

COMPOSITION GRADIENTS IN SPIRAL GALAXIES: A CONSISTENCY CHECK ON THE DENSITY-WAVE THEORY

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ABSTRACT

Radial composition gradients in spiral galaxies are compared with expectations based on the spiral density-wave picture. It is presumed that star formation along the spiral arms is triggered when disk gas encounters the density-wave pattern and is compressed in a shock region near the wave crest. The frequency of star-forming events at a given radius in the galaxy is thus proportional to the difference between the angular speed of the gas and that of the pattern. The efficiency of star formation may be related to the compression suffered by the disk gas as it passes through the wave pattern. Radial changes in disk gas chemical composition can be related to variations in the star-formation frequency and in the star-formation efficiency across the face of a galaxy. The observations of emission-line strengths in the disks of 12 late-type galaxies, reported here, support this picture but do not exclude other, more ad hoc, star-formation and metal-enrichment scenarios.

Subject headings: galaxies: general — galaxies: structure — abundances — image processing

I. INTRODUCTION

The existence in galaxies of radial gradients in the emission-line ratio $[\text{O III}]/\text{H}\beta$ has been known since the pioneering work of Aller (1942). This gradient (usually called the "excitation gradient") can be very large. In M101, for example, $[\text{O III}]/\text{H}\beta$ increases by nearly a factor of 100 from the innermost observed H II regions to the outermost. Other emission-line ratios such as $[\text{O II}]/[\text{N II}]$, $[\text{S II}]/[\text{N II}]$ and $[\text{N II}]/\text{H}\alpha$ also show strong radial variations. The radial dependence of these emission-line ratios has been the object of a number of recent studies (Burbidge and Burbidge 1965; Peimbert 1968; Peimbert and Spinrad 1970). A comprehensive attempt to understand these emission-line gradients was made by Searle (1971). With the help of idealized H II region models, he was able to show that the $[\text{O III}]/\text{H}\beta$ and $[\text{N II}]/[\text{O II}]$ gradients probably resulted from radial variations in the abundance of oxygen relative to hydrogen and in the abundance of nitrogen relative to oxygen. His models suggest a monotonic decrease in the O/H ratio and in the N/O ratio as the radial distance from the nuclear bulge increased. Searle's conclusions have been carefully reexamined several times since their appearance. Shields (1974) constructed a series of elaborate models of H II regions in order to predict the behavior of the emission-line ratios as a function of gas clumpiness, exciting star

temperature, and gas-to-dust ratio. He was unable to find any plausible combination of factors which could reproduce the observed emission-line gradients without appeal to a systematic decrease of metal abundance with radius. He concluded that radial gradients in the abundance of O/H amounting to as much as a factor of 15 characterized the disks of late-type spiral galaxies.

Smith (1975) restudied many of the H II regions observed by Searle and, in addition, provided observations of H II regions in several more galaxies. The interpretation of the observed line strength gradients was aided considerably by his observations of the weak $[\text{O III}] \lambda 4363$ line in several H II regions. These observations, combined with the measured strengths for $\lambda 4959$ and $\lambda 5007$, permit direct determination of the electron temperatures in the volume where doubly ionized oxygen is present. His findings qualitatively substantiate Searle's conclusion that the oxygen abundance in these outer H II regions is low relative to the solar value. For M101, he estimates that O/H varies by a factor of 10 across the disk, while N/O decreases by about a factor 4 from the innermost to the outermost H II regions. Recently, Shields and Tinsley (1976) have argued that some of the excitation gradient may be caused by a radial gradient in the mean effective temperature of the exciting stars. However, Sarazin (1976) contends that this effect is not the principal contributor to the excitation gradients observed. He argues instead that a radial dependence of the dust-to-gas ratio in H II regions can best match the observed variations both of the equivalent width of the $\text{H}\beta$ line and of the $[\text{O III}]/\text{H}\beta$ ratio. While

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changing the dust/gas ratio can affect the emission-line ratios, a large abundance gradient, possibly correlated with the dust-to-gas ratio, still appears necessary in order to explain the observations. Finally, Balick and Sneden (1976) have argued that the metal abundance will affect the ultraviolet flux emitted by the early-type stars responsible for ionizing the H II regions. Adjustments in the predicted ultraviolet flux necessitated by varying the metal abundance tend to reduce the abundance gradients required to explain the observed excitation gradients in M101 and M33.

The prediction from H II region observations of metal abundance gradients in the disks of spiral galaxies is supported by several independent observations:

1. Janes and McClure (1972) have shown from a statistical study of the kinematics of nearby K giants that those giants with weaker CN (and presumably smaller metal-to-hydrogen ratios) have orbits with larger perigalactic distances.

2. The dependence of the Cepheid period-luminosity and period-frequency relation on radial position in the galaxy suggests that the anticenter Cepheids may have lower metal abundance than those observed in the center direction.

3. A recently completed study of galactic planetary nebulae by D'Odorico, Peimbert, and Sabbadin (1976) suggests a decrease with increasing radial distance in the abundances of sulfur, oxygen, nitrogen, and helium.

4. The strength of stellar absorption features close to and in the nuclei of galaxies (McClure and van den Bergh 1968; McClure 1969; Spinrad *et al.* 1971; Spinrad, Smith, and Taylor 1972; Welch and Forrester 1972; Joly and Andrillat 1973) and the color gradients in elliptical galaxies (Tifft 1961; McClure 1969; Strom *et al.* 1976) all suggest a decrease of metal abundance as the distance from the nucleus increases. It should be noted that although the sense of these latter gradients seems consistent with those derived for disk systems, they may not be directly relevant to a discussion of disk composition gradients. Nonetheless, we regard the above evidence as sufficient to support the belief that significant radial composition gradients are found in late-type spiral galaxies. However, the absolute abundances derived from various techniques as well as the magnitude of abundance gradients are uncertain. We will therefore avoid attempts to interpret *absolute* abundances derived from extragalactic H II regions.

Until recently, the study of composition gradients has centered on establishing their reality; little attention has been paid to the possible causes of the observed abundance gradients. Both Searle (1971) and Smith (1975) discussed the apparent increase in the mean galactic metal abundance for galaxies of earlier morphological type. Smith noted that this increase correlated with the general decrease in the average ratio of neutral hydrogen to stellar mass M_H/M_S for earlier spiral types. Simple models of star formation and element enrichment quite naturally predict an increase in the metal/hydrogen ratio of the disk gas, as

a greater fraction of the gas is processed into stars (Searle and Sargent 1972). These models are able to reproduce qualitatively the metallicity-morphological type correlation. Moreover, the gradients in individual galaxies can be understood in the context of this picture, since, in general, the most metal-poor regions in late-type spirals are located in regions where M_H/M_S is relatively high, while high metal-to-hydrogen ratios are found in gas-poor regions. More elaborate models have been computed by Talbot and Arnett (1975). These authors follow the chemical evolution of idealized disk galaxies in which the initial gas density distribution with radial distance is specified. By adopting reasonable but ad hoc star-formation rates, which depend implicitly on the density and temperature of the gas, they are able to reproduce the range of composition gradients observed in external galaxies.

Many qualitative aspects of the above models may be correct. However, to some extent, we believe them to be either ad hoc or incomplete. For example, the Searle and Sargent model fails to suggest the *mechanisms* which drive differential gas depletion both in the disks of individual galaxies and between galaxies of disparate morphology, although one assumes implicitly that regions of low M_H/M_S are regions in which either "primordial" or disk star-formation rates were high. Talbot and Arnett's models predict differential star-formation rates which depend both on the initial density distribution of disk gas and on the physical conditions in the evolving disk-star complex. They deduce a star-formation rate which depends on the local density. Composition gradients and differences between morphological types result primarily from differences in the initial gas density distributions in their models. While these models provide some important insight into the details of chemical enrichment in the disk, possible driving mechanisms for star formation are largely ignored. For example, the fact that, at least at the present time, newly formed stars in spiral galaxies are found primarily in the arms is inconsistent with the assumption that the average density at a given radial distance alone controls the star-formation efficiency.

In this paper, we wish to test a picture in which the observed compositions and composition gradients result from density wave-driven star formation. The density-wave model of spiral structure was introduced originally in order to understand the persistence of spiral patterns for times comparable to the Hubble time. If the arms represent local material enhancements in the disk, differential galactic rotation would force the material arms to "wind up" in only a few galactic rotation periods. The density-wave picture suggests that the spiral arms are actually a wave pattern which results from a self-sustaining departure from the axisymmetric gravitational field of a disk system. The pattern rotates around the galaxy with a characteristic angular velocity called the pattern speed Ω_p . This quantity is currently treated as a free parameter in the density-wave theory but can, in principle, be specified for a given galactic mass

distribution. The gas and the stellar subsystem rotate around the galactic center at an angular velocity $\Omega(R)$ which depends primarily on the axisymmetric gravitational field. Calculations of the flow pattern of the gas in the vicinity of the spiral wave suggest that the gas is shocked and compressed when the component of gas velocity perpendicular to the wave pattern $w_\perp$ exceeds the local acoustic speed a . The amount of compression, expressed as the ratio of compressed-to-ambient density, depends primarily on the ratio $(w_\perp/a)^2$ and on the amplitude of the spiral wave. The compression of disk gas as it encounters the density wave is presumed to trigger star formation. The frequency with which the disk gas encounters the density wave depends on the relative difference $\Omega(R) - \Omega_p$. The suggestion of shock-induced star formation is particularly attractive because it provides a natural explanation for the prevalence of active star formation in the arm regions. Qualitatively, composition gradients in the disk gas can also be understood in terms of density-wave-driven star formation. In the inner parts of the galaxy, $\Omega(R) - \Omega_p$ is larger; hence the presumed frequency of star formation is large as well. This, in turn, should result in a large rate of gas depletion and chemical enrichment. Oort (1974) suggests that the present-day distribution of neutral hydrogen in M81 can be understood in the context of this picture. In his view, the depletion of gas toward the center of M81 results directly from a high frequency of star-formation events driven by the large number of times disk gas has passed through the density wave. In the outer regions where Ω approaches Ω_p , the star-formation frequency is low; consequently, the chemical-enrichment and gas-depletion rates should be low as well. Differences between the mean composition of individual galaxies may also be explained if the mean compression suf-

fered by the gas in the arm regions varies from galaxy to galaxy. The implicit presumption here is that regions suffering high compression produce stars with a high efficiency per generation.

We shall henceforth assume, as a working hypothesis, that disk composition gradients result primarily from differences in the frequency of star-forming events across galactic disks and from differences in the efficiency of star formation resulting from variations in gas compression in the arm regions. We recognize the oversimplification implicit in this viewpoint. For example, we have chosen to ignore star-formation events not induced by the density wave. The existence of elliptical galaxies and nuclear bulges in spirals bears dramatic witness to the efficacy of star formation in the absence of density waves. Moreover, we ignore the importance of composition differences "built into" the disk subsystem during the collapse of the galaxy. Furthermore, we disregard the possible roles of infalling halo gas or expelled nuclear gas on disk chemical evolution. However, we believe that it is of considerable value to explore the degree to which density-wave-driven star formation can explain the observed chemical composition variations both within and between disk systems. This represents both a natural extension of and a challenging test for a theoretical picture which has proved successful in explaining a large variety of phenomena characteristic of spiral galaxies.

