THE EXTREME OUTER REGIONS OF DISK GALAXIES. I. CHEMICAL ABUNDANCES OF H II REGIONS

ANNETTE M. N. FERGUSON1,2,3
Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218

J. S. GALLAGHER2
Department of Astronomy, University of Wisconsin at Madison, 475 North Charter Street, Madison, WI 53706

AND

ROSEMARY F. G. WYSE2,3
Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218

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ABSTRACT

We present the first results of an ongoing project to investigate the present-day chemical abundances of the extreme outer parts of galactic disks, as probed by the emission-line spectra of a new sample of H II regions. The galaxies studied here, NGC 628, NGC 1058, and NGC 6946, are all late-type spiral galaxies, characterized by larger than average H I–to–optical sizes. Our deep Hz images have revealed the existence of recent massive star formation, traced by H II regions, out to and beyond two optical radii in these galaxies (defined by the B-band 25th magnitude isophote). Optical spectra of these newly discovered H II regions are used to investigate their densities, ionization parameters, extinctions, and, in particular, their oxygen and nitrogen abundances. Our measurements reveal gas-phase abundances of O/H \( \sim 10\%–15\% \) of the solar value and N/O \( \sim 20\%–25\% \) of the solar value at radii of \( (1.5–2)R_{25} \). Clear evidence also exists for diminished dust extinction \( (A_V \sim 0–0.2 \text{ mag}) \) at large radii. The combination of our measurements of outer disk H II region abundances with those for inner disk H II regions published in the literature is a powerful probe of the shape of abundance gradients over unprecedented radial baselines. The predictions of models of chemical evolution often diverge most strongly in the outer parts of galaxies. Both the oxygen and the nitrogen-to-oxygen abundances generally decrease with increasing radius. Within the limits of the current data set, the radial abundance variations are consistent with single log-linear relationships, although the derived slopes can often differ considerably from those found if only inner disk H II regions are used to define the fit. The small number of H II regions in our present sample, together with uncertainties in the calibrations of the empirical methods used here to determine abundances, limit the ability to constrain both subtle changes in the radial gradient and intrinsic scatter at a fixed radius. Nitrogen-to-oxygen ratios appear to be consistent with a combination of primary and secondary production of nitrogen. Interestingly, both the mean level of enrichment and the N/O ratio measured in extreme outer galactic disks are similar to those values measured in some high-redshift damped Lyα absorbers, suggesting that outer disks at the present epoch are relatively unevolved.

Key words: galaxies: abundances — galaxies: ISM — galaxies: spiral

1. INTRODUCTION

Radial variations in the abundances of elements within galaxies are well-established as providing important constraints on models of disk galaxy formation and evolution (e.g., Pagel & Edmunds 1981; Vila-Costas & Edmunds 1992; Zaritsky, Kennicutt, & Huchra 1994, hereafter ZKH; Prantzos & Aubert 1995). H II regions play a unique role in such studies because they yield relatively reliable elemental abundances from measurements of emission-line intensities. The early work of Searle (1971) and Shields (1974) used observations of H II regions in spirals to establish the existence of negative radial gradients in the abundance of oxygen. Subsequent work has shown that such gradients are a generic feature of disk galaxies, although the magnitude and the shape of the gradient, as well as the characteristic abundance, are observed to vary considerably from galaxy to galaxy (e.g., Vila-Costas & Edmunds 1992; ZKH).

Unfortunately, most H II region abundance studies carried out to date have probed only the bright, easily observed inner regions of galactic disks, lying at or within the classical optical radius, \( R_{25} \) (defined by the B-band 25th magnitude isophote). It is well known, however, that disk galaxies have H I disks that extend to typically \( \gtrsim (1.5–2)R_{25} \) (e.g., Cayatte et al. 1994; Broeils 1994), and in some rare cases to \( \gtrsim 3R_{25} \) (e.g., van der Kruit & Shostak 1984). These outer regions are characterized by low H I columns, high gas fractions, and long dynamical timescales, and thus provide an opportunity to study star formation and chemical evolution in rather unique physical environments. Indeed, the outer regions of disks have physical properties that are reminiscent of those thought to exist during the early stages of galaxy formation, as well as those in giant low surface brightness galaxies, such as Malin 1 (e.g., Pickering et al. 1997). Studying the mean enrichment level, the shape of the abundance gradient, and the amount...
of intrinsic scatter at fixed radius in outer galactic disks will therefore forward our understanding of a broad range of astrophysical objects. Furthermore, since the predictions of models of chemical evolution often diverge most strongly in the outer parts of galaxies, abundance determinations extending as far in the outer disk as possible are needed to discriminate between competing theories.

Only a handful of outer disk H II regions have measured abundances, and of these, very few lie at galactocentric radii significantly beyond the optical radius (e.g., Garnett & Shields 1987; Garnett, Odewahn, & Skillman 1992; Garnett & Kennicutt 1994). The bias of previous studies of H II regions to the inner disk has certainly been due in part to the lack of known H II regions lying at large radii. In the course of a large, deep, Hα imaging survey to search for and study star formation in the extreme outer regions of disk galaxies (Ferguson 1997), we have discovered numerous faint H II regions in the low gas surface density (N_HI ≤ a few times 10²⁰ cm⁻²) outer limits of several galaxies. These H II regions are typically small (diameter ~150–500 pc), of low luminosity [L_Hα ~ (1–10) L_Orion], and do not clump into the giant complexes that populate the inner disks of spiral galaxies. They are often observed to trace out narrow spiral arms, which are sometimes coincident with underlying H I arms and faint stellar arms (μJ ~ 26–28 mag arcsec⁻²). A study of the ongoing and past star formation in the outer disks of these galaxies and its implications for models of disk galaxy evolution will be presented elsewhere (Ferguson et al. 1998a, 1998b).

We present here the first results from a long-slit spectroscopic study to determine the chemical abundances in the extreme outer parts of nearby disk galaxies using the emission-line spectra of some of our newly discovered H II regions. This paper presents results for three late-type spiral galaxies, namely, NGC 628, NGC 1058, and NGC 6946. These galaxies have particularly extended disks of neutral hydrogen and are among our best examples of galaxies with extreme outer disk star formation. A summary of their properties is presented in Table 1. Chemical abundances for H II regions in the inner disks of NGC 628 and NGC 6946 have been derived by McCall, Rybski, & Shields (1985, hereafter MRS). Chemical abundances have not been previously measured for H II regions in NGC 1058, and we present here a study of both inner and outer disk H II regions in that galaxy.

### Table 1

| Property | NGC 628 | NGC 1058 | NGC 6946 | Note |
|----------|---------|----------|----------|------|
| Type | SA(rs)c | SA(rs)c | SAB(rs)cd | 1 |
| Adopted D (Mpc) | 10.7 | 10.0 | 5.3 | 2 |
| M_B | -20.4 | -18.5 | -20.8 | 3 |
| R_25 (arcmin) | 5.2 | 1.5 | 5.7 | 1 |
| R_1 (kpc) | 16.2 | 4.4 | 8.8 | 1 |
| R_H/ R_25 | 2.3 | 3.1 | 2.8 | 4 |
| Star formation rate (M_☉ yr⁻¹) | 4.6 | 0.35 | 2.0 | 5 |

**Notes.**—(1) From the RC3 (de Vaucouleurs et al. 1991). (2) Distances are calculated from the heliocentric velocities through use of the linear Virgocentric infall model of Schechter 1980 with parameters γ = 2, v_0 = 976 km s⁻¹, α_v = 220 km s⁻¹ (Binggeli, Tammann, & Sandage 1987), and D_Vir = 15.9 Mpc (i.e., H₀ = 75 km s⁻¹ Mpc⁻¹). (3) Derived from B_20 as provided in the RC3, assuming the adopted distance. (4) Values for NGC 628 and NGC 6946 are taken from Cayatte et al. 1994, adjusting to the values of adopted here; value for NGC 1058 derived from Dickey, T. & Helou 1990. R_H is calculated to be the radius at which the H I column density has fallen to 10²⁰ cm⁻². (5) Ferguson et al. 1998a.

