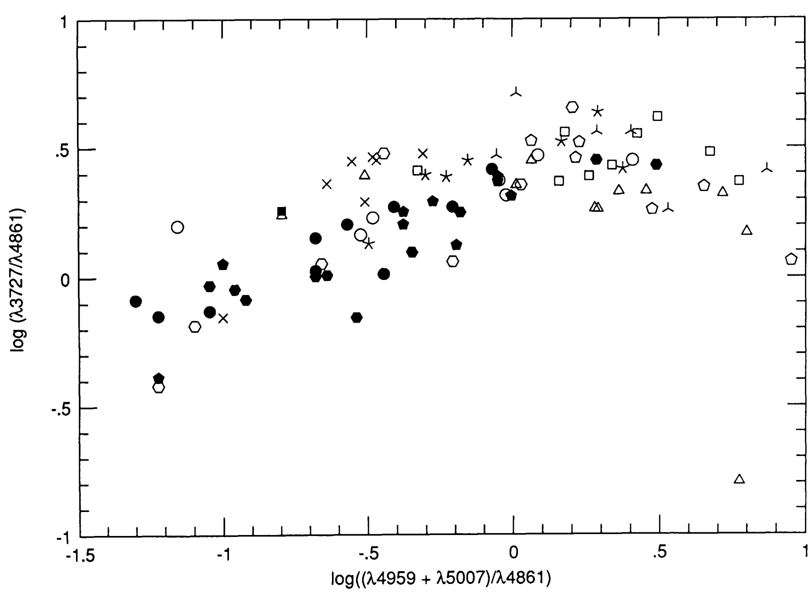

FIG. 2.—A comparison of the [O II] and [O III] line strengths. The same symbols are used as in Fig. 1.

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by X-ray emission surrounding M87 (Fabricant & Gorenstein 1983) and ram pressure stripping (Warmels 1986). Thus, infall onto spirals in the core of the Virgo Cluster seems unlikely. If the field galaxies have experienced prolonged infall not shared by the Virgo spirals, the latter should more closely approximate the simple model. We might then expect abundances in the field galaxies to be of order $Z \approx y$, and in the Virgo galaxies $Z \approx y \ln \mu^{-1}$. The Virgo galaxies, with $\ln \mu^{-1} \approx 1.5$–3, should have values of Z roughly twice as large as the field galaxies. This is in rough accord with the observed ΔZ_V.

Pagel (1989) employs the analytic infall model of Clayton (1985) to achieve a good fit to the metallicity distribution of stars in the solar neighborhood. He uses a star-formation time scale of 3.1 billion yr and an infall time scale of 6.2 billion yr, with Clayton's parameter $k = 4$, an initial metallicity $Z_0 = 0.02$ of the solar value ($Z_\odot$), and a yield for oxygen of 0.8 $Z_\odot$. We show in Figure 3 the Z–μ relation for this model and for the simple model with the same yield.

The infall model gives substantially lower Z at a given μ, but the difference is less than the observed ΔZ_V. The Virgo galaxies have higher abundances than can be explained by the simple model with Pagel's yield, whereas the field spirals actually have lower abundances than predicted by the infall model. We conclude that curtailment of infall makes a substantial contribution to the Virgo abundance differential, if infall indeed occurs in field galaxies. However, infall may have difficulty accounting for the entire effect.

Radial flows in gas disks can be effective in establishing radial abundance gradients (Lacey & Fall 1985; Clarke 1989). Clarke investigates models in which viscous transport of angular momentum causes radial flows on a time scale comparable with star formation (Lin & Pringle 1987). This initially causes radial outflow that establishes an exponential stellar surface density profile and forms an outer hydrogen disk. Later, inflow from the outer disk occurs, similar to that postulated by Lacey & Fall. If there is an outer star formation cutoff radius (van der Kruit & Searle 1982), then metal-poor gas becomes progressively enriched as it moves inward from this radius. A strong abundance gradient is thus established. If this picture applies to field galaxies, then the observed truncation of the gas disk in Virgo spirals will have important effects. In the Virgo spirals, the gas is now stripped well inside the outer radius of the stellar disk; and there is no outer reservoir of virgin gas whose transport inward would serve to hold down the abundance in the inner disk and maintain a strong gradient. After stripping has occurred, we would expect the Virgo galaxies to evolve more nearly like the simple model, reaching higher values of O/H; in particular, the outer parts of the surviving gas disk should rise well above the low O/H values observed in the outskirts of field spirals. This qualitatively agrees with Figure 1, in which the outermost observed H II regions in Virgo have high abundances.