II. OBSERVATIONS

In order to compare observed composition gradients with the predictions of the density-wave theory, we selected a sample of galaxies in which to observe abundance-sensitive line-intensity ratios. Our sample was chosen in such a way that a large range in mass, luminosity, morphological type, and the mean value

TABLE 1
BASIC DATA FOR GALAXIES IN OUR SAMPLE

NGC	Type (deV)	Luminosity Class (vdB)	Position Angle	Distance (Mpc)	Holmberg Radius (arcmin)	Mass ($\times 10^{10} M_\odot$)	Rotation Curve Reference
157.....	Sc	I	30	28.7	2.9	8.1	Burbidge <i>et al.</i> 1961
224(M31).....	Sb	I-II	35	0.69	98.5	17.8	Rubin and Ford 1970
598(M33).....	Scd	II-III	23	0.72	41.5	6.8	Rogstad and Shostak 1972
925.....	Sd	II-III	113	14.8	7.0	3.9	Rogstad <i>et al.</i> 1967 Rubin <i>et al.</i> 1964
972.....	IO	II:	153	28.4	1.6	1.3	Burbidge <i>et al.</i> 1965b
1084.....	Sc	I-II	32	18.1	1.5	1.8	Burbidge <i>et al.</i> 1963
2403.....	Scd	III	125	3.25	14.5	2.3	Rogstad and Shostak 1972
2903.....	Sbc	I-II	24	7.6	7.0	4.1	Burbidge <i>et al.</i> 1960
3031(M81).....	Sab	I-II	157	3.25	17.5	11.0	Gottesman and Weliachew 1975
3593.....	SOa	III	92	26.8	2.4	0.8	Demoulin 1969
5194(M51).....	Sbc	I	0	9.6	7.1	6.6	Burbidge and Burbidge 1964
5457(M101).....	Scd	I		7.2	14.0	14.5	Rogstad and Shostak 1972
6181.....	Sc	I	161	49	1.4	7.1	Burbidge <i>et al.</i> 1965a
6503.....	Scd	III	124	10.*	5.6	0.3	Burbidge <i>et al.</i> 1964
7331.....	Sbc	I-II	176	14.4†	6.8	7.8	Rubin <i>et al.</i> 1965

* Distance estimate from Burbidge *et al.* 1964 adjusted to $H_0 = 55 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

† Distance estimate is mean of three estimates: (a) assuming NGC 7331 has same absolute luminosity as M31; (b) assuming NGC 7331 has same radius at $V = 26 \text{ mag arcsec}^{-2}$ as M31; (c) assuming NGC 7331 is at distance given by its redshift using $H_0 = 55 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

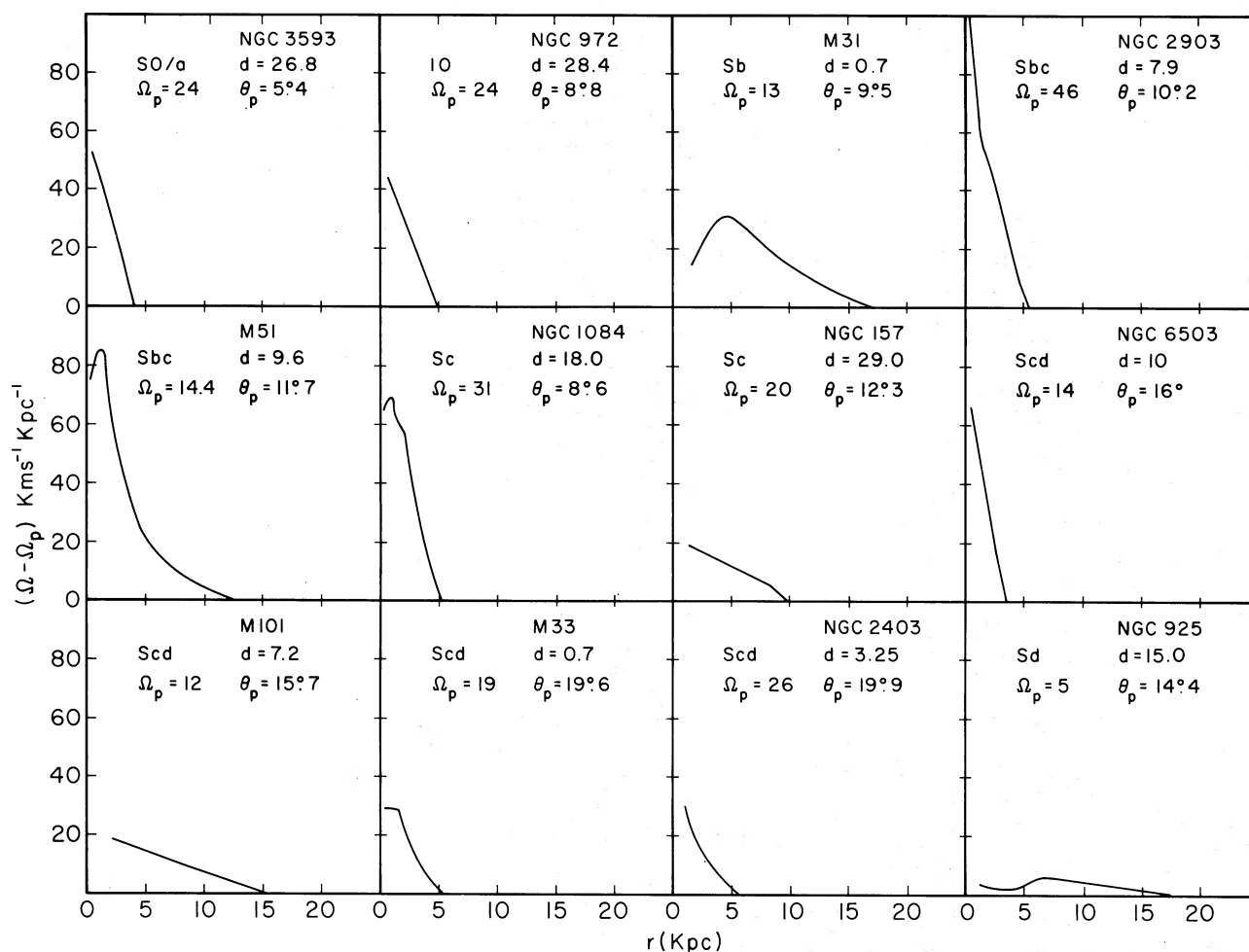


FIG. 1.—A plot of $(\Omega - \Omega_p)$ against normalized radius ρ/ρ_H , the ratio of radial distance to the Holmberg radius

of $\Omega(R) - \Omega_p$ was present. To this list, we later added galaxies selected from systems studied by Roberts, Roberts, and Shu (1975). In Table 1, we have assembled the basic observational data and relevant rotation curve references for all galaxies in our sample. The masses and luminosities presented in this table have been adjusted to place our program galaxies on the self-consistent distance scale given by Sandage and Tammann (1974*a, b*; 1975). The morphological types listed are the revised types given by de Vaucouleurs and de Vaucouleurs (1964), while the luminosity classes are taken from van den Bergh (1960*a, b*). Four other galaxies, NGC 1232, NGC 1808, NGC 1832, and NGC 628, were also observed. However, the emission-line strengths in the first three galaxies proved too weak to measure, while for NGC 628, no reliable rotation curve is as yet available. In Figure 1, we have plotted the parameter $\Omega(R) - \Omega_p$ against galactocentric distance. The curves plotted in this figure are based on the data cited in Table 1; the values of the pattern speed Ω_p were consistently chosen from the velocity observed for the outermost point in

the optical rotation curve. Examination of this figure suggests that we have selected galaxies which should exhibit wide variations in star-formation frequency and hence chemical enrichment, if our picture is correct.

The image-tube spectrographs used in conjunction with the Mayall 4 m telescope (M) and with the Steward Observatory 2.3 m telescope (SO) were used to record long slit spectrograms along the major axis of each galaxy in our sample. At the 4 m telescope, the scale at the spectrograph entrance slit is $6''.7 \text{ mm}^{-1}$ and on the plate $25'' \text{ mm}^{-1}$, while for the Steward system, the corresponding numbers are $10'' \text{ mm}^{-1}$ and $55'' \text{ mm}^{-1}$. Examples of these spectrograms appear in Figure 2. For most galaxies, emission lines arising both in bright "arm" H II regions and from diffuse interarm gas have been recorded. Previous studies have relied primarily on photoelectric observations of individual H II complexes (Searle 1971; Smith 1975). A virtue of these studies is that, by selection, a relatively homogeneous sample of H II regions has been observed. Our data probably sample a more

heterogeneous set of density and ionization conditions, although as we shall see in § IV, the trends in the emission-line ratios are no different from those obtained by Smith and by Searle.

To convert our data from photographic density to relative intensities, we relied on step-wedge calibration devices. Transformations to an absolute intensity scale were derived from observations of the well-studied H II region NGC 604 in M33. After correcting our observed relative intensities for atmospheric extinction by using a mean of the extinction coefficients derived by Oke (1965) and by Hayes (1970), we adjusted all line ratios, with the exception of $[\text{N II}]/\text{H}\alpha$ and $[\text{N II}]/[\text{S II}]$, to the values obtained by Searle for NGC 604. For $[\text{N II}]/\text{H}\alpha$ and $[\text{N II}]/[\text{S II}]$, we used the values directly determined from our plate material. By adopting this convention, we differ from Searle by 0.2 dex and from Smith by 0.1 dex in the sense that our nitrogen strengths are larger by the quoted amounts. We suspect that these differences arise primarily from variations in the $[\text{N II}]/\text{H}\alpha$ ratio within NGC 604 rather than from systematic errors in either our own or other data. This impression was confirmed by sampling the $[\text{N II}]/\text{H}\alpha$ ratio at a few points in NGC 604 by using the Kitt Peak National Observatory (KPNO) image dissector scanner. Internal checks on the accuracy of our density-intensity conversion were provided by comparing the expected ratios of $\lambda 6584$ with $\lambda 6548$ of $[\text{N II}]$ and $\lambda 5007$ with $\lambda 4959$ of $[\text{O III}]$; in both cases, the ratio, as determined by the atomic parameters for these transitions, is nearly 3:1. In no case did our line ratios differ from the expected values by more than 10 percent. We estimate the typical internal plus external error for all measured line strengths in our survey to be ± 0.07 dex, unless otherwise noted.

III. DATA REDUCTION

Reduction of the large body of data that we obtained was greatly aided by the availability of KPNO's new Interactive Picture Processing System (IPPS) (Wells 1975). In order to prepare our data for display on the IPPS, we first scanned our spectra with the KPNO PDS microdensitometer. The resulting digital data were recorded on magnetic tape, converted to intensity, and then displayed on the COMTAL television screen of the IPPS. Following this, we visually selected an appropriate "galaxy-free" region from the picture display and defined this region as "sky." To correct for geometrical distortions introduced by the image tubes, an interactive program was developed which allowed us to "follow" the centers of two bright, night-sky features across the plate. Interpolation between two parabolic functions fitted to these centers proved quite successful in estimating geometrical distortions over short wavelength regions. After correcting for the local distortion, the averaged "sky" intensity was subtracted from each row in the scan. To provide a visual impression of the efficacy of this scheme, we compare, in Figure 3, the raw, intensity-converted spectrogram of NGC 2903 with

the picture which results from the application of the sky-subtraction algorithm.

Following sky-subtraction, the emission-line regions deemed suitable for measurement were selected. An intensity-wavelength trace along the dispersion, averaged over an appropriate number of pixels perpendicular to the dispersion, was then displayed on the Tektronix graphics screen. We then used the cursor facility of the Tektronix graphics device to specify the edges of a chosen emission line and to initiate computation of the line strength. The resulting "equivalent width" (in units of pixels times arbitrary intensity units) was then recorded for further analysis. In Figure 4, we illustrate both the appearance of the COMTAL screen and the Tektronix display during the reduction of a typical galaxy spectrogram.