### 2. Observations

The typical Hα fluxes of the outer H II regions we have identified range from 1–70 x 10⁻¹⁵ ergs s⁻¹ cm⁻², which for reference is roughly 10–1000 times fainter than the usual H II regions in late-type spirals that have previously been studied spectroscopically (e.g., MRS; ZKH). Our strategy was to first target the brightest outer disk H II regions in our sample. The data discussed here were obtained during 1994 November using the KPNO 4 m telescope and the Ritchey-Chrétien spectrograph plus Tektronix CCD. The T2KB chip was run with a gain of 2e⁻ ADU⁻¹ and read noise of ~4e⁻. We used a 2” x 300” slit with a single moderate-resolution grating (KPC-10A; 316 lines mm⁻¹) to cover the wavelength range of 3600–7500 Å, with spectral resolution of ~7 Å. The grating was used in first order with an order-blocking filter (WG 345) to eliminate second-order blue light from below ~3200 Å. The seeing was typically 1.5–2”. Of the three nights of our run, two nights were mostly clear, hampered only by light to moderate cirrus during the later parts of each night, but the third night was completely lost. In this paper, we discuss measurements of H II regions in the disks of NGC 628, NGC 1058, and NGC 6946.

Blind offsets were required for all of our target outer H II regions. These were derived from deep narrowband images obtained using the KPNO 0.9 m and Lowell 1.8 m telescopes and were based on either nearby bright stars or the nucleus of the galaxy. The images were astrometrically calibrated using a grid of stars measured on the digitized POSS plates and are accurate to ≤0.5”.

Individual exposure times were 30 minutes per region, and we usually obtained two to four exposures per target region, depending on the faintness of the target. Experience indicated that if no metal lines were detected in a single 30 minute exposure, then there was negligible chance of obtaining useful data for abundance determinations by stacking additional exposures. Most
Fig. 1.—Hα continuum-subtracted image of NGC 628 obtained using the KPNO 0.9 m telescope, with the target H II regions identified. R25 is marked. North is to the top, and east to the left.

### TABLE 2

Properties of Observed H II Regions

| Our ID     | Other IDs       | X (arcsec) | Y (arcsec) | R/R25 (pc) | D (pc) | F(Hα) (ergs s⁻¹ cm⁻²) | L(Hα) (ergs s⁻¹) | N (O5 V) |
|------------|-----------------|------------|------------|------------|--------|------------------------|------------------|----------|
| FGW 628A   | MRS NGC 0628 (−074 −022), HK 451 | −73        | −29        | 0.25       | 970    | 1.8 × 10⁻¹³            | 2.4 × 10¹⁰       | 52       |
| FGW 628B   | HK 330          | 231        | 3          | 0.74       | 1500   | 1.9 × 10⁻¹³            | 2.6 × 10¹⁰       | 57       |
| FGW 628C   | ...             | −260       | 239        | 1.14       | 360    | 7.5 × 10⁻¹⁵            | 1.0 × 10¹⁰       | 2        |
| FGW 628D   | ...             | 144        | −326       | 1.14       | 290    | 6.1 × 10⁻¹⁵            | 8.3 × 10⁹        | 3        |
| FGW 628E   | ...             | 190        | 357        | 1.30       | 430    | 1.1 × 10⁻¹⁴            | 1.5 × 10¹⁰       | 3        |
| FGW 628F   | ...             | 495        | 209        | 1.73       | 470    | 1.9 × 10⁻¹⁴            | 2.7 × 10¹⁰       | 3        |
| FGW 1058A  | ...             | 10         | −15        | 0.20       | 700    | 8.2 × 10⁻¹⁴            | 9.8 × 10⁹        | 21       |
| FGW 1058B  | ...             | −20        | −12        | 0.26       | 240    | 3.0 × 10⁻¹⁴            | 3.6 × 10⁹        | 8        |
| FGW 1058C  | ...             | −35        | −10        | 0.41       | 550    | 5.7 × 10⁻¹⁴            | 6.9 × 10⁹        | 15       |
| FGW 1058D  | ...             | −10        | −53        | 0.60       | 410    | 4.3 × 10⁻¹⁴            | 5.1 × 10⁹        | 11       |
| FGW 1058E  | ...             | −10        | −92        | 1.03       | 550    | 6.8 × 10⁻¹⁴            | 8.1 × 10⁹        | 18       |
| FGW 1058F  | ...             | −114       | −12        | 1.28       | 170    | 1.8 × 10⁻¹⁵            | 2.1 × 10¹⁰       | 1        |
| FGW 1058G  | ...             | −9         | −169       | 1.88       | 360    | 5.9 × 10⁻¹⁵            | 7.1 × 10¹⁰       | 2        |
| FGW 1058H  | ...             | 148        | 89         | 1.93       | 260    | 5.8 × 10⁻¹⁵            | 6.9 × 10⁹        | 2        |
| FGW 6946A  | MRS NGC 6946 (+182 +103), HK 29 | 182        | 107        | 0.61       | 460    | 3.4 × 10⁻¹³            | 1.1 × 10¹⁰       | 25       |
| FGW 6946B  | HK 16           | 215        | 39         | 0.65       | 370    | 2.1 × 10⁻¹³            | 7.1 × 10⁹        | 15       |
| FGW 6946C  | ...             | −481       | −38        | 1.50       | 195    | 1.1 × 10⁻¹⁴            | 3.5 × 10⁹        | 1        |

Notes.—Col. (1): H II identification used in this work. Col. (2): cross identifications—MRS indicates those H II regions observed in the MRS study, and HK refers to the Hodge & Kennicutt (1983) atlas of H II regions; approximate offset of the H II region with respect to the galaxy nucleus is given in cols. (3) (east positive) and (4) (north positive). Col. (5): deprojected galactocentric distance, expressed in terms of the optical radius, R25. Col. (6): diameter. Col. (7): observed Hα flux. Col. (8): Hα luminosity, calculated using the distances presented in Table 1 and with no correction made for internal extinction. Col. (9): approximate number of O5 V stars enclosed, assuming ionization bounded H II regions, and the Lyman continuum fluxes presented in Vacca et al. 1996.
objects were observed at low air mass, and we rotated the slit to parallactic angle whenever possible to eliminate the loss of blue light. We also attempted to position the slit in such a manner as to include as many H II regions as possible, but the small angular size, faintness, and relative isolation of our outermost targets made this difficult. Spectra of HeNeAr lamps were obtained before and after each object exposure, and we made multiple observations of standard stars from the list of Massey et al. (1988).

In Figures 1–3, we show continuum-subtracted Hz images of each galaxy with the target H II regions identified. Table 2 lists the identifications, positions, and properties of our sample of H II regions. The diameters and fluxes presented are approximate and are intended simply to illustrate the range in physical properties that exists within our sample. In particular, it is very difficult (and subjective) to assign sizes and fluxes to inner disk H II regions, which often are part of large complexes composed of many “cores.” We have not corrected the fluxes and luminosities for the effects of internal extinction. Most of the outer disk H II regions in our sample have luminosities consistent with their being ionized by only a few equivalent O5 V stars, as calculated using the Lyman continuum fluxes in Vacca, Garmany, & Shull (1996); these estimates are strictly lower limits to the
number of enclosed massive stars, since the H II regions may
well not be ionization bounded (see, e.g., the discussion of
the origins of diffuse ionized gas by Ferguson, Wyse, &
Gallagher 1996a and Ferguson et al. 1996b). Two inner disk
H II regions from the sample of are included in our
sample in order to provide an external consistency check on
our measurements.