One potential discriminant between infall and inflow may be the N/O ratio. Observed N/O ratios vary roughly as O/H for $[O/H] \geq -0.6$, but are constant for lower O/H, albeit with substantial scatter (Pagel 1985; Garnett 1990). A reasonable interpretation is that nitrogen production involves both primary and secondary contributions, the secondary one dominating above $[O/H] \approx -0.6$ (e.g., Pagel 1985; Matteucci 1986). For infall, dilution tends to lower O/H at a given N/O (Serrano & Peimbert 1983); and this might cause field spirals to have higher N/O than cluster spirals, at a given O/H.

Since very few of the H II regions in the Virgo spirals have measured electron temperatures, comparing values of N/O (derived from the N^+/O^+ ratio) is not straightforward. Instead, in Figure 4 we have compared values of the [N II]/[O II] ratio, $I(\lambda6584)/I(\lambda3727)$, as a function of O/H. The electron temperature is known to vary as a function of O/H, and so the [N II]/[O II] ratio, which is temperature-dependent, will also vary, even at constant N/O. For this reason we have included a line for constant N/O (assuming the solar value; Anders & Grevesse 1989) assuming that T_e and O/H are related as

$$\log (T_e) = -0.35 \log (O/H) + 2.74 \quad (3)$$

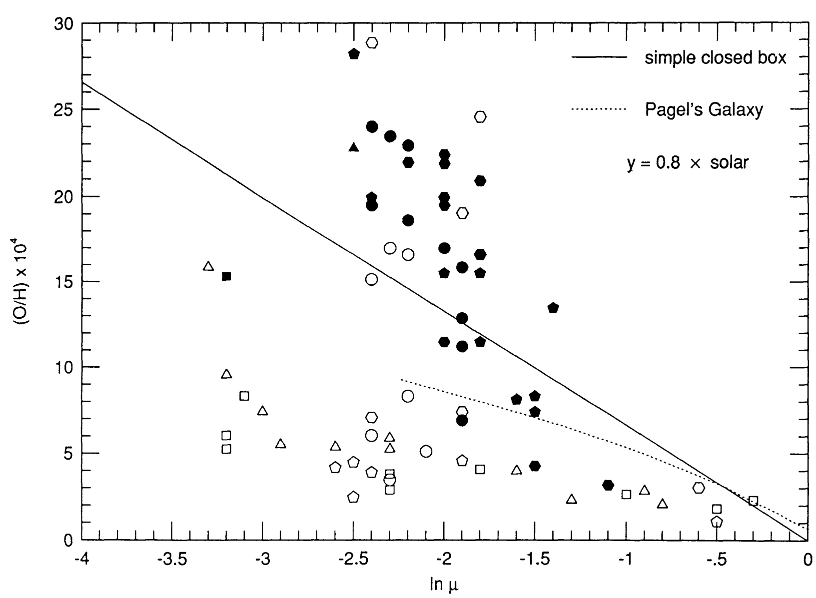

FIG. 3.—The same data from the lower panel of Fig. 1 are replotted, except that the y-axis is not logarithmic. In this diagram a constant yield corresponds to a straight line with an intercept at (0, 0). Representative lines are shown for the assumption of simple closed box evolution and Pagel's (1989) model of the evolution of the Galaxy.