In Table 2, we present, as a function of radial distance (arcsec), the logarithmic emission-line ratios $\text{H}\alpha/\text{H}\beta$, $\text{H}\alpha/[\text{N II}]$, $[\text{N II}]/[\text{S II}]$, $[\text{N II}]/[\text{O II}]$, and $[\text{O III}]/\text{H}\beta$ derived from our spectra of 12 galaxies. These ratios have been corrected for the effects of atmospheric extinction and for instrumental response. They are *not* corrected for interstellar extinction either within our own Galaxy or within the external galaxy. We expect each of the line ratios to have an internal precision of ± 0.1 dex (m.e.); entries followed by a colon are believed to have uncertainties in excess of this value. This estimate is based on our assessment of the errors introduced by (a) improper selection of continuum levels and line edges, and (b) uncertainties in the characteristic curves. We note that $[\text{O III}]$ refers to the sum of $\lambda 5007$ and $\lambda 4959$, $[\text{N II}]$ to the sum of $\lambda 6548$ and $\lambda 6584$, $[\text{S II}]$ to the sum of $\lambda 6716$ and $\lambda 6731$, and $[\text{O II}]$ to the sum of $\lambda 3727$ and $\lambda 3729$. In cases where either $\lambda 4959$ or $\lambda 6548$ could not be distinguished, we multiplied the observed strengths for $\lambda 5007$ and $\lambda 6584$ by the factor 1.33.

IV. CHOICE OF A "CHEMICAL ENRICHMENT INDICATOR"

Before comparing local "chemical enrichment" in our sample galaxies with the predictions of the density-wave theory, it is essential to select appropriate indices which measure enrichment. The most likely enrichment indicators are the $[\text{O III}]/\text{H}\beta$ and $[\text{N II}]/[\text{O II}]$ ratio. The $[\text{O III}]/\text{H}\beta$ ratio has a number of substantial advantages:

1. It is extremely sensitive to the O/H abundance ratio because the strength of the $[\text{O III}]$ lines depends critically on the local electron temperature T_e ; T_e is, in turn, fixed primarily by the balance between heating by photoionizing radiation from the exciting stars and cooling through collisional excitation of fine structure transitions (at 88μ and 52μ) in O III. Hence the cooling rate depends primarily on the oxygen abundance; where O/H is large, the cooling is large and the ratio $[\text{O III}]/\text{H}\beta$ is small.

2. It does not depend sensitively on an accurate determination of selective interstellar extinction within and external to the ionized regions observed.

3. This wavelength region is nearly devoid of strong atmospheric emission features, thus minimizing the importance of extremely accurate sky subtraction.

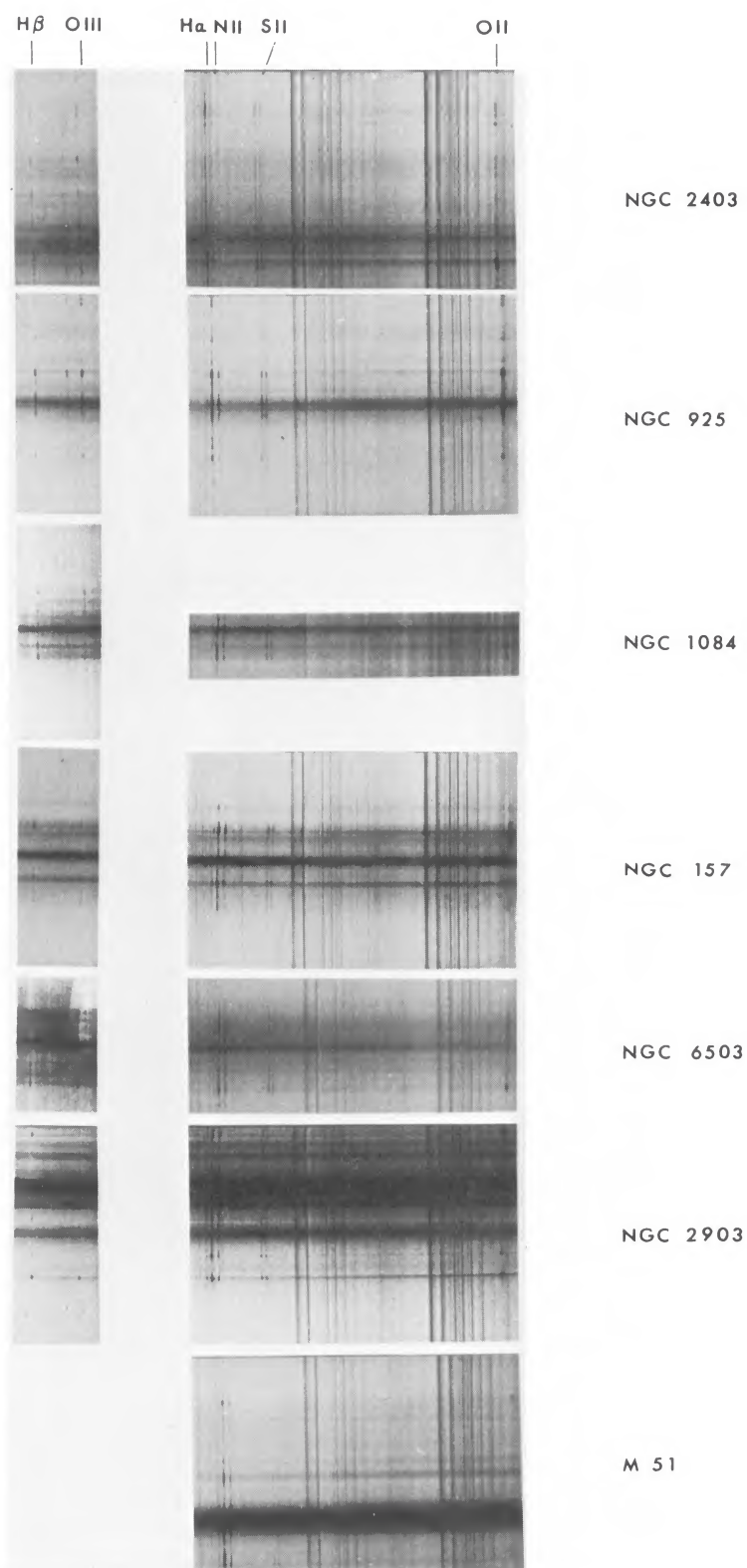


FIG. 2.—A montage of spectrograms, ordered by $[O\ III]/H\beta$ ratio, for seven galaxies in our sample. The original dispersion is $56\ \text{\AA}\ \text{mm}^{-1}$ (first order). The scale along the slit can be estimated from the length of the widest spectrograms reproduced ($\sim 300''$). Note the increase in mean $[N\ II]/[O\ II]$ ratio as the mean $[O\ III]/H\beta$ ratio decreases.

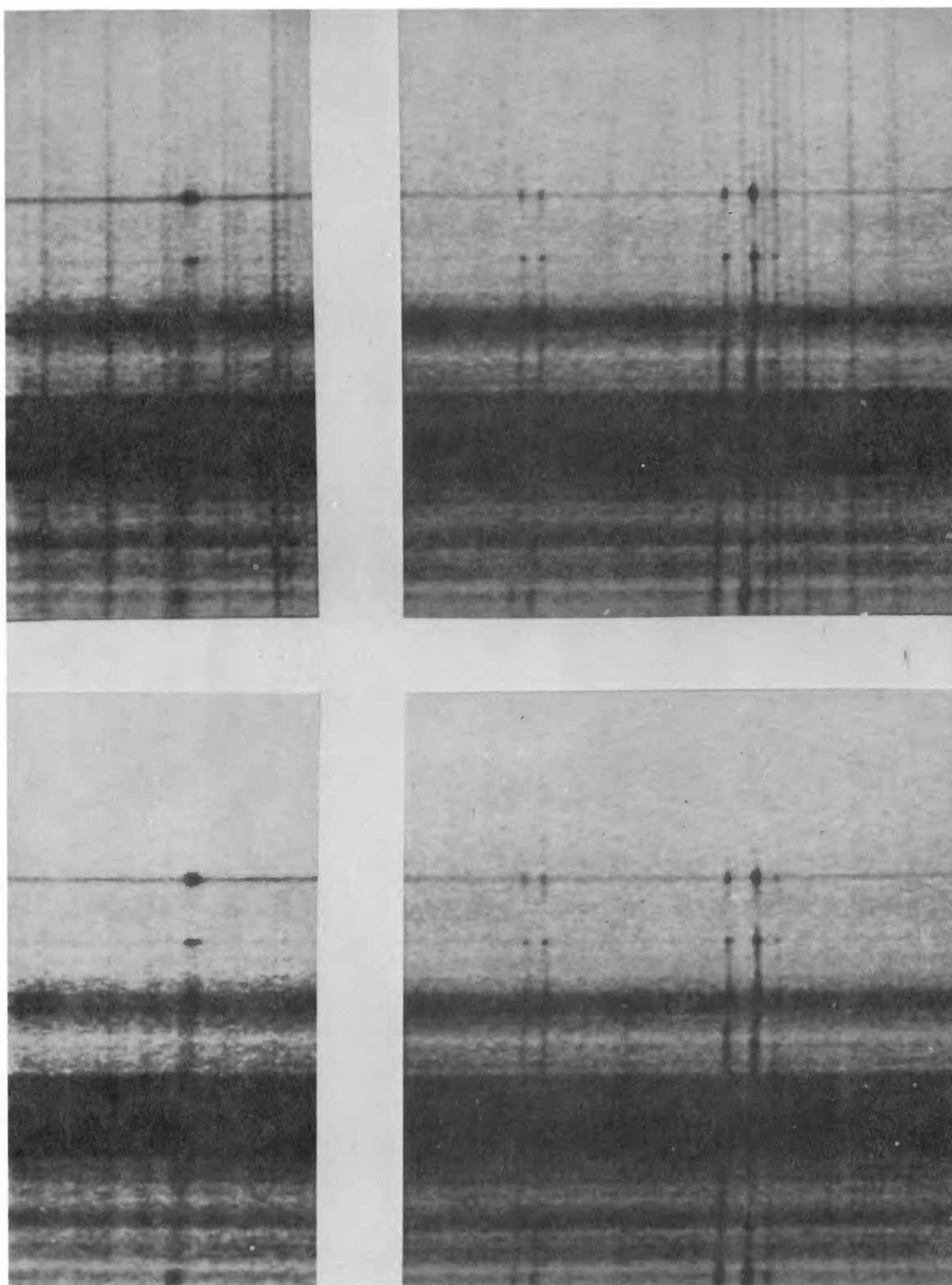
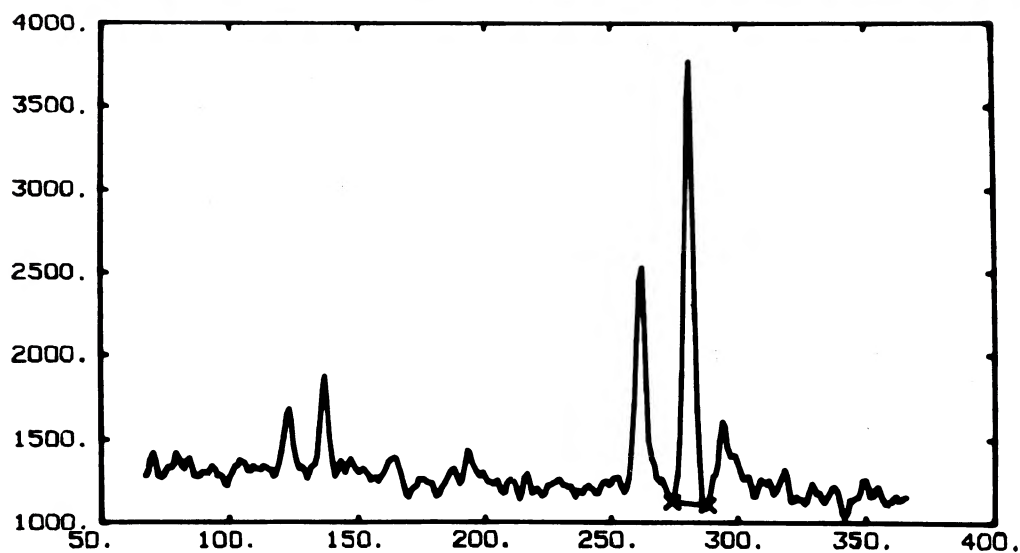
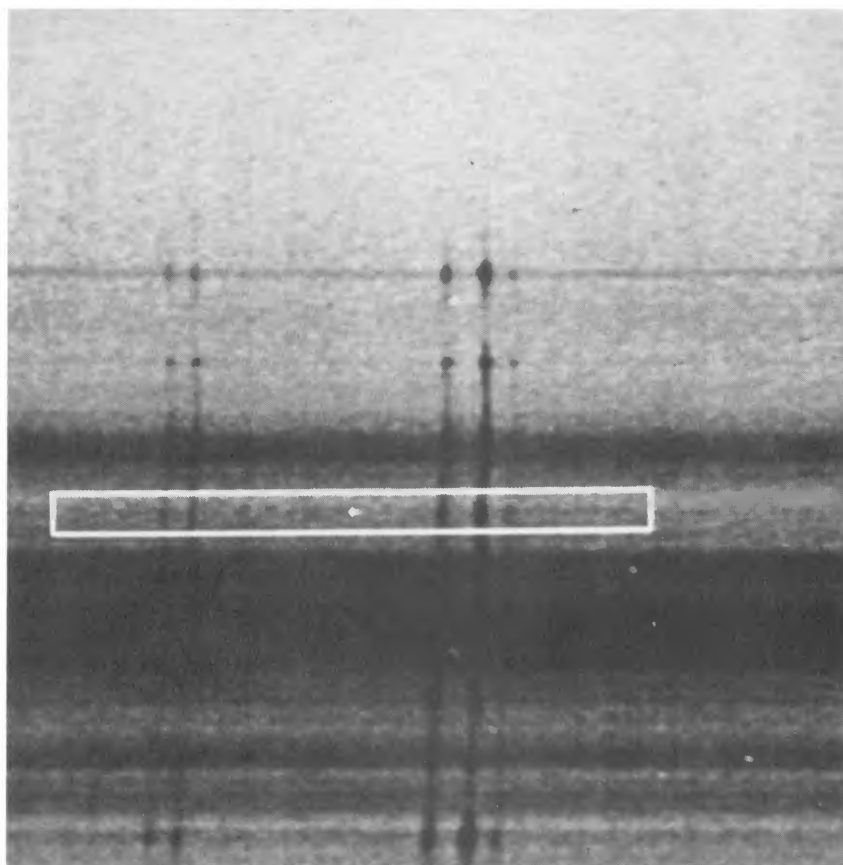