3. DATA ANALYSIS

Preliminary data reduction was carried out using stan-
dard procedures. A DC offset was subtracted from each
frame using the overscan region. Bias frames and quartz
lamp exposures were used to remove any residual structure
in the DC offset and pixel-to-pixel gain variations, respec-
tively. Dark frames were also obtained, but the dark current
was found to be negligible, and the frames were not utilized
in the analysis. Exposures of the twilight sky were obtained
to map out the illumination pattern along the slit and
flatten the data in the spatial direction.

One-dimensional spectra were extracted with apertures
ranging in size from 3′ to 15′, depending on the seeing and
on the size and brightness of the object in question. The sky
to be subtracted was selected from adjacent regions and
fitted with a low-order polynomial. An important step in
the extraction process is mapping the location of the spec-
trum at each point along the dispersion axis. In the bright-
est H II regions observed, this “trace” could be well defined
and revealed only a small amount of distortion from the
blue to the red, which was typically much less than the size
of the extraction box. Only a weak continuum, if any, was
present in the outer disk H II regions, however. In those
cases where we could not trace the continuum along the
entire dispersion axis, we chose to fit a low-order poly-

ominal anchored to the position of one of the brightest lines
present. The individual extracted spectra were wavelength-
calibrated using HeNeAr exposures, with the typical accu-

racy of the transformation being a few tenths of a pixel, or,
equivalently, ~0.5 Å. Flux calibration was carried out by
using observations of standard stars (with the same slit
width as our program objects), and the sensitivity functions
showed residuals of only ~0.02–0.03 mag (after a zero-
point offset). At this point, individual spectra of the same
H II region were checked for consistency and then averaged
together. Spectra that had been dispersion-corrected, but
not flux-calibrated, were also averaged for the purpose of
computing uncertainties in the line intensities. In Figure 4,
we present extracted, combined, calibrated spectra for four
H II regions in NGC 1058 that are representative of the
typical spectra obtained in this study.

Inspection of the spectra reveals the presence of many
emission lines. Most prominent are the bright oxygen,
nitrogen, and sulfur lines, as well as the Balmer lines of
hydrogen. In addition, several H II region spectra show
detections of fainter lines, such as those due to helium,
argon, neon, and in some cases neutral oxygen. We focus here on only those bright lines that lead to determinations of the oxygen and nitrogen abundances through the semiempirical methods discussed in § 4.2. Emission-line fluxes were measured via Gaussian fits to the line profiles. The logarithmic extinction at H$\beta$, $C(H\beta)$, was derived from measurements of the Balmer lines, using the equation

$$\frac{I_b}{I_{H\beta}} = \frac{F_b}{F_{H\beta}} 10^{C(H\beta) / f(\lambda)},$$

where $I_b$ is the intrinsic line flux, $F_b$ is the observed line flux, and $f(\lambda)$ is the Galactic reddening function normalized to H$\beta$. The reddening function of Seaton (1979) was adopted, as parameterized by Howarth (1983), and assuming $R \equiv A_v/E(B-V) = 3.1$. Intrinsic Balmer line ratios were taken from Osterbrock (1989), assuming an electron density of $N_e = 100$ cm$^{-3}$ and an electron temperature $T_e = 10^4$ K. The determination of the amount of underlying stellar Balmer absorption is an important concern in the estimation of the required extinction correction. Our data are of insufficient signal-to-noise ratio to determine the absorption equivalent width directly, so we adopted the standard approach of assuming a correction of 2 Å to the measured equivalent width due to underlying stellar absorption (e.g., MRS; Oey & Kennicutt 1993), and we proceeded to derive the logarithmic extinction at H$\beta$ based on the H$\beta$ and Hx lines alone. We also corrected the forbidden line/H$\beta$ ratios for the effects of underlying H$\beta$ absorption, but this is generally a small effect since most spectra have moderate to large H$\beta$ equivalent widths.

Formal errors in the derived line ratios were determined by summing in quadrature the statistical noise from the number of counts, the uncertainty in the continuum placement (proportional to the width of the line times the rms in the nearby continuum, corrected for the effects of pixelization), and the uncertainty in the flux calibration. In addition, the error in the $C(H\beta)$ term was accounted for when deriving extinction-corrected line ratios. Tables 3–5 present the observed line intensities, both uncorrected and corrected, for reddening and Balmer absorption, as well as some relevant line ratios for our sample of H II regions. Formal errors on the quantities are indicated in parentheses.

### 4. DERIVING NEBULAR ABUNDANCES

#### 4.1. Direct Method

The “direct” method for determining chemical compositions from nebular emission lines requires a knowledge of the electron temperature (and density) of the emitting gas in order to transform reddening-corrected emission-line ratios to ionic abundance ratios and, finally, to elemental abundances (e.g., Osterbrock 1989). The electron temperature $T_e$ is commonly derived from the O$^{++}$ ion, via the ratio

$$\frac{[O III] \lambda 4959 + [O III] \lambda 5007}{[O III] \lambda 4363} = \frac{7.73 \times 10^4}{1 + 4.5 \times 10^{-4}N_e/T_e^{1/2}}$$

(Osterbrock 1989). Unfortunately, the temperature-sensitive line [O III] $\lambda 4363$ is typically very weak in extragalactic H II regions and decreases in strength rapidly with increasing abundance; as a result, this method is limited to only the hottest (i.e., most metal-poor) and brightest objects. The faintness of our outer disk H II regions, coupled with the low signal-to-noise ratio of our spectroscopy, severely limit the detectability of this key diagnostic line. A marginal detection of [O III] $\lambda 4363$ was made in one of the individual spectra we obtained for the brightest outer disk H II region of our sample, 1058E, but the significance of the detection is low. It can be used only to place an upper limit on the electron temperature of the region and, hence, a lower limit on the oxygen abundance. We measure [O III] $\lambda 4363$/H$\gamma \lesssim 0.067$, which, when combined with measurements of the [O III] $\lambda 4959$, 5007 lines, translates into an upper limit of 12,700 K on the temperature in the O$^{++}$ zone (assuming $N_e = 100$ cm$^{-3}$), and a lower limit on the oxygen abundance of log(O/H) $\gtrsim -4.07$ (both derived using the FIVEL program [de Robertis, Dufour, & Hunt 1987] as implemented in IRAF). As shown below, this limit is consistent with the abundance derived via the semiempirical method.

#### 4.2. Semiempirical Methods

Fortunately, in the absence of a reliable [O III] $\lambda 4363$ detection, there exist alternative methods for deriving nebular abundances that rely on observations of the bright lines alone (e.g., Pagel et al. 1979; Skillman 1989; McGaugh 1991; Thurston, Edmunds, & Henry 1996). Empirical methods to derive the oxygen abundance exploit the interrelationship between O/H, $T_e$, and the intensities of the strong lines, [O II] $\lambda 3727$ and [O III] $\lambda 4959$, 5007, via the parameter

$$R_{23} \equiv \frac{[O II] \lambda 3727 + [O III] \lambda 4959, 5007}{H\beta}.$$
As O/H decreases, the cooling efficiency of the nebular gas drops because there are fewer metal ions, and as a result $T_c$ increases. This leads to a substantial brightening in the 4959 and 5007 Å lines and, hence, an increase in $R_{23}$. On the other hand, as O/H increases cooling becomes more efficient, leading to a decrease in $T_c$. Most of the cooling then occurs through the fine-structure IR lines at 52 and 88 μm, leading to a decrease in the strength of the optical $[\text{O \ II}]$ lines and therefore in $R_{23}$. These variations in $[\text{O \ III}]$ line strength can clearly be seen in the representative spectra shown in Figure 4, which are stacked in order of decreasing metallicity. This simple relationship between $R_{23}$ and O/H is complicated by the fact that at low O/H (~30% solar), the sheer lack of oxygen causes the bright lines (and hence $R_{23}$) to decrease as O/H decreases, because of the growing importance of Ly$\alpha$ cooling (Edmunds & Pagel 1984). As a result, while a single value of $R_{23}$ can uniquely specify O/H over most of the range in metallicity, there is a turnover region (20%–50% solar) where the relationship becomes double valued.