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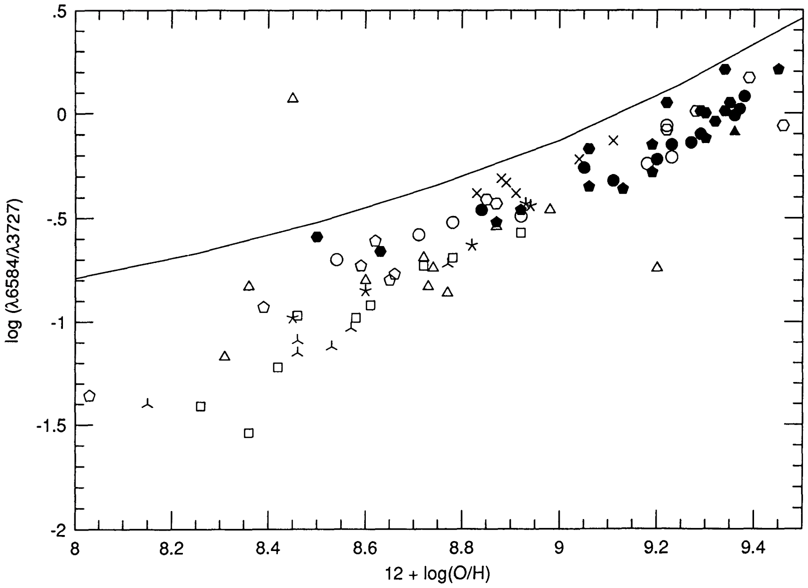

FIG. 4.—A plot of the [N II]/[O II] ratio as a function of O/H for both Virgo and field spirals. The same symbols are used as in Fig. 1. The solid line is the predicted ratio for constant N^+/O^+ = the solar value with the assumption $N^+/O^+ = N/O = 0.13$ (Anders & Grevesse 1989).

(Terlevich 1985). No significant offset in N/O is seen between the Virgo and field spirals, but there is little overlap in O/H. More observations of lower abundance H II regions in Virgo spirals and higher abundance H II regions in field spirals are needed, together with model predictions of N/O for the alternate explanations of ΔZ_V.

5. DISCUSSION

We have offered evidence that spiral galaxies in the Virgo Cluster have systematically higher interstellar abundances than comparable field galaxies. Curtailment of infall in the cluster environment and stripping of the outer gas disk may both play a role in causing this difference. Unfortunately, the observations and models both are inadequate to clarify the precise factors involved. Observations of more H II regions in more Virgo spirals are needed, including measurements of additional lines and, ideally, electron temperatures. If stripping of the outer disk is important, then observations of abundance gradients should be made for galaxies with strongly different H I envelopes in all environments. Of particular interest would be any galaxies in the periphery of the Virgo Cluster showing no stripping, but moving at velocities too high for accretion of intergalactic gas. Also interesting would be a comparative study of galaxies suspected of having larger or smaller infall rates, on the basis of criteria such as star formation rate larger than the gas return rate from existing stars.