FIG. 3.—The top frame is a photograph from the COMTAL screen of an intensity-rectified spectrogram of NGC 2903. The bottom frame provides an indication of the efficacy of the sky-subtraction algorithm described in the text. The [O II] doublet at 3797 Å appears on the left-hand side of the figure; the [S II] doublet at 6717, 6731 Å and the H α [N II] region appear on the right-hand side.



PICK OUT ONE EDGE OF LINE WITH CURSOR AND SLAP KEYBOARD
 NOW PICK OUT OTHER EDGE AND SLAP KEYBOARD
 EQUIVALENT WIDTH IS 11968.
 POINT NUMBER IS 1. CENTER Y-PIXEL IS 290 OK
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FIG. 4.—An indication of the interactive data reduction procedure with the KPNO IPPS. The top frame illustrates the sky-subtracted spectrogram of NGC 2903 reproduced in Fig. 3. Superposed on this frame is a “graphics overlay” rectangular box whose size and position is selected on-line by the user. The bottom frame represents the intensity-wavelength plot which appears on the screen of a Tektronix 4010 terminal after the intensities are averaged over the height of the box illustrated in the top frame. Also illustrated in the bottom frame is a sample of the interactive equivalent width computation procedure as applied to the $H\alpha$ line in the NGC 2903 spectrogram.

TABLE 2
Observed Line Strength Ratios for Galaxies in Our Sample

$\Delta r''$	ρ	$\Omega - \Omega_p$	$w_\perp$	[OIII]/H β	[NII]/[SII]	H α /[NII]	[NII]/[OII]	H α /H β	A_V
NGC 157 $\Omega_p = 20 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 12^\circ.3$ $\Delta r_s = 15''$									
71 NE	0.41	0	0	0.19	-0.03	0.26	-0.36	0.39	0.0
56	0.32	7	12	0.14	0.00	0.34	-0.29	0.51	0.3
35	0.20	13	13	-0.31	-0.19	0.52	-0.18	0.45	0.0
17	0.10	17	9	0.27:	0.10	0.24	-0.06	0.84:	2.5:
0	0.00			0.24:	0.42	0.07	-0.18	0.78:	2.1:
17	0.10	17	9	0.28:	0.34	0.21	-0.04	0.95:	3.2:
30	0.17	14	13	0.03	0.19	0.23	0.01	0.82	2.3
45	0.26	10	13	-0.45	0.20	0.33	0.20	0.51	0.3
78 SW	0.45	0	0	-0.23	0.14	0.23	-0.06	0.60	0.9
NGC 925 $\Omega_p = 5 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 14^\circ.4$ $\Delta r_s = 15''$									
147 SE	0.35	2:	5:	0.48	-0.23:	0.75	-0.84	0.42	0.0
93	0.22	2:	3:	-0.11	-0.16	0.55	-0.54	0.43	0.0
62	0.15	2:	2:	0.19:	-0.33	0.53	-0.60:	0.78:	2.1:
44	0.11	2:	2:	0.30:	-0.10	0.48	-0.39	0.44	0.0
0	0.00			0.14	-0.03	0.42	-0.39	0.43	0.0
16	0.04	2:	1:	0.01	0.02	0.40	-0.31	0.44	0.0
50	0.12	2:	2:	0.36:	-0.03	0.35	-0.30	0.88:	2.7:
80 NW	0.19	2:	3:	0.09	-0.08	0.58	-0.44	0.49	0.2
NGC 972 $\Omega_p = 24 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 8^\circ.8$ $\Delta r_s = 4''.5$									
31.5 SE	0.33	6	4	0.02	0.33	0.35	0.64	0.81	2.3
29.2	0.30	9	6	-0.15	0.36	0.35	0.39	0.80	2.2
27.0	0.28	12	7	-0.13	0.29	0.40	0.24	0.82	2.3
25.0	0.26	15	8	0.06	0.17	0.38	0.34	0.82	2.3
22.5	0.23	19	9	-0.05	0.22	0.33	0.55	0.86	2.6
20.2	0.21	22	9	-0.08	0.26	0.29	0.58	0.85	2.5
18.0	0.19	24	9	0.20	0.25	0.34	0.49	0.86	2.6
15.7	0.16	27	9	0.12	0.29	0.32	0.45	0.93	3.1
13.5	0.14	30	9	-0.10	0.34	0.30	0.41	0.98	3.4
11.2	0.12	34	8	-0.50	0.35	0.27	0.44	0.98	3.4
9.0	0.09	34	6	-0.22	0.31	0.29	0.49	1.12	4.3
6.7	0.07	40	6	-0.04	0.23	0.29	0.52	1.15	4.5
4.5	0.05	> 43		0.63	0.95	0.25	0.57	1.30	5.5
2.2	0.02			0.46	0.33	0.17	0.77	1.05	3.8
0.0	0.00			0.32	0.37	0.18	0.84	0.91	2.9
2.2	0.02			0.22	0.31	0.21	0.75	0.95	3.2
4.5	0.05	> 43		0.26	0.32	0.28	0.53	1.10	4.2
6.7	0.07	40	6	0.00	0.28	0.31	0.51	1.12	4.3
9.0	0.09	34	6	0.03	0.21	0.32	0.55	0.97	3.3
11.2	0.12	34	8	-0.09	0.27	0.31	0.53	0.92	3.0
13.5	0.14	30	9	-0.18	0.36	0.31	0.63	0.88	2.7
15.7	0.16	27	9	-0.25	0.37	0.32	0.62	0.85	2.5
18.0	0.19	24	9	-0.35	0.33	0.33	0.55	0.79	2.1
20.2	0.21	22	9	-0.38	0.31	0.32	0.55	0.79	2.1
22.5	0.23	19	9	-0.22	0.37	0.33	0.56	0.97	3.3
24.7	0.26	15	8	-0.39	0.27	0.34	0.57	0.97	3.3
27.0	0.28	12	7	-0.51	0.21	0.37	0.58	0.91	2.9
29.2	0.30	9	6	-0.43	0.21	0.37	0.55	0.84	2.5
31.5	0.33	6	4	-0.28	0.19	0.36	0.37	0.69	1.5
33.7	0.35	3	2	-0.27	0.17	0.29	0.15	0.61	1.0
36.0 NW	0.38	0	0		0.08	0.26	-0.05	1.04:	3.8:
NGC 1084 $\Omega = 31 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta = 8^\circ.6$ $\Delta r_s = 15''$									
54 SW	0.60	1	1	0.23	0.16			0.71	1.6
29	0.32	38	15	0.07	0.39			0.78	2.1
14	0.16	64	12		0.46	0.25	0.26	0.93	3.1
0	0.00			-0.29	0.58	0.31	0.54	0.82	2.3
11	0.12	68	10			0.25	0.45:	0.80	2.2
22	0.24	53	16	-0.13	0.31	0.41	0.14	0.67	1.4
42 NE	0.47	18	11	0.00	0.13	0.44	0.11	0.60	0.9