There have been several calibrations of the $O/H - R_{23}$ relationship over the past years, based on both observations of H II regions with known abundances and the results of photoionization models (e.g., Edmunds & Pagel 1984; MRS; Dopita & Evans 1986; Skillman 1989; McGaugh 1991; ZKH). Of particular importance for the present study is the calibration at the low-abundance end [log (O/H) < 3.8] and in the turnover region [3.4 ≥ log (O/H) ≥ 3.8], where a single value of $R_{23}$ corresponds to two values of O/H. Skillman (1989) and McGaugh (1991) have illustrated the importance of accounting for the ionization state of the nebula in deriving an abundance estimate at low metallicities; however, only the McGaugh calibration takes explicit account of this (see McGaugh 1994). McGaugh's calibration has the further advantages that with it one can predict oxygen abundances on both upper and lower branches of the O/H-$R_{23}$ relation and, also, the volume-averaged ionization parameter $U$, defined as

$$ U = \frac{Q}{4\pi R_S^2 N_c} $$

where $Q$ is the ionizing photon luminosity, $R_S$ is the radius of the Strömgren sphere, $N_c$ is the number density of the gas, and $c$ is the speed of light. For these reasons, we have adopted this calibration here.

Several methods have been proposed by which to distinguish between upper and lower branches for objects with values of $R_{23}$ that place them in the double-valued region.
McGaugh (1994) advocates the use of the $[\text{N} \, \text{ii}] \lambda 6584/\text{O} \, \text{ii}] \lambda 3727$ ratio, noting that it varies monotonically with O/H and that it is not very sensitive to the ionization parameter $U$, since the two ions have similar ionization potentials. The division between upper and lower branches of $R_{23}$ is fairly well defined, with $\log ([\text{N} \, \text{ii}] / [\text{O} \, \text{ii}] ) > -1$ (reddening corrected) indicating the upper branch and $\log ([\text{N} \, \text{ii}] / [\text{O} \, \text{ii}] ) < -1$ indicating the lower branch. Another diagnostic that has been used in the literature is the value of the line ratio $[\text{O} \, \text{iii}] / \text{[N} \, \text{ii}]$ (e.g., Skillman 1989), with the transition between upper and lower branches occurring at $\log ([\text{O} \, \text{iii}] / [\text{N} \, \text{ii}] ) = -2$. While this parameter also varies monotonically with abundance, it is sensitive to the ionization parameter and is thus of limited use in the low-abundance regime, where such effects are important.

In Figure 5, we plot our H II regions on the model grid of $\log (\text{O/H})$ versus $\log R_{23}$ from McGaugh (1991). One can clearly see the effect of the ionization parameter, $U$, in the turnover region and on the lower branch. All models converge toward a single upper branch, reflecting the fact that

| LINE          | FGW 1058A | FGW 1058B | FGW 1058C |
|---------------|-----------|-----------|-----------|
| $[\text{O} \, \text{iii}] \lambda 3727$ | 1.368 (0.037) | 1.857 (0.130) | 1.223 (0.030) | 1.452 (0.097) | 1.272 (0.037) | 1.595 (0.113) |
| $\text{H}_b$ (4861 Å) | 1.000 (0.038) | 1.000 (0.038) | 1.000 (0.034) | 1.000 (0.034) | 1.000 (0.037) | 1.000 (0.037) |
| $[\text{O} \, \text{iii}] \lambda 4959$ | 0.018 (0.007) | 0.017 (0.007) | 0.019 (0.005) | 0.019 (0.005) | 0.016 (0.009) | 0.016 (0.009) |
| $[\text{N} \, \text{ii}] \lambda 6584$ | 0.120 (0.010) | 0.115 (0.010) | 0.206 (0.008) | 0.201 (0.008) | 0.274 (0.012) | 0.265 (0.012) |
| $[\text{S} \, \text{ii}] \lambda 6717$ | 0.341 (0.015) | 0.233 (0.021) | 0.394 (0.014) | 0.318 (0.027) | 0.303 (0.013) | 0.229 (0.021) |
| $[\text{S} \, \text{ii}] \lambda 6731$ | 4.130 (0.148) | 2.820 (0.249) | 3.529 (0.118) | 2.847 (0.239) | 3.791 (0.132) | 2.856 (0.251) |

**Rainbow**

| LINE          | FGW 1058D | FGW 1058E | FGW 1058F |
|---------------|-----------|-----------|-----------|
| $[\text{O} \, \text{iii}] \lambda 3727$ | 1.965 (0.047) | 2.381 (0.157) | 2.739 (0.064) | 3.025 (0.196) | 2.511 (0.085) | 2.790 (0.252) |
| $\text{H}_b$ (4861 Å) | 1.000 (0.034) | 1.000 (0.034) | 1.000 (0.033) | 1.000 (0.033) | 1.000 (0.053) | 1.000 (0.053) |
| $[\text{O} \, \text{iii}] \lambda 4959$ | 0.219 (0.008) | 0.215 (0.008) | 0.786 (0.026) | 0.779 (0.026) | 0.932 (0.050) | 0.923 (0.049) |
| $[\text{N} \, \text{ii}] \lambda 6584$ | 0.512 (0.018) | 0.499 (0.018) | 2.298 (0.076) | 2.267 (0.077) | 2.735 (0.126) | 2.695 (0.128) |
| $[\text{S} \, \text{ii}] \lambda 6717$ | 3.616 (0.120) | 2.844 (0.237) | 3.231 (0.106) | 2.854 (0.235) | 3.534 (0.162) | 3.100 (0.0354) |
| $[\text{S} \, \text{ii}] \lambda 6731$ | 0.219 (0.008) | 0.215 (0.008) | 0.786 (0.026) | 0.779 (0.026) | 0.932 (0.050) | 0.923 (0.049) |

| LINE          | FGW 1058G | FGW 1058H |
|---------------|-----------|-----------|
| $[\text{O} \, \text{iii}] \lambda 3727$ | 4.133 (0.101) | 4.251 (0.297) | 4.150 (0.052) | 2.019 (0.142) |
| $\text{H}_b$ (4861 Å) | 1.000 (0.037) | 1.000 (0.037) | 1.000 (0.037) | 1.000 (0.037) |
| $[\text{O} \, \text{iii}] \lambda 4959$ | 0.114 (0.010) | 0.110 (0.013) | 0.099 (0.009) | 0.095 (0.011) |
| $[\text{N} \, \text{ii}] \lambda 6584$ | 2.943 (0.103) | 2.842 (0.252) | 2.980 (0.106) | 2.853 (0.254) |
| $[\text{S} \, \text{ii}] \lambda 6717$ | 0.321 (0.015) | 0.310 (0.029) | 0.179 (0.009) | 0.171 (0.017) |
| $[\text{S} \, \text{ii}] \lambda 6731$ | 0.242 (0.017) | 0.255 (0.053) | 0.238 (0.011) | 0.228 (0.023) |

* Emission-line equivalent width, measured in angstroms.
outer disk H regions cluster around the “knee” of the calibration. We have also overlapped a heterogeneous sample of H regions that have oxygen abundances determined in the literature via the “direct” method (see § 5.2 for a discussion of this sample). The objects in this sample populate the same general region of the diagram as H regions in our sample. As discussed in detail below, comparison of the abundances determined via the “direct” method and via the model calibration for this sample shows very good agreement. Thus, the McGaugh calibration generally provides reliable abundance estimates for objects that lie in this region of the diagram.