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REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Brocklehurst, M. 1971, MNRAS, 153, 471
Clarke, C. J. 1989, MNRAS, 238, 283
Clayton, D. D. 1985, in Nucleosynthesis: Challenges and New Developments, ed. W. D. Arnett & J. W. Truran (Chicago: Univ. Chicago Press), 65
de Vaucouleurs, G., de Vaucouleurs, A., & Corwin, H. G. 1976, Second Reference Catalogue of Bright Galaxies (Austin: Univ. Texas Press) (RC2)
Edmunds, M. G., & Pagel, B. E. J. 1984, MNRAS, 211, 507
Fabricant, D., & Gorenstein, P. 1983, ApJ, 267, 535
Fierro, J., Torres-Peimbert, S., & Peimbert, M. 1986, PASP, 98, 1032
Filippenko, A. V., & Greenstein, J. L. 1984, PASP, 96, 530
Garnett, D. R. 1990, ApJ, 363, 142
Garnett, D. R., & Shields, G. A. 1987, ApJ, 317, 82
Giovanelli, R., & Haynes, M. P. 1985, ApJ, 292, 404
Guhathakurta, P., van Gorkom, J. H., Kotanyi, C. G., & Balkowski, C. 1988, AJ, 96, 851
Gunn, J. E. 1981, in Astrophysical Cosmology, ed. M. S. Longair, G. V. Coyne, & H. A. Brück (Citta del Vaticano: Pontifica Academia Scientarum), 233
———. 1983, in IAU Symposium 100, Internal Dynamics of Galaxies, ed. E. Athanassoula (Dordrecht: Reidel), 379
Hawley, S. A., & Phillips, M. M. 1980, ApJ, 235, 783
Hodge, P. W., & Kennicutt, R. C. 1983, AJ, 88, 296
Howarth, I. D. 1983, MNRAS, 203, 301
Israel, F. P. 1988, in Millimetre and Submillimetre Astronomy, ed. R. D. Wolstencroft & W. B. Burton (Dordrecht: Kluwer), 281
Jackson, J. M., Snell, R. L., Ho, P. T. P., & Barrett, A. H. 1989, ApJ, 337, 680
Kenney, J. D., & Young, J. S. 1988, ApJS, 66, 261
———. 1989, ApJ, 344, 171
Kennicutt, R. C. 1983, AJ, 88, 483
Lacey, C. G., & Fall, S. M. 1985, ApJ, 290, 154
Larson, R. B. 1972, Nature Phys. Sci., 236, 7
Lin, D. N. C., & Pringle, J. E. 1987, ApJ, 320, L87
Maloney, P., & Black, J. H. 1988, ApJ, 325, 389
Matteucci, F. 1986, MNRAS, 221, 911
McCall, M. L. 1982, Ph.D. thesis, University of Texas
McCall, M. L., Rybski, P. M., & Shields, G. A. 1985, ApJS, 57, 1
Oke, J. B. 1974, ApJS, 27, 21
Pagel, B. E. J. 1985, in Production and Distributions of C, N, O Elements, ed. I. J. Danziger, F. Matteucci, & K. Kjar (Munich: ESO), 155
———. 1989, Rev. Mexicana Astr. Ap., 18, 161
Pagel, B. E. J., & Edmunds, M. G. 1981, ARAA, 19, 77
Pagel, B. E. J., Edmunds, M. G., Blackwell, D. E., Chun, M. S., & Smith, G. 1979, MNRAS, 189, 95
Sandage, A. 1961, The Hubble Atlas of Galaxies (Washington, DC: Carnegie Institution)
Sandage, A., & Tammann, G. A. 1981, A Revised Shapley-Ames Catalog of Bright Galaxies (Washington, DC: Carnegie Institution) (RSA)
Sarazin, C. L. 1988, X-Ray Emission from Clusters of Galaxies (Cambridge: Cambridge Univ. Press)
Savage, B. D. 1987, in Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson, Jr. (Dordrecht: Reidel), 123
Schmidt, M. 1963, ApJ, 137, 758

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1991ApJ...371...82S

Seaton, M. J. 1979, MNRAS, 187, 73P
Serrano, A., & Peimbert, M. 1983, Rev. Mexicana Astr. Ap., 8, 117
Solomon, P. M., Barrett, J., Sanders, D. B., & de Zafra, R. 1983, ApJ, 266, L103
Stark, A. S., Knapp, G. R., Bally, J., Wilson, R. W., Penzias, A. A., & Rowe, H. E. 1986, ApJ, 310, 660
Tacconi, L. J., & Young, J. S. 1986, ApJ, 308, 600
Talbot, R. J., & Arnett, W. D. 1971, ApJ, 170, 409
Terlevich, R. 1985, in Star Forming Dwarf Galaxies, ed. D. Kunth, T. X. Thuan, & J. Tran Thanh Van (Gif sur Yvette: Ed. Fontieres), 395
Tinsley, B. M. 1980, Fund. Cosmic Phys., 5, 287
———. 1981, ApJ, 250, 758
Tinsley, B. M., & Larson, R. B. 1978, ApJ, 221, 554
van der Hulst, J. M., Skillman, E. D., Kennicutt, R. C., & Bothun, G. D. 1987, A&A, 177, 63
van der Kruit, P. C., & Searle, L. 1982, A&A, 110, 79
Vilchez, J. M., Pagel, B. E. J., Diaz, A. I., Terlevich, E., & Edmunds, M. G. 1988, MNRAS, 235, 633
Walsh, J. R., & Roy, J.-R. 1989, ApJ, 341, 722
Warmels, R. H. 1986, Ph.D. thesis, University of Groningen
Woosley, S., & Weaver, T. 1986, ARAA, 24, 205
Young, J. S. 1987, in Star Formation in Galaxies, ed. C. J. Lonsdale-Persson (Washington, DC: NASA), 197
Young, J. S., & Scoville, N. 1982, ApJ, 258, 467
Zaritsky, D., Elston, R., & Hill, J. M. 1990, AJ, 99, 1108

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