TABLE 2 - Continued

$\Delta r''$	ρ	$\Omega - \Omega_p$	$w_\perp$	[OIII]/H β	[NII]/[SII]	H α /[NII]	[NII]/[OII]	H α /H β	A_V
NGC 2403 $\Omega_p = 26 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 19^\circ.9$ $\Delta r_s = 15''$									
254 W	0.29	0	0	0.66				0.38	0.0
196	0.23	7	7	0.21	-0.23	0.60	-0.48	0.53	0.5
170	0.20	10	9	0.34	-0.15	0.55		0.73	1.8
129	0.15	17	11	0.37		0.38		0.39	0.0
120	0.14	16	10	0.56		0.34		0.87	2.7
105	0.12	20	11	0.20	-0.32	0.40	-0.50	0.59	0.8
80	0.09	24	10	0.17		0.59		0.46	0.0
63	0.07	27	9	0.52	-0.28	0.36	-0.40	0.92	3.0
24	0.03	30	4	0.26	-0.13	0.32	-0.59	0.70	1.6
0	0.00			0.33	-0.09	0.11	-0.77	0.65	1.2
18	0.02	30	3	0.29	-0.02	0.36	-0.63	0.93	3.1
36	0.04	30	5	0.18	0.07	0.41	-0.65	0.45	0.0
55	0.06	28	8	-0.17		0.27	-0.49	0.27	0.0
70 E	0.08	26	9		-0.09		-0.97		
NGC 2903 $\Omega_p = 46 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 10^\circ.2$ $\Delta r_s = 15''$									
137 SW	0.33	0	0	-0.15	0.22	0.38	-0.20	0.41	0.0
105	0.25	17	12	-0.38	0.21	0.31	0.15	0.45	0.0
73	0.17	37	18	-0.43	0.35	0.20	0.17	0.55	0.6
48	0.11	51	16		0.37	0.27	0.28		
29	0.07	68	13	-0.05	0.47	0.26	0.15	0.71	1.6
0	0.00						0.55		
74 NE	0.18	37	18	-0.65	0.42	0.35	0.41	0.62	1.0
M 81 $\Omega_p = 15 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 11^\circ.8$ $\Delta r_s = 24''$									
270: E	0.26	38	32	0.05				0.26	0.0
NGC 3593 $\Omega_p = 24 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 5^\circ.4$ $\Delta r_s = 4''.5$									
20 W	0.14	21	5	0.06	0.61			0.96	3.3
18	0.13	25	5	-0.26	0.64	-0.02	0.47	0.98	3.4
16	0.11	29	6	-0.21	0.49	0.20	0.21	1.33	5.7
14	0.10	33	6	-1.19	0.38	0.23	0.35	0.93	3.1
11	0.08	39	5	-0.56	0.38	0.28	0.40	0.91	2.9
9	0.06	44	5	-0.47	0.34	0.32	0.36	0.82	2.3
7	0.05	47	4	-0.54	0.33	0.32	0.34	0.75	1.9
5	0.03	50	3	-0.19	0.37	0.25	0.39	0.84	2.5
2	0.01	> 52		-0.03	0.36	0.22	0.30	1.00	3.5
0	0.00			-0.15	0.31	0.25	0.20	0.99	3.4
2	0.01	> 52		-0.18	0.20	0.28	0.24	0.99	3.4
5	0.03	50	3	-0.44	0.24	0.33	0.35	0.86	2.6
7	0.05	47	4	-0.50	0.32	0.34	0.45	0.85	2.5
9	0.06	44	5	-0.95	0.34	0.29	0.40	0.79	2.1
11	0.08	39	5	-0.73	0.28	0.31	0.27	0.80	2.2
14	0.10	33	6	-0.73	0.34	0.29	0.18	0.77	2.0
16	0.11	29	6	-0.46	0.27	0.26	-0.06	0.80	2.2
18	0.13	25	5	-1.11	0.25	0.23	0.01	0.85	2.5
20	0.14	21	5	-0.51	0.45	0.25	-0.03	0.89	2.8
23	0.16	14	4	-0.76	0.38	0.29	-0.11	1.02	3.6
25	0.17	10	3		0.34	0.27	-0.16	0.79:	2.1:
27	0.19	6	2		0.26	0.35	-0.16		
29 E	0.20	0	0		0.16		0.00		
M51 $\Omega_p = 15 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 11^\circ.7$ $\Delta r_s = 9''$									
64 SW	0.15	44	27	-0.50	0.29	0.50	0.19	0.54	0.5
20	0.05	85	16	0.42	0.32	0.06	0.43	0.96	3.3
11 SW	0.03	77	8	-0.06	0.50	0.27	0.07	0.38	0.0
20 NE	0.05	85	16	-0.10	0.24	0.31	0.24	0.43	0.0
50	0.12	56	26	-0.04	0.41	0.32	0.26	0.82	2.3
60	0.14	47	26	-0.74	0.35	0.40	0.14	0.59	0.9
70	0.16	40	26	-0.94	0.30	0.38	0.82:	0.69	1.5
132	0.31	16	20	-0.42	0.32	0.28	-0.05	0.66	1.3
146 NE	0.34	13	18	-0.02	0.42	0.26	0.02	0.66	1.3

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TABLE 2 - Continued

$\Delta r''$	ρ	$\Omega - \Omega_p$	$w_{\perp}$	[OIII]/H β	[NII]/[SII]	H α /[NII]	[NII]/[OII]	H α /H β	A_v
NGC 6181 $\Omega_p = 46 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 10''$ $\Delta r_s = 3''$									
24	SE	0.29	0	0	0.30		0.35	0.87	3.0
0		0.00			-0.11:		0.43	1.12	4.4
NGC 6503 $\Omega_p = 14 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 16''$ $\Delta r_s = 9''$									
65	NW	0.20	2	2	0.03	0.18	0.40	0.04	0.0
61		0.19	4	4	-0.07	0.18	0.45	0.10	0.0
56		0.17	6	6	-0.20	0.13	0.45	0.18	0.0
52		0.16	8	7	-0.18	0.18	0.39	0.10	0.0
47		0.14	10	8	-0.27	0.19	0.37	0.01	0.0
43		0.13	10	8	-0.19	0.23	0.37	0.17	0.0
38		0.12	18	12	-0.30	0.27	0.33	0.20	0.3
34		0.10	24	14	-0.50	0.35	0.24	0.07	0.0
29		0.09	30	16	-0.42	0.27	0.18	0.23	0.0
25		0.08	38	17	-0.63	0.30	0.10	0.18	0.0
20		0.06	45	16	-0.75	0.36	0.03	0.18	0.0
16		0.05	58	12		0.14	-0.01	-0.02	
11		0.03	64	9		0.08	-0.21	0.02	
7		0.02	> 65			0.21	0.01	0.00	
2		0.01				0.24	-0.07	0.12	
2		0.01				0.26	-0.10	0.19	
7		0.02	> 65			0.24	-0.18	0.33	
11		0.03	64	9		0.28	-0.16	0.16	
16		0.05	58	12		0.18	-0.09	-0.07	
20		0.06	45	16		0.03	-0.05	-0.12	
25		0.08	38	17		0.10	0.13	-0.18	
29		0.09	30	16		0.01	0.25	0.08	
34		0.10	24	14		0.14	0.35	0.16	
38		0.12	18	12		0.10	0.31	0.05	
43		0.13	10	8		0.15	0.29	-0.09	
47		0.14	10	8		0.12	0.37	-0.09	
52		0.16	8	7		0.10	0.37	-0.01	
56		0.17	6	6		0.29	0.21:	-0.22	
61	SE	0.19	4	4		0.31		-0.12	
NGC 7331 $\Omega_p = 8 \text{ km s}^{-1} \text{ kpc}^{-1}$ $\theta_p = 4''.9$ $\Delta r_s = 15''$									
23	SE	0.06	95	14	-0.42	0.38	0.34	0.84	2.5
17	SE	0.04	>100		-0.28	0.29	0.21	1.00	3.5
21	NW	0.05	94	14	-0.31	0.30	0.42	0.99	3.4
31		0.08	86	16	-0.12	0.29	0.24	0.88	2.7
57	NW	0.14	60:	19	0.50:		0.35		

4. The proximity in wavelength of the [O III] and H β transitions, which minimizes uncertainties due to variable instrumental response with wavelength.

There are, however, some possible disadvantages to this choice:

1. The volumes in which H β and [O III] are formed may be significantly different, since the ionization potentials for neutral hydrogen (13.6 eV) and singly ionized oxygen (35.1 eV) differ greatly.

2. As a consequence of the above problem, [O III]/H β may depend not only on the O/H ratio but on the details of the ionizing radiation field and of selective extinction within the ionized region.

3. The ionization characteristics of the disk gas may differ significantly from those which apply in H II complexes. Comte and Monnet (1974) suggest, on the basis of a somewhat indirect argument, that the [O III] may be entirely absent in the disk gas located in the vicinity of H II complexes which show relatively high [O III]/H β ratios. The regions selected for study

here do not appear to suffer significantly from this problem.

4. Models by Talbot and Arnett (1974) suggest that O/H may actually reach a maximum slightly above the solar value and then decrease with further chemical evolution. If this effect is reflected in the behavior of the [O III]/H β ratio, then interpretation of this ratio in metal-rich regions becomes ambiguous.

The [N II]/[O II] ratio also appears, at first glance, to have major advantages as an abundance indicator:

1. The ionization potentials of neutral N (14.5 eV) and neutral O (13.6 eV) are nearly identical; hence, these species should be formed in approximately the same volume.

2. The ratio is also sensitive to T_e and hence to the O/H ratio.

3. Because nitrogen may be formed as a "secondary" nuclear product (from conversion of C and O to N in the CNO cycle), the [N II]/[O II] ratio may be sensitive not only to the overall "metal" abundance

TABLE 3
 GROUP AVERAGED [O III]/H β RATIOS

$\Omega - \Omega_p$	NGC 157	M31	M33	NGC 925	NGC 1084	NGC 2403	NGC 2903	M51	M101	NGC 6503
0-5.....	-0.02	+0.31	+0.81	0.23	+0.21	0.67	-0.30	-0.27	+0.76	+0.10
5-10.....	-0.16	+0.37	+0.42	...	...	0.37	...	-0.61	+0.32	-0.07
10-15.....	-0.16	+0.16	+0.47	...	...	0.37	...	-0.52	-0.40	-0.11
15-20.....	+0.23	-0.12	...	...	-0.01	0.41	-0.38	-0.62	-0.95	-0.18
20-25.....	...	-0.04	-0.10	...	...	0.17	...	...	...	-0.38
25-30.....	...	-0.25	-0.11	...	...	0.23	...	...	...	...
30-35.....	...	-0.31	-0.55	...	+0.04	0.26	...	...	...	-0.30
35-40.....	...	...	...	...	...	...	-0.56	< -1.0	...	-0.51
40-45.....	...	...	...	...	...	...	...	-0.74	...	...
45-50.....	...	...	...	...	...	...	...	-0.75	...	-0.63
50-55.....	...	...	...	...	-0.15	...	...	...	...	...
55-60.....	...	...	...	...	...	...	...	...	...	...
60-65.....	...	...	...	...	...	...	...	< -1.0	...	...
65-70.....	...	...	...	...	...	...	< -1.0	...	...	...

but to the relative abundances of oxygen and nitrogen, which may in turn indicate the degree of processing.

4. The model of Talbot and Arnett (1974) predicts a monotonic increase of N/O with time.

However, there are several difficulties, both intrinsic and technical, which render this choice somewhat less attractive:

1. Both features can be significantly contaminated by night-sky emission. Although our sky-subtraction technique proved highly effective in general, in a few cases, galaxy emission stretched across the entire length of the slit rendering our subtraction procedure useless.

2. In the 4 m spectrograms, the [O II] line was contaminated both by infrared and by ultraviolet night-sky features, since we chose to observe this line simultaneously with H α and [N II] by superposing first and second order spectra.

3. Because the [N II] and [O II] lines appear at such widely separated wavelengths, interstellar extinction corrections become important. In principle, one can estimate a total visual extinction A_v from comparing the observed and theoretical (Brocklehurst 1971) ratios of H α /H β . By assuming a Whitford extinction law, the [N II]/[O II] ratio can then be corrected. However, any systematic departures from the Whitford law, both within and among galaxies, will introduce (unknown) systematic differences in the final [N II]/[O II] ratio. In Table 2, we have included a formal value for A_v computed according to the above prescription. However, we have chosen to present the observed [N II]/[O II] ratios, corrected only for instrumental sensitivity and atmospheric extinction.

Despite these difficulties, our study shows a generally good correlation between the [N II]/[O II] and [O III]/H β line ratios. In Figure 5, we have plotted the [O III]/H β observations listed in Table 2 against our measured [N II]/[O II] ratios. Drawn on the same figure are straight-line fits to the relations between these quantities derived by Smith (1975) and by Searle (1971); the Searle line has been shifted by 0.2 dex in order to correct for the difference between the [N II] line strengths found for NGC 604 (see § III). While the scatter in the figure is somewhat large,

primarily because of the uncertainties in our [N II]/[O II] ratios, it is not substantially greater than the scatter present in both Smith's and Searle's surveys.

Because our data show the same slope and range as those of Smith and Searle, we believe that even though we have observed a more heterogeneous selection of ionized regions, we have not seriously compromised the reliability of [O III]/H β or [N II]/[O II] as abundance indicators.