Nitrogen-to-oxygen abundances (N/O) may be determined in the absence of a measurement of the strength of H regions that have oxygen abundances determined in the literature via the “direct” method (see § 5.2 for a discussion of this sample). The objects in this sample populate the same general region of the diagram as H regions in our sample. As discussed in detail below, comparison of the abundances determined via the “direct” method and via the model calibration for this sample shows very good agreement. Thus, the McGaugh calibration generally provides reliable abundance estimates for objects that lie in this region of the diagram.

In Table 6, we list the derived oxygen and nitrogen-to-oxygen abundances for our sample, as well as the mean volume-averaged ionization parameter, derived by our adopted techniques.

5. Uncertainties

The uncertainties in the derived metallicities are a combination of both measurement errors and the intrinsic uncertainties in the model calibrations. As we show below, various tests reveal that the formal errors on the line strengths appear to underestimate considerably the actual uncertainties in the line ratios and in the final derived chemical abundances and, thus, are of limited use for understanding the intrinsic uncertainty in our abundance estimates.

5.1. Measurement Errors

Measurement errors can arise from a variety of causes, such as extraction, sky subtraction, varying sky conditions, and profile fitting. We investigated the magnitude of the measurement errors in our data by conducting a series of experiments. First of all, we compared the line intensity measurements as derived from two different techniques—Gaussian fitting and direct integration under the line profile. Defining the “mean fractional difference” to be the result from either method minus the mean, divided by the mean, we find values of 1% ± 3%. While the mean fractional difference was greatest at the smallest fluxes, it is still less than 10%. Next we compared line strength measurements.
for those H II regions for which we had obtained multiple spectra (which were subsequently combined). Since multiple observations of a given H II region were always made consecutively, this comparison should not be influenced to a great extent by slit positioning. Considering only those lines that are well detected, we calculate the mean fractional difference from multiple line measurements to be 8% ± 10%.

Fainter lines tend to show more scatter than strong lines; for example, \([\text{O III}]\) 4959 and \([\text{N II}]\) 6584/6548 have mean fractional differences of ~15%. A conservative estimate of the uncertainties in the individual line strengths inferred from this comparison is ±10%, from which we expect uncertainties of ~15% in the line ratios.

We also calculated the mean values of the ratios \([\text{O III}]\) λ5007/λ4959 and \([\text{N II}]\) λ6854/λ6548 for the H II regions in our sample. Since these ratios have a fixed theoretical value, comparison of our sample average with the expected values provides an additional gauge of our measurement errors. Considering again only those lines that are well detected, we find \(\langle[\text{O III}]\rangle = 2.88\) with standard deviation 0.31 and \(\langle[\text{N II}]\rangle = 2.96 ± 0.39\), which compare favorably to the theoretical values of 2.88 (Nussbaumer & Storey 1981) and 2.95 (Mendoza & Zeippen 1981), respectively.

As a final check on measurement errors, we included in our sample two H II regions that were observed by MRS. Despite the likely differences in pointings and aperture sizes employed, we find an excellent agreement in the values of \(R_{23}: \Delta \log R_{23} = 0.144\) for FGW 628A [MRS identification NGC 6028 (−074−022)] and −0.068 for FGW 6496A [MRS NGC 6946 (+182+103)]. These differences in \(R_{23}\) lead to differences of only −0.08 and 0.07 dex in log (O/H), and −0.16 and 0.08 in log (N/O).

In summary, these various tests reveal that our measurement errors are small, and we conservatively estimate line ratios to be accurate to better than 15%, or ~0.1 dex.

5.2. Calibration Errors

The dominant source of uncertainty in our results is without a doubt that due to the model calibrations of the semiempirical relationships between line strength and elemental abundance. Propagating the formal errors on the line strengths through the equations used to derive the abundances produces formal errors on the metallicities of only ~0.05 dex. As we discuss below, the uncertainty in the absolute value of the calibration is likely to be larger than this.

Uncertainties in the calibration arise from the limitations in the inputs to the models used to construct the calibration, and from the ability of the calibration to reproduce model input data and, indeed, to reproduce the values of chemical abundances that have been determined via a measurement of the electron temperature. As discussed by McGaugh (1994), while these uncertainties can have an important effect on the absolute metallicities derived, they have a much smaller impact on the relative values.

One of the most important input parameters is the shape of the ionizing spectrum, which depends on both the mass and the metallicity of the ionizing stars (McGaugh 1991). McGaugh (1991) treats this problem by assuming that a cluster containing several tens of OB stars is responsible for the ionization, which, when averaged over, produces a constant ionizing spectrum, relatively insensitive to both the metallicities and individual effective temperatures of the enclosed stars and, hence, the initial mass function. We note however that many of our outer disk H II regions, if ionization bounded, are consistent with ionization by only a few massive stars (see Table 2), and hence the assumptions that have gone into McGaugh's calibration may not be entirely appropriate for the objects under study here.

Concerning the ability of the calibrations to reproduce model input data, both McGaugh (1994) and Thurston et al. (1996) report relative uncertainties of 0.1–0.2 dex over a wide range in metallicities. In the turnover region, where \(R_{23}\) is double valued, McGaugh (1994) estimates uncertainties of ~0.2 dex, although as he points out they cannot be too much larger than this since strong \(R_{23}\) guarantees that an H II region lies in the range \(-3.4 \leq \log (O/H) \leq -3.8\). Thurston et al. (1996) see increasing deviations from the output, relative to model input, at low metallicities, but their conclusion is based on tests with only two low-metallicity models: at 30% solar the deviation is less than

| H II Region | R/R_23 | A_v | O/H | N/O | \(<U>\) | [S II] λ6717/6731 |
|------------|-------|-----|-----|-----|-------|------------------|
| FGW 628A   | 0.25  | 1.66| −3.08 (u)| −0.98| 2.2 × 10^{-4} | 1.34 |
| FGW 628B   | 0.74  | 0.27| −3.40 (l)| −1.23| 1.2 × 10^{-3} | 1.38 |
| FGW 628C   | 1.14  | 0.33| −3.92 (l)| −1.41| 9.3 × 10^{-4} | 1.38 |
| FGW 628D   | 1.14  | 0.25| −3.87 (l)| −1.32| 7.3 × 10^{-4} | 1.65 |
| FGW 628E   | 1.30  | 0.21| −3.98 (l)| −1.36| 3.1 × 10^{-4} | 1.50 |
| FGW 628F   | 1.73  | 0.13| −3.93 (l)| −1.45| 3.7 × 10^{-3} | 1.71 |
| FGW 1058A  | 0.20  | 1.11| −3.04 (u)| −1.07| 1.2 × 10^{-4} | 1.43 |
| FGW 1058B  | 0.26  | 0.62| −3.01 (l)| −0.85| 3.9 × 10^{-4} | 1.32 |
| FGW 1058C  | 0.41  | 0.82| −3.03 (u)| −0.99| 5.0 × 10^{-4} | 0.75 |
| FGW 1058D  | 0.60  | 0.70| −3.15 (l)| −0.99| 6.3 × 10^{-4} | 1.32 |
| FGW 1058E  | 1.03  | 0.36| −3.40 (u)| −1.23| 2.2 × 10^{-3} | 1.41 |
| FGW 1058F  | 1.28  | 0.38| −3.41 (l)| −1.19| 2.9 × 10^{-3} | 1.36 |
| FGW 1058G  | 1.88  | 0.10| −3.82 (l)| −1.51| 1.7 × 10^{-4} | 1.36 |
| FGW 1058H  | 1.93  | 0.13| −4.05 (l)| −1.29| 3.2 × 10^{-3} | 1.62 |
| FGW 6946A  | 0.61  | 1.40| −3.28 (u)| −0.96| 2.1 × 10^{-3} | 1.32 |
| FGW 6946B  | 0.65  | 1.46| −3.10 (l)| −0.98| 4.7 × 10^{-4} | 1.55 |
| FGW 6946C  | 1.50  | 0.87| −3.93 (l)| −1.61| 2.8 × 10^{-4} | 1.63 |

Notes.—The letter that follows the O/H abundance indicates whether the upper (u) or lower (l) branch of the log (O/H)−log R_{23} relation was assumed in the calculation. The probable errors on the quantities presented here are discussed in the text.
0.1 dex, whereas it is ~0.3 dex for the lowest metallicity model tested, which has an oxygen abundance of 7% solar.

Perhaps the most robust measure of the accuracy of the semiempirical technique is a direct comparison of predicted abundances with those measured for low-metallicity H II regions that have published abundance determinations based on a measurement of the electron temperature. We have gathered from the literature a sample of low-metallicity H II regions, in a heterogeneous set of parent galaxies, ranging from low-metallicity dwarfs, including blue compact dwarfs (e.g., Izotov, Thuan, & Lipovetsky 1994; Skillman & Kennicutt 1993; Skillman et al. 1994; Miller 1994), irregulars (Webster & Smith 1983; Pagel, Edmunds, & Smith 1980; Miller 1994), and spirals (Webster & Smith 1983; Edmunds & Pagel 1984; Pagel et al. 1979, 1980; Garnett et al. 1997a; Vilchez et al. 1988). The sample also includes two outlying H II regions in the spirals M81 and M101 (Garnett & Shields 1987; Garnett & Kennicutt 1994); for reference the M81 H II region is comparable in luminosity to those outer disk H II regions in our sample, having an Hz luminosity of $4 \times 10^7$ erg s$^{-1}$, while the M101 H II region is significantly more luminous.

Figure 6a shows the difference between the “direct” abundance determination (using the derived value of $T_e$) and that which is returned by the McGaugh calibration based on only the bright line strengths. As can be seen, the agreement between the two techniques improves significantly with decreasing abundance. While the larger discrepancy between the two techniques at high abundances may be due in part to shortcomings of the McGaugh calibration (e.g., the lack of accounting for dust and depletion of heavy elements; see Shields & Kennicutt 1995), it also reflects the increasing difficulty of measuring accurate [O III] $\lambda$4363 strengths, and hence abundances via the “direct” method, at metallicities close to solar. We confirm the effect noted by McGaugh (1991) that the model calibration tends to slightly overpredict O/H at very low abundances. Still, the agreement between the independent determinations is generally very good, with an average offset of only $-0.02$ dex and a standard deviation of 0.28 dex across the entire range of abundances spanned by our comparison sample. Over the particular region of interest for outer disk H II regions (10%-30% solar), we find a mean offset between the different methods of $-0.06 \pm 0.23$ dex. Hence, we will adopt 0.2 dex as the typical uncertainty in our derived oxygen abundances.

Figure 6b shows the same comparison for the nitrogen-to-oxygen abundances determined via the Thurston et al. (1996) calibration. As can be seen, the Thurston calibration provides N/O abundances that are in excellent agreement with those measured directly, deviating significantly only at extremely low metalicities. Averaging over all metallicities, we find a mean offset of 0.06 dex with a standard deviation of 0.16 dex. Over our prime region of interest (10%-30% solar), the mean offset between the “direct” abundance and model predictions is only $-0.03$ dex, and the dispersion is 0.08 dex. We also confirm their noted trend of the model underpredicting true abundances at very low O/H; systematic deviations of $\geq 0.3$ dex appear for metallicities less than 5% solar. Thus, the semiempirical techniques adopted in the present work appear to be able to reproduce (surprisingly) well the chemical abundances in this heterogeneous sample of low-metallicity objects. In the discussion that follows, we will thus adopt a $\pm 0.2$ dex uncertainty in our oxygen abundances and $\pm 0.1$ dex in N/O abundances.

### 6. RESULTS

#### 6.1. Electron Densities

Electron densities can be estimated via the ratio of the [S II] $\lambda\lambda 6717, 6731$ lines (e.g., Osterbrock 1989). The derived ratios for our entire sample are plotted in Figure 7 as a function of deprojected radius, normalized to the optical radius. The horizontal line indicates the low-density limit of 1.42 (Czyzak, Keyes, & Aller 1986); H II regions with ratios comparable to this value are not affected by collisional de-excitation, while those with lower values are. As can be seen, most of our sample appears consistent with the low-density limit, and hence we infer electron densities $\leq 100$ cm$^{-3}$. There is one notable exception, FGW 1058C, for which we infer a density of $\sim 10^3$ cm$^{-3}$. No evidence exists for trends in electron density with galactocentric radius.

#### 6.2. Ionization Parameter

The ionization parameter of a nebula, previously defined in § 4.2, is essentially the local ratio of Lyman continuum

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6 For those H II regions that clearly lie on the upper branch, we also calculated what the abundance would be if we used the $R_{13}$ calibration of ZKH. We find an average offset of $0.13 \pm 0.06$ dex between the different determinations of log(O/H), which is consistent with the uncertainty produced by either method alone.
Variation of the density-sensitive ratio \([\text{S II}] 6717/6731\) for our entire sample of \(\text{H II}\) regions, plotted as a function of radius, normalized to the size of the optical disk. The dashed line indicates the low-density limit.

Photons to gas density, which determines the degree of ionization at any particular location within the nebula. Figure 8 shows the variation of the mean volume-averaged ionization parameter, \(<U>\), as derived by the McGaugh (1994) calibration, as a function of both galactocentric radius and oxygen abundance. \(\text{H II}\) regions at large radii are observed to exhibit a large range in \(<U>\), and there is no obvious trend in ionization parameter with either radius or oxygen abundance. This latter finding is in agreement with the results of ZKH and Kennicutt & Garnett (1996) but contrary to Evans & Dopita (1985), who have proposed that \(U\) is anticorrelated with abundance.

6.3. Reddening and Extinction

Figure 9 shows the radial variation of the extinction for each galaxy, as derived from the reddening of the Balmer decrement. Also shown are the extinction measures from MRS for their inner disk \(\text{H II}\) regions. A large dispersion in extinction can be seen over the face of these galaxies, clearly indicating the dominant effect of local variations over radial variations within the optical disk. Our derived extinctions for the two \(\text{H II}\) regions in common with MRS show deviations of \(\sim 1\) mag, which may partly reflect variations in extinction over very small scales, accountable for by differences in pointing alone. Despite the large scatter that typifies the inner disk, clear evidence exists for diminished extinction at large radii. When account is made for the Galactic extinction toward these galaxies (indicated by the horizontal dashed line in Fig. 9), the outer \(\text{H II}\) regions are consistent with internal extinctions of only \(A_v < 0.2\) mag.