The [N II]/[S II] ratio also has some value as an enrichment index. To the extent that nitrogen is a secondary nuclear product and sulfur a primary species, this index measures the degree of secondary processing. However, because the ionization potentials of neutral (14.5 eV) and singly ionized (29.6 eV)

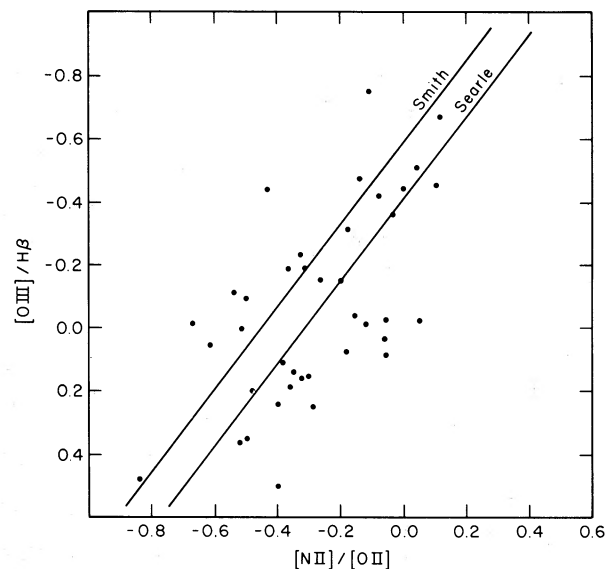


FIG. 5.—A plot of observed log [O III]/H β against the observed log [N II]/[O II] for galaxies in our sample. Superposed on this plot are the mean relations between these emission-line ratios deduced by Smith (1975) and by Searle (1971). No corrections for interstellar reddening have been applied to these ratios.

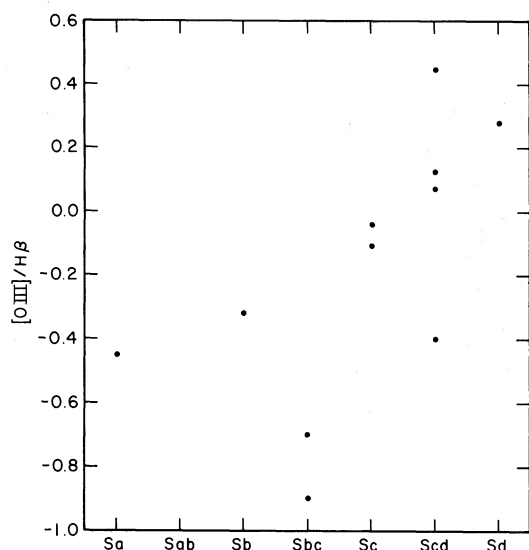


FIG. 6.—A plot of the galaxian mean $\log [\text{O III}]/\text{H}\beta$ against morphological type for the galaxies in our sample.

nitrogen differ significantly from the corresponding values for sulfur (10.4 eV and 23.4 eV), the volumes sampled by the $[\text{N II}]$ and $[\text{S II}]$ may differ.

A consideration of all the above factors led us to adopt the $[\text{O III}]/\text{H}\beta$ ratio as our *primary index* of chemical enrichment. In the discussion which follows, regions of high excitation (large $[\text{O III}]/\text{H}\beta$ ratios) are denoted “metal-poor” whereas low-excitation regions (small $[\text{O III}]/\text{H}\beta$ ratios) are denoted “metal-rich.” While we shall indicate the behavior of $[\text{N II}]/[\text{O II}]$ in metal-rich and metal-poor regions, we will depend most heavily on the $[\text{O III}]/\text{H}\beta$ ratio to select such regions. Because of the well-known difficulties in deriving absolute element abundances from data such as ours (e.g., Sarazin 1976), we are reluctant to phrase our discussion of element enrichment in absolute terms. Rather, we choose to argue our case in terms of an observed parameter ($[\text{O III}]/\text{H}\beta$) which shows considerable promise of providing a transformation to abundance sometime in the future.

V. COMPARISON OF “ENRICHMENT INDICES” WITH THE PREDICTIONS OF DENSITY-WAVE-DRIVEN STAR FORMATION

a) Correlations of Abundance with Galaxy Morphology, Mass, and Normalized Galactocentric Radius

Before embarking on a more elaborate discussion of our data, it is useful to recall two fundamental observational characteristics of intra- and intergalactic abundance indices: (1) the general decrease in mean abundance, as inferred from $[\text{O III}]/\text{H}\beta$, as one examines galaxies of increasingly later morphological type, and (2) the decrease in $[\text{O III}]/\text{H}\beta$ with increasing galactocentric distance.

Both these trends are apparent from visual inspection of the spectrograms reproduced in Figure 2. A more quantitative measure of the first of these

characteristics is illustrated in Figure 6, where the $[\text{O III}]/\text{H}\beta$ ratio averaged over all radii for a given galaxy is plotted against galaxy type. The second is shown in Figure 7 in which we show the variation of $[\text{O III}]/\text{H}\beta$ with a normalized radius parameter, the ratio of radial distance to the Holmberg radius (Holmberg 1958) ρ/ρ_H . In making these plots, (1) we have excluded points which fall within the nuclear bulge regions of the galaxies studied, since we desire to study trends in abundance variations in regions where spiral structure dominates. The excluded regions are denoted by the dashed boundaries in Table 2 and were selected by inspection of galaxy photographs in the *Hubble Atlas* (Sandage 1961), or of those published in conjunction with the rotation curve studies cited in Table 1. (2) We have “binned” our data such that each plotted point represents a mean of all points in a given range (0.1) in ρ/ρ_H in order to minimize “noise” in the mean ratios arising both from observational scatter and from intrinsic variations in these ratios among ionized regions located at the same distance. (3) We have included values of the $[\text{O III}]/\text{H}\beta$ ratios reported by Searle (1971), Smith (1975), and Rubin, Kumar, and Ford (1972) for M31, M33, M51, M101, and NGC 2403.

The correlations summarized in Figures 6 and 7 have been noted by both Searle (1971) and by Smith (1975), and our additional data merely confirm their conclusions.

In § I, we argued that the degree of chemical enrichment is controlled primarily by two factors:

1. Differences in the star formation and consequent gas depletion and chemical enrichment rates driven by differences in the frequency with which disk gas encounters the density-wave pattern; this frequency is proportional to the quantity $(\Omega - \Omega_p)$.

2. Differences in the efficiency per star-forming event related to differences in the compression suffered by the gas in the spiral-arm region. The compression depends on the square of the value of $w_\perp = (\Omega - \Omega_p) R \sin i$ and on the amplitude of the spiral wave; R is the galactocentric distance, and i , the pitch angle of the spiral pattern.

Figures 6 and 7 may be understood crudely in terms of the density-wave picture. Examination of Figure 1, in which $\Omega - \Omega_p$ is plotted against r , reveals a general decrease of $\Omega - \Omega_p$ toward later morphological types. Consequently, we expect fewer star-forming events and less chemical enrichment in these galaxies, if our basic picture is correct. This trend appears confirmed by the data plotted in Figure 6. However, because the magnitude of $\Omega - \Omega_p$ and its variation with normalized radius depends implicitly on the total galactic mass and the mass distribution, we thought it important to determine whether the intergalactic abundance differences are determined primarily by $(\Omega - \Omega_p)$ or by galaxy mass. This check is particularly important because studies of elliptical galaxies (e.g., Faber 1973) suggest a decrease in mean chemical abundance with decreasing galaxy mass. In Figure 8, we plot the galaxian radial mean $[\text{O III}]/\text{H}\beta$ ratio against galaxy mass derived from the rotation curves

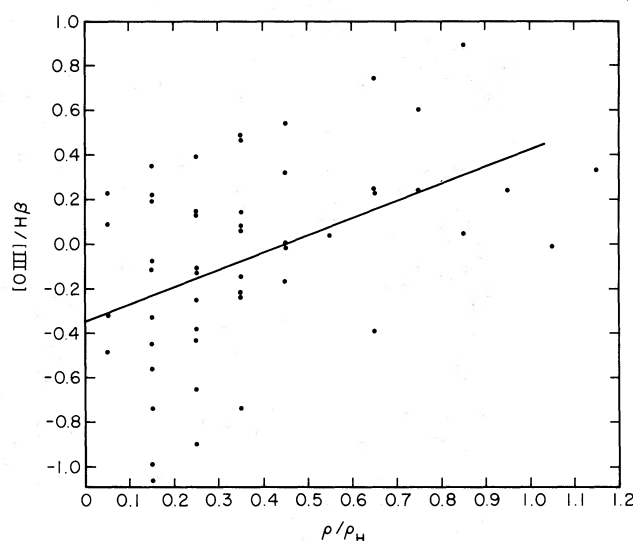


FIG. 7.—A plot of $\log [\text{O III}]/\text{H}\beta$ against the normalized radius parameter ρ/ρ_H , the ratio of observed radial distance to the Holmberg radius. For each galaxy, the $[\text{O III}]/\text{H}\beta$ points represent means of this emission-line ratio for “bins” range of 0.1 in ρ/ρ_H . No points inside the nuclear bulge region are plotted.

and adjusted to the internally consistent distance scale quoted in Table 1. For our sample galaxies, there is no apparent trend in mean chemical abundance with mass. This conclusion confirms and extends the result obtained by Smith (1975).

The decrease of inferred chemical composition at large values of ρ/ρ_H can be understood by reference to Figure 1. The ionized regions studied fall primarily exterior to the maximum in the $(\Omega - \Omega_p)$ versus R curve. Consequently, the number of star-forming events and the degree of enrichment of the remaining disk gas can be related to the decrease of $(\Omega - \Omega_p)$ with increasing normalized radius. However, the decrease of $(\Omega - \Omega_p)$ is also indicative of a decrease

in the surface mass density in the galaxy. It could be argued that the initial gas density in the disk follows the inferred decrease of surface mass density. If one then invokes a star-formation efficiency proportional to some positive power of the local gas density, then the observed trends in abundance enrichment (and gas depletion) can be understood in this way also. None of our subsequent discussion can exclude this possibility. Indeed, density-wave-driven star formation demands a similar trend in the star-formation frequency. However, the predictive power of the density-wave picture permits, in our view, a less ad hoc understanding of the range and absolute value of the inferred disk chemical composition.

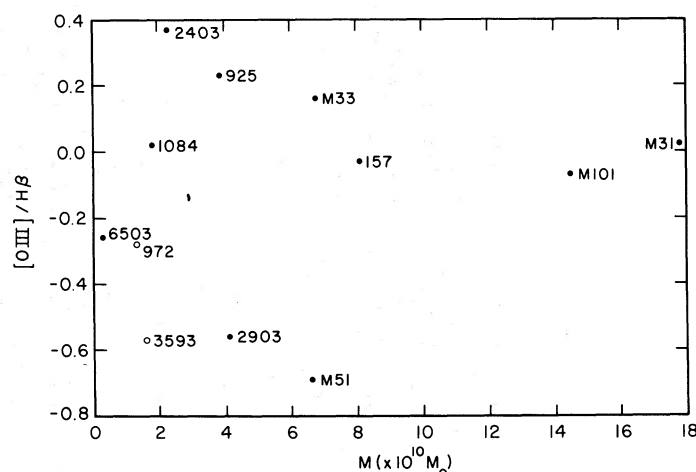


FIG. 8.—A plot of the galaxian mean $\log [\text{O III}]/\text{H}\beta$ as a function of galaxy mass. If the $[\text{O III}]/\text{H}\beta$ ratio is a measure of the mean abundance in a given galaxy, then we conclude that for disk systems in this mass range factors other than the mass play a dominant role in determining the chemical composition.