We have used a weighted linear least-squares algorithm to fit the radial behavior of the extinction in each galaxy and find \(A_v = 1.73 - 1.07R/R_{25}\) (NGC 628), \(0.95 - 0.46R/R_{25}\) (NGC 1058), and \(2.28 - 0.97R/R_{25}\) (NGC 6946). Although clearly not an appropriate way to characterize the actual extinction in galactic disks, these parameterizations serve as a means to compare the global extinction properties of different galaxies. As can be seen, both the central value and the amplitudes of the gradients vary considerably from galaxy to galaxy. A radial gradient in extinction has also recently been detected in M101 by Kennicutt & Garnett (1996), but most previous studies have found evidence for only a very weak radial dependence. Our results suggest that this may be due in part to the limited radial coverage of such studies, which typically have sampled only the inner parts of galaxies where the amount of scatter dominates over any existing radial trend (e.g.,
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Fig. 9.—Radial variation of extinction for our galaxy sample, expressed in terms of the optical radius $R_{25}$. Our data points are indicated by circles, those from MRS by diamonds. The horizontal dashed lines indicate the level of Galactic extinction toward these galaxies, taken from the RC3 (de Vaucouleurs et al. 1991). The dash-dotted lines indicate a linear least-squares fit to the points. Thick lines join independent measurements of the same H II region.

ZKH; MRS; Belley & Roy 1992; Scowen, Dufour, & Hester 1992). Interestingly, the radial gradients in $A_V$ found here are comparable in magnitude to those found for the radial variation of the oxygen abundance (see below), lending support to the idea that the changes in $A_V$ are driven largely by a decrease in available metals (see Table 7).

6.4. Oxygen

In Figure 10, we present the derived O/H abundances for the three galaxies in our sample as a function of the deprojected galactocentric radius, normalized to the optical radius. Since we have demonstrated that the dominant errors in the abundance determinations arise from the use of model calibrations and not from the measurements themselves, we omit placing formal error bars on the data points and instead place a representative error bar in each corner of the plot to indicate the estimated calibration uncertainty ($\pm 0.2$ dex) as derived above. Also shown are the abundances we derived using our present technique for the inner disk H II regions observed in NGC 628 and NGC 6946 by MRS (calculated from their published reddening-corrected line strengths). Our repeat measurements of the two MRS inner disk H II regions are indicated by a solid line that joins the independent measurements. As can be seen, there is excellent agreement between these determinations.

Inner disk abundances typically range from 20% above solar to 40% below solar, while beyond the edge of the optical disk, the measured oxygen abundances are $\sim 10\%$–$50\%$ solar. The outermost abundances in all three galaxies are $\sim 10\%$–$15\%$ solar, measured at radii in the range $(1.5–2)R_{25}$. We have used a linear (uniformly weighted) least-squares routine to fit the variation of O/H as a function of deprojected galactocentric radius, expressed in terms

![Table 7: Derived Radial Abundance Gradients](image-url)

Table 7

| Galaxy     | log (O/H) at $R = 0$ | log (O/H) (dex $R_{25}^{-1}$) | log (N/O) at $R = 0$ | log (N/O) (dex $R_{25}^{-1}$) | log (N/O) (dex $R_{25}^{-1}$) | $A_V$ (dex $R_{25}^{-1}$) |
|------------|----------------------|-------------------------------|----------------------|-------------------------------|-------------------------------|--------------------------|
| NGC 628    | $-2.92$              | $-0.73 \pm 0.12$              | $-0.05 \pm 0.01$     | $-0.90$                       | $-0.37 \pm 0.06$              | $-0.02 \pm 0.01$          | $-1.07$                 |
| NGC 1058   | $-2.85$              | $-0.55 \pm 0.11$              | $-0.13 \pm 0.01$     | $-0.89$                       | $-0.26 \pm 0.06$              | $-0.06 \pm 0.01$          | $-0.46$                 |
| NGC 6946   | $-2.77$              | $-0.70 \pm 0.19$              | $-0.08 \pm 0.01$     | $-0.59$                       | $-0.63 \pm 0.10$              | $-0.07 \pm 0.01$          | $-0.97$                 |
defining the abundance gradient. In this case, we find $\log (O/H) = -2.91 - (0.69 \pm 0.12)R/R_{25}$ (NGC 628), $-2.95 - (0.30 \pm 0.14)R/R_{25}$ (NGC 1058), and $-2.93 - (0.39 \pm 0.16)R/R_{25}$ (NGC 6946). These gradients are consistent with those derived for NGC 628 and NGC 6946 by ZKH, which were determined using weighted linear least-squares fits to only the inner disk samples of and MRS employing a different calibration of the $O/H$-$R_{23}$ relationship than that which is adopted here. For comparison, they found gradients in units of the optical radius of $-0.96 (\pm 0.32)$ for NGC 628 and $-0.55 (\pm 0.26)$ for NGC 6946. As is evident, the values of the outer disk abundances play a crucial role in defining the abundance gradient across the disk. Consideration of only inner disk abundances results in significantly flatter gradients for NGC 1058 and NGC 6946.

As we have discussed, a crucial aspect of the abundance determination via the semiempirical method is determining whether a given H II region lies on the upper or lower branch of the calibration. Several of the extreme outer disk H II regions in our sample have values of $\log ([N\,\text{II}]/[O\,\text{II}])$ close to unity, which makes the branch placement uncertain. In Figure 11, we show the effect of choosing the other branch in those cases in which the branch placement is somewhat ambiguous (defined here to be those cases where $\log ([N\,\text{II}]/[O\,\text{II}])$ lies within $\pm 0.1$ dex of $-1$). Only NGC 628 and NGC 1058 have H II regions that fall in this category. As can be seen, choice of the opposing branch for these H II regions can have a profound effect on the nature of the gradient; however, it leads to rather strange (and unlikely) behaviors at large radii. We intend to obtain measures of $[O\,\text{III}]$ $\lambda 4363$, and thus the oxygen abundance via the “direct” method, for those H II regions in which the abundance determination from the semiempirical method is uncertain.

### 6.5. Nitrogen-to-Oxygen

Nitrogen-to-oxygen abundance ratios range from 50% above solar to 40% below solar across the inner disks, and from 20% to 50% solar beyond the optical radius (see Fig. 12). The outermost regions have typical abundances of $20\%$–$25\%$ solar. Linear least-squares (uniformly weighted) fits have been carried out to characterize the radial behavior (see Table 7). Fitting only those points lying at or within $R_{25}$ produces gradients of $\log (N/O) = -0.74 - (0.76 \pm 0.13)R/R_{25}$ (NGC 628), $-0.97 - (0.02 \pm 0.36)R/R_{25}$ (NGC 1058), and $-0.72 - (0.40 \pm 0.09)R/R_{25}$ (NGC 6946). Once again, it can be seen that the outermost abundances play a key role in defining the abundance gradient. In particular, one might deduce no gradient in N/O for NGC 1058 if presented with only the inner disk measurements, whereas the outer disk measurements clearly show a decline at large radii.

### 7. DISCUSSION

#### 7.1. Constraining Outer Galactic Abundance Gradients

The results presented here constitute the largest set of extreme outer disk abundances ever measured and probe the chemical abundance content of these optically faint, previously unexplored regions of present-day galactic disks. We have found that the outermost H II regions studied have O/H abundances in the range of $10\%$–$15\%$ solar and N/O abundances in the range of $20\%$–$25\%$ solar. Such low abundances have rarely been measured before in spiral disks (e.g., Garnett & Kennicutt 1994).
We have shown that the outermost abundances play an important role in defining abundance gradients across the disks and, indeed, often change the slope of the gradient. For example, in two of the galaxies studied here the oxygen gradients are observed to steepen considerably when account is taken of the outermost H II regions. Within the limits of the current data set, the radial abundance gradients are consistent with single log-linear relationships, although hints of interesting behavior can be seen at large radii in two of the galaxies. There could be a flattening of the oxygen abundance beyond the edge of the optical disk in NGC 628 (although this result largely hinges on the metallicity of the outermost H II region), as well as a steepening of the outer gradient in NGC 1058. Unfortunately, given the relatively large errors in our abundance determinations, as well as the relatively small size of the current sample, it is not yet possible to assess the significance of these features. Similarly, it is not yet possible to constrain the amount of intrinsic scatter in the abundances as a function of galactocentric radius, which is of interest for understanding the efficiency and timescales for elemental mixing at large radii. While the two outermost H II regions in NGC 1058 show differences of \( \geq 0.2 \) dex in both O/H and N/O despite lying at very similar radii, a knowledge of the electron temperatures of these regions will be required before we can distinguish between real scatter and uncertainties inherent in the model calibrations.

Chemical evolution models predict a variety of different behaviors for galactic abundance gradients (e.g., Prantzos & Aubert 1995; Möllá, Ferrini, & Diaz 1996; Wyse & Silk 1989; Clarke 1989). Of these models, some predict simple exponential declines while others produce steepenings or flattennings in the outer disk. Our current data set is not yet sufficient to discriminate between various chemical evolution models, but we are continuing to obtain more and better data on these and other galaxies, spanning a range of physical environments and Hubble types.

7.2. Comparison with Other Galaxies

It is of great interest to compare our measurements of outer disk abundances with the few published measurements in the literature. High-quality measurements exist for the Galaxy (Fich & Silkey 1991; Vilchez & Esteban 1996; Rudolph et al. 1997; Afferbach, Churchwell, & Werner 1997), M81 (Garnett & Shields 1987), and M101 (Garnett & Kennicutt 1994), but these measurements do not extend to the extreme galactocentric radii that we have studied here.

In case of our Galaxy, outer disk H II regions have been studied via optical and far-IR techniques out to 1.3\( R_{\text{edge}} \), where \( R_{\text{edge}} \) the edge of the optical stellar disk, is taken to be 14 kpc (Ruphy et al. 1996).\(^7\) Both Fich & Silkey (1991) and Vilchez & Esteban (1996) found evidence for flat gradients in the nitrogen abundance beyond the solar circle; in addition, Vilchez & Esteban found evidence for only a mild outer gradient in oxygen abundance, with outer values of \( \sim 20\% \) solar and outer disk values of N/O consistent with those measured in the solar neighborhood. More recently, Rudolph et al. (1997) have reexamined outer abundance gradients using far-IR lines for a sample of five H II regions. Combining their results with those of other studies, these authors do not see compelling evidence for a flattening of the outer abundance gradients and are able to fit the available data with single log-linear relationships. They caution, however, that their present sample is not yet sufficient to rule out the possible existence of a flattening of the abundance gradient in the outer Galaxy. They also find the variation of N/O throughout the Galactic disk to be consistent with a step function, with a mean log (N/O) of \(-0.50 \pm 0.02\) for \( R < 6.2 \) kpc and \(-0.83 \pm 0.04\) for \( R > 6.2 \) kpc. We note that H II regions have been discovered at much larger Galactocentric radii, out to \( \sim 28 \) kpc or 2\( R_{\text{edge}} \) (de Geus et al. 1993); however, no abundance determinations have been made for these as of yet.

In M81, the outermost H II region (lying at \( \sim 1.3R_{\text{edge}} \)) has an O/H abundance of roughly 20% solar, consistent with an extrapolation of the inner gradient, whereas the N/O abundance is close to solar and consistent with there being no gradient across the disk (Garnett & Shields 1987). On the other hand, the outermost H II region studied in M101 (\( \sim 1.1R_{\text{edge}} \)) has an O/H abundance of only 10% solar and an N/O abundance of 25% solar; both N/O and O/H are observed to decrease more or less smoothly with increasing galactocentric radius across the disk (Garnett & Kennicutt 1994). Curiously, these abundances are as low as those observed in the extremities of the galaxies studied here, despite that fact that we have probed the gas at significantly larger distances beyond the optical disk.

We find that the galaxies studied in the present work are more akin to M101 than to the Galaxy or M81 since the outermost abundances of both O/H and N/O are observed to decrease relatively smoothly across their disks. The striking difference between the level of N/O enrichment seen in the outer disks of galaxies studied here (and M101) and in the outer disks of the Galaxy and M81 is particularly puzzling and clearly warrants further study.

7.3. Implications for Understanding the Evolution of Galactic Disks

Our outer disk measurements are largely consistent with those observed in other low gas surface density objects, such as gas-rich dwarf irregulars (e.g., Garnett 1990; Skillman, Kennicutt, & Hodge 1989; Skillman, Bomans, & Kohlennicky 1997; Thuan, Izotov, & Lipovetsky 1995; Miller & Hodge 1996)\(^8\) and some low surface brightness galaxies (McGaugh 1994). It has often been suggested that outer galactic disks are “built up” through the accretion of gas, either smoothly (e.g., Gunn & Gott 1972; Larson 1976) or as gas-rich low-mass companions (e.g., White & Rees 1987; Kauffmann, White, & Guiderdoni 1993; Kamphuis 1993; Zaritsky 1995). There would appear to be no obvious argument against this hypothesis on the basis of chemical abundance content alone.

On the other hand, one might consider the scenario in which outer galactic disks evolve in relative isolation, with

\(^{7}\) It remains unclear what is the relationship between the optical edge, as defined by star counts, and the 25th B-magnitude isophote.

\(^{8}\) Note, however, that the measured outer disk metallicities are still considerably in excess of the most metal-poor, gas-rich objects known locally, e.g., I Zw 18, UGC 4483, and SBS 0335-052. These objects have O/H abundances of only 2%–3% solar (e.g., Skillman & Kennicutt 1993; Skillman et al. 1994; Izotov et al. 1997), even although there is evidence for moderately long periods (\( \geq 10\) Myr) of star formation in at least one case (e.g., Garnett et al. 1997b).
little inflow or outflow. The simple "closed box" model of Schmidt (1963) can be used to predict the mean metallicity expected for such regions, under the assumption of instantaneous recycling (appropriate for oxygen). The closed-box model can be represented by a simple relation,

\[ Z = -p \ln \mu \]

(Searle & Sargent 1972), where \( p \) is the yield of the element in question and \( \mu \) is the gas fraction, defined as the ratio of baryonic mass in gas to the total baryonic mass (stars plus gas). Our deep B-band surface photometry yields B-band surface brightnesses at 2 optical radii of \( \sim 0.1 \text{ L}_\odot \text{ pc}^{-2} \) in NGC 628 and NGC 6946 and \( \sim 1.2 \text{ L}_\odot \text{ pc}^{-2} \) in NGC 1058 (Ferguson et al. 1998b). Under the assumption that \( M/L \sim 2 \), this leads to surface mass densities of 0.2 and 2.4 \( \text{M}_\odot \text{ pc}^{-2} \), respectively. The B-band mass-to-light ratio is sensitive to the star formation history of the outer disk but is unlikely to be too much larger than the adopted value, which is found for the solar neighborhood (Kuijken & Gilmore 1989). Inspection of the H I maps of these galaxies reveals typical H I surface densities of \( \sim 1 \text{ M}_\odot \text{ pc}^{-2} \) (NGC 628) to \( \sim 3 \text{ M}_\odot \text{ pc}^{-2} \) (NGC 1058, NGC 6946) in the extreme outer disks (van der Kruit & Shostak 1984; Shostak & van der Kruit 1984; Kamphuis 1993). Correcting for helium (a factor of 1.3), we derive gas fractions of \( \sim 0.6 \) in NGC 1058 and \( \sim 0.90 \) in NGC 628 and NGC 6946. If we adopt a yield of 0.5 \( Z_\odot \), consistent with the observed mean metallicity of stars in the solar neighborhood (Wyse & Gilmore 1995), the simple model then predicts oxygen abundances of 6% solar for NGC 628, 25% solar for NGC 1058, and 2% solar for NGC 6946. These values can be compared with the observed metallicities