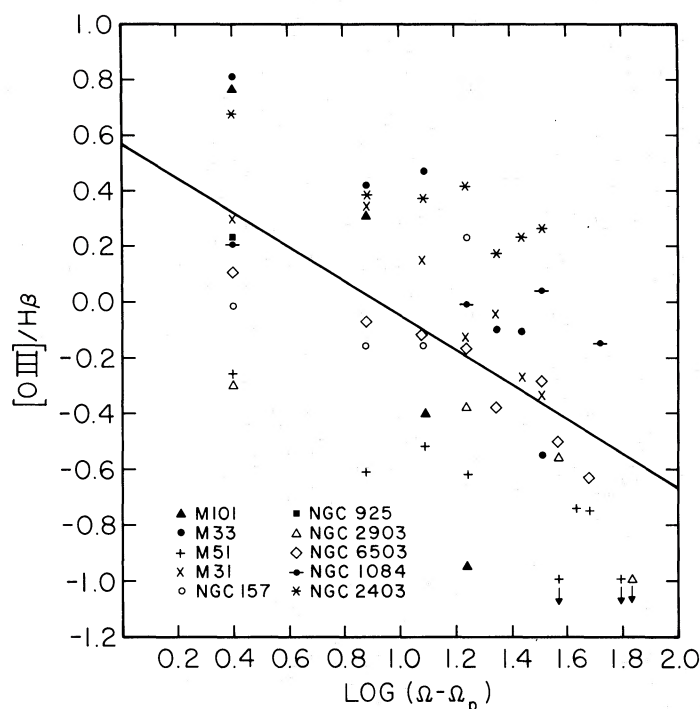


FIG. 9.—A plot of $\log [O III]/H\beta$ measured in our sample galaxies against the quantity $(\Omega - \Omega_p)$. For each galaxy, the plotted points represent the average of $[O III]/H\beta$ line ratios for “bins” of width $5 \text{ km s}^{-1} \text{ kpc}^{-1}$ in $(\Omega - \Omega_p)$. The values of $[O III]/H\beta$ derived by Smith (1975), Searle (1975), and Rubin *et al.* (1972) have also been included. The points observed for each galaxy are plotted using the symbols noted in the lower left-hand corner of the figure. The solid line represents a least-squares regression line fitted to the entire data set. Note the increase of the $[O III]/H\beta$ ratio (lower presumed abundance) in regions of low $(\Omega - \Omega_p)$.

We note, however, that the nuclear bulge regions, thus far excluded from this discussion, in some galaxies (NGC 972, NGC 2903, NGC 3593) exhibit an *increase* in the $[O III]/H\beta$ ratio compared with the values which apply at the innermost manifestation of spiral structure. While the significance of this observation is somewhat uncertain, since the mechanisms of ionization in nuclear bulge regions are not clear, it may suggest that the chemical abundance does not increase monotonically toward the nucleus. If so, this observation further suggests that chemical processing of the disk gas by density-wave-driven star formation may be the dominant factor in determining the run of composition with radius outside the nuclear bulge.

b) Direct Correlations of Abundance with $(\Omega - \Omega_p)$ and Compression Strength

In Figure 9, we plot the observed $\log [O III]/H\beta$ ratios for our sample galaxies against $(\Omega - \Omega_p)$. In this, and in subsequent plots, we have (1) excluded all galaxy regions not judged to show obvious evidence for spiral structure (see § Va), (2) excluded entirely the galaxies NGC 972 and NGC 3593; careful examination of photographs of these galaxies suggests no definite spiral structure in the region sampled by our spectrograms, and (3) “binned” the data so that the plotted points represent averages for $5 \text{ km s}^{-1} \text{ kpc}^{-1}$ intervals in $(\Omega - \Omega_p)$. Table 3 summarizes the binned data used in our analysis.

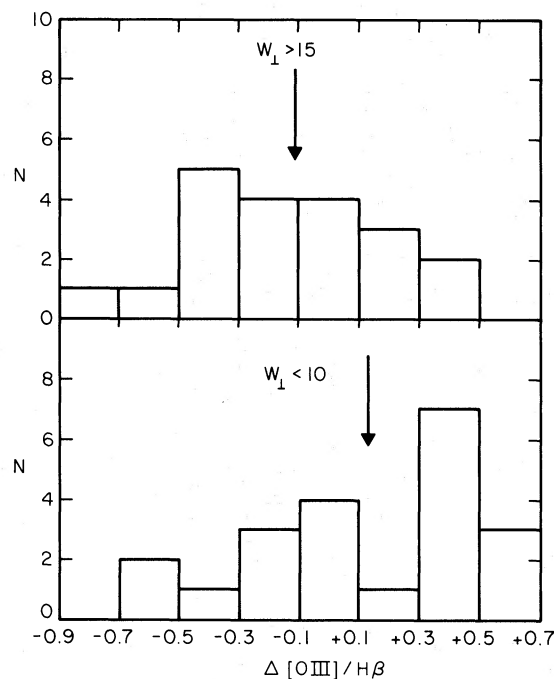


FIG. 10.—Two histograms summarizing the frequency of departures from the mean line plotted in Fig. 7. The upper histogram includes all points with $w_{\perp}$ (the gas velocity normal to the spiral arm) $> 15 \text{ km s}^{-1}$; the lower histogram includes all points with $w_{\perp} < 10 \text{ km s}^{-1}$. The arrows indicate the means of each distribution. Regions of higher $w_{\perp}$ appear to have systematically higher abundances as estimated from $\log [O III]/H\beta$.

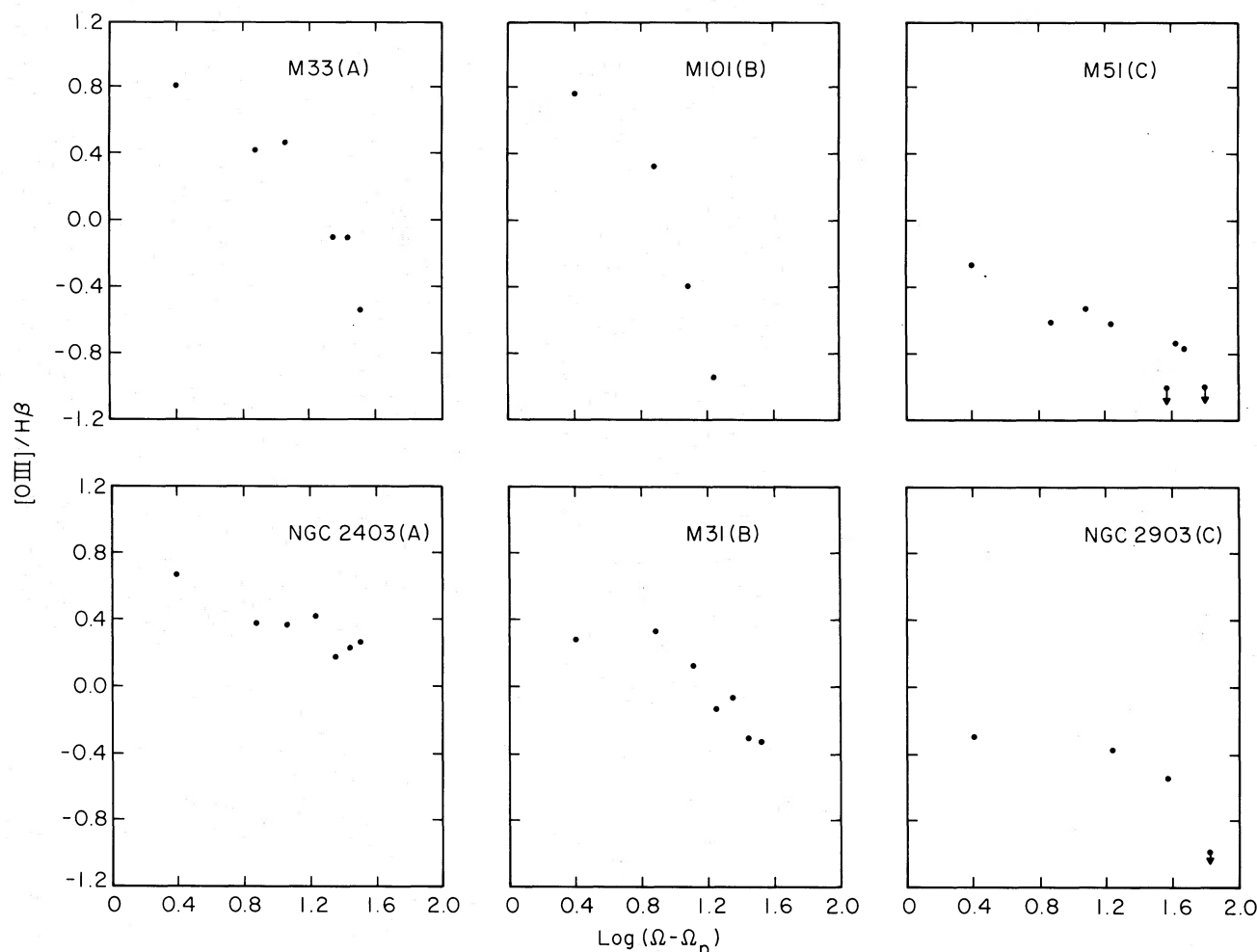


FIG. 11.—A plot of $\log [\text{O III}]/\text{H}\beta$ as a function of $(\Omega - \Omega_p)$ for the six galaxies for which estimates of mean compression are available from van der Kruit (1973). Galaxies characterized by low compression are denoted by A, by intermediate compression by B, and by high compression by C. Note the systematic decrease of the $[\text{O III}]/\text{H}\beta$ values [at equivalent $(\Omega - \Omega_p)$] as the compression increases. This indicates an increase in mean abundance as the mean compression increases.

The linear least-squares regression-line fit to these data plotted in Figure 9 shows a statistically significant correlation between $[\text{O III}]/\text{H}\beta$ and $(\Omega - \Omega_p)$; the correlation coefficient is $r = 0.40$ which, for the number of points fitted (52), suggests a real correlation at the 99 percent confidence level. The relation is in the sense expected from density-wave-driven star formation: regions of low $[\text{O III}]/\text{H}\beta$ (high abundance) correspond, statistically, to regions of high $(\Omega - \Omega_p)$. While the scatter in this figure is at first glance alarmingly high, careful scrutiny of the dependence of $[\text{O III}]/\text{H}\beta$ on $\Omega - \Omega_p$ for individual galaxies in our sample suggests that much of this scatter arises from the superposition of parallel relationships having somewhat similar slopes but displaced relative to one another.

A possible explanation for an increase in measured $[\text{O III}]/\text{H}\beta$ (decrease in abundance) at a fixed $(\Omega - \Omega_p)$ is a decrease in the efficiency of star formation per generation. The density-wave picture implicitly predicts such a decrease if we associate regions of low

compression with regions of low star-formation efficiency. In regions where $w_\perp$ and/or the wave amplitude is low, the compression suffered by the disk gas is low as well. Because neither an *a priori* prediction of wave amplitude nor direct observation of this quantity for the galaxies in our sample is available as yet, we first seek a correlation between $w_\perp$ and the displacement of a given $[\text{O III}]/\text{H}\beta$ measurement from the mean line in Figure 9. In Figure 10, we plot two histograms which summarize the displacement frequency for galaxian regions with $w_\perp > 15 \text{ km s}^{-1}$ and with $w_\perp < 10 \text{ km s}^{-1}$. There is a clear and statistically significant (at the 3σ level) tendency for regions of large $w_\perp$ to have lower $[\text{O III}]/\text{H}\beta$ values (higher abundance) while regions of low $w_\perp$ tend to have higher $[\text{O III}]/\text{H}\beta$ values. Because regions of high $(\Omega - \Omega_p)$ tend to have high $w_\perp$ values and vice versa, the $[\text{O III}]/\text{H}\beta - (\Omega - \Omega_p)$ relationship is fixed at the high $(\Omega - \Omega_p)$ end predominantly by regions of high $w_\perp$, while at low $(\Omega - \Omega_p)$ values, the low $w_\perp$ regions are the major contributors. Thus, by seeking

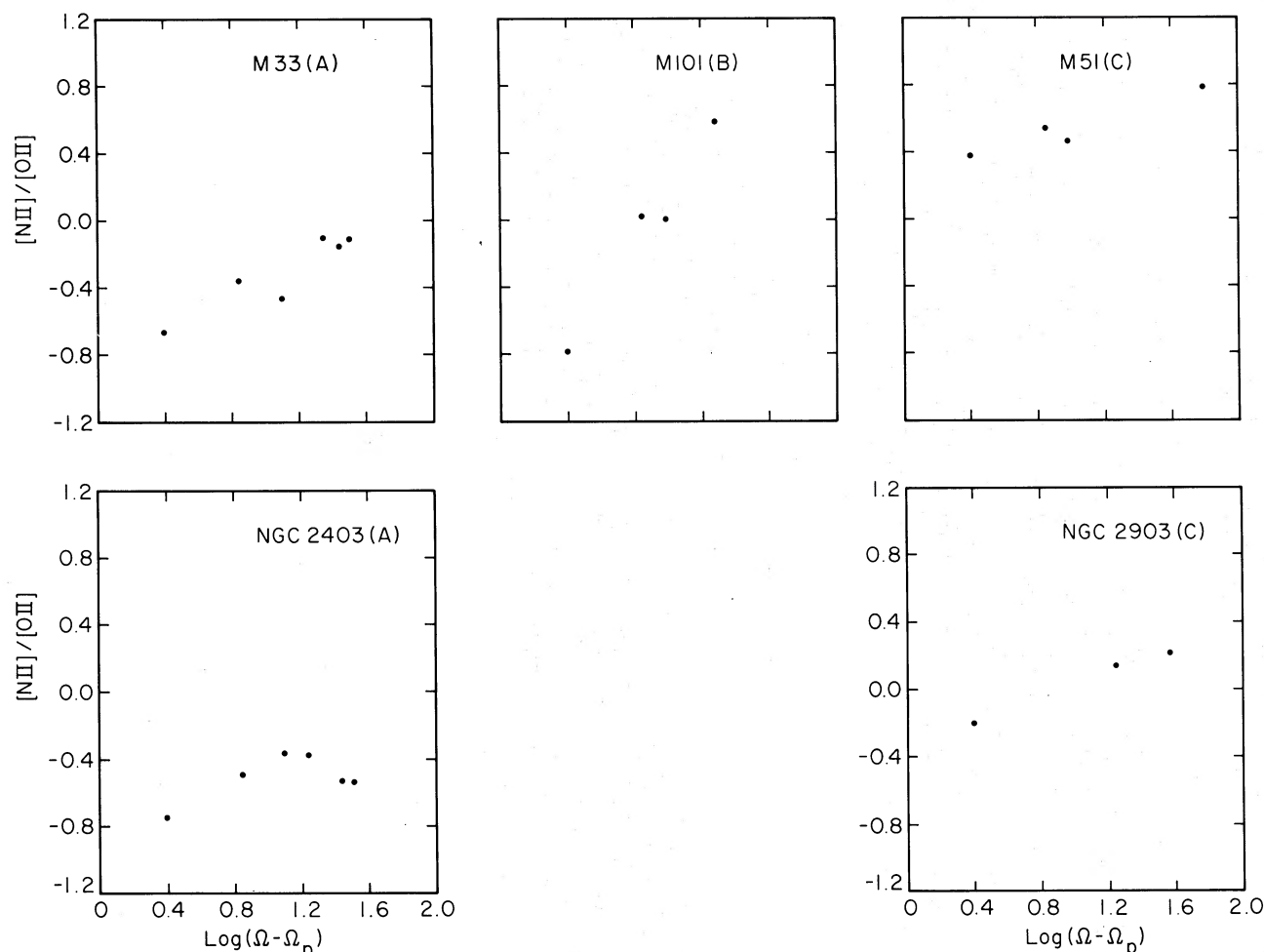


FIG. 12.—A plot similar to Fig. 9 except that $\log [N \text{ II}]/[O \text{ II}]$ is used as the abundance indicator

displacements of individual $[O \text{ III}]/H\beta$ from the mean relationship, we tend to diminish somewhat the separation in terms of $w_{\perp}$. Furthermore, any errors in the adopted galaxian distances will enter linearly in the derived values of $(\Omega - \Omega_p)$, thus shifting all points for a given galaxy parallel to the abscissa of Figure 9.

We regard the evidence presented in Figure 10 as significant support for the belief that regions of greater chemical enrichment are characterized by high values of $w_{\perp}$. A plot of $[O \text{ III}]/H\beta$ against the quantity $w_{\perp}(\Omega - \Omega_p)$ reduces the scatter significantly when compared with Figure 9; however, significant galaxy-to-galaxy displacements remain in this plane as well. This suggests that another parameter which affects compression, such as the wave amplitude, may be needed in order to explain the observed intergalaxian differences in chemical enrichment.

Lacking theoretical or empirical estimates of the wave amplitude, we seek another method for selecting galaxies differing in mean compression. Empirical estimates of mean compression strengths are provided by van der Kruit's (1973) high spatial resolution

measurements with the Westerbork array of the 21 cm continuum surface brightness in the arms and disks of several of our sample galaxies. The observed arm and disk continuum radiation is presumed to arise from synchrotron radiation. An increase in the synchrotron radiation in the arm regions is thought to be caused by an increase in the mean magnetic field which is expected in regions of strong gas compression. The sensitivity of available observations and difficulties with the detailed theoretical interpretation at present preclude a precise statement regarding the degree of compression and its variation across galactic disks. However, van der Kruit's estimates of mean compression strength—(A) for galaxies of low arm-to-disk contrast, (B) for galaxies of intermediate contrast, and (C) for galaxies showing the highest contrast and presumably the highest compression—appear to offer a useful qualitative sorting of our sample.

In Figure 11, we plot the relation between $[O \text{ III}]/H\beta$ and $(\Omega - \Omega_p)$ for the six galaxies in our sample for which compression estimates are available. Examination of this figure reveals a systematic increase in deduced abundance at a given value of

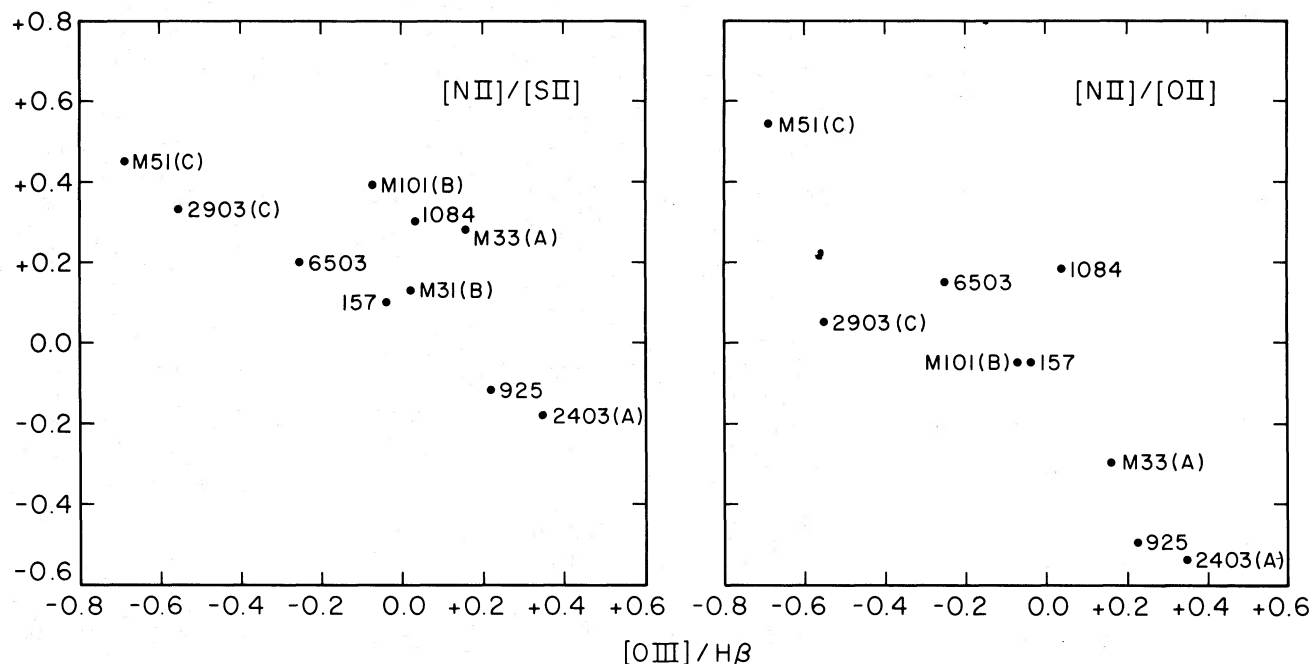


FIG. 13.—A plot of the galaxian mean $\log [N II]/[S II]$ and $\log [N II]/[O II]$ against galaxian mean $\log [O III]/H\beta$. The compression strengths derived by van der Kruit (1973) are indicated in parentheses following the galaxy designation. As expected, the $[N II]/[O II]$ and $[N II]/[S II]$ ratios appear well correlated with our basic abundance index $[O III]/H\beta$.

$(\Omega - \Omega_p)$ as the mean compression increases. This trend is also apparent in Figure 12 where we plot $[N II]/[O II]$ against $(\Omega - \Omega_p)$ for five of these galaxies; no data on the $[N II]/[O II]$ ratio are available for M31. Again, regions of presumed higher chemical enrichment (high $[N II]/[O II]$) are found where both $(\Omega - \Omega_p)$ and the compression are higher. The partially anomalous behavior of M101 in both Figures 11 and 12 may be explicable by a variation in compression strength across the disk, undetectable given the current sensitivity of the Westerbork array at 21 cm. We believe, however, that the bulk of the evidence suggests that for the galaxies in our sample the degree of chemical enrichment increases with increasing $(\Omega - \Omega_p)$, and the enrichment at a given $(\Omega - \Omega_p)$ value is generally higher in regions of high compression.

In Figure 13, we plot the mean galaxian $[N II]/[O II]$ and $[N II]/[S II]$ ratios against the mean values of $[O III]/H\beta$. Galaxies characterized by lower mean $(\Omega - \Omega_p)$ and lower compression again appear to have suffered less chemical processing.

VI. CONCLUSIONS

We have adopted the simplified view that star formation in the disks of spiral galaxies is triggered solely by passage of disk gas through a density wave. The frequency of star-formation events is then proportional to the difference between material and pattern angular speeds, $(\Omega - \Omega_p)$. The efficiency of

star formation is assumed proportional to the compression suffered by the disk gas as it flows through the arm regions. Star-formation frequency and efficiency in turn affect the rate of depletion of disk gas and hence the degree of chemical enrichment at a given radius in the galaxy. The possible influence of (a) infalling material from the halo, (b) enriched material expelled by the nucleus, (c) star formation preceding the formation of the disk, or (d) star formation in the disk not induced by compression in spiral shock regions on the chemical evolution of the disk has been ignored. By assuming that $[O III]/H\beta$ provides a single-valued index of the chemical abundance, we have compared both the absolute abundance level and the radial gradients in abundance with the predictions of the density-wave-driven star-formation picture for sample galaxies. We conclude that chemical abundances are higher in regions of high $(\Omega - \Omega_p)$. Moreover, at a constant $(\Omega - \Omega_p)$, the abundance is higher in regions of higher compression. While other, more ad hoc models can no doubt explain the abundance variations reported here, we believe that our results provide a strong and encouraging consistency check on the predictions of the density-wave model.

Additional observational study of density-wave amplitudes similar to the study by Schweizer (1976) would be of considerable help as a next step toward estimating values of gas compression near the spiral arms. Furthermore, observational and theoretical work on the ionization structure of both disk gas and

individual H II complexes is needed before accurate absolute abundances can be derived. If such results were available, more sophisticated models of disk chemical enrichment and gas depletion could be evolved in the context of the density-wave picture. Estimates of star-formation rates at the present epoch coupled with maps of radial variations in neutral hydrogen surface density would permit further refinement of such models. Further study of abundance distributions in flattened elliptical galaxies and of S0 galaxies may provide plausible limits on the "built-in" disk composition gradients. Combined with the above listed studies, it may then be possible to evolve a working empirical picture of spiral galaxy evolution.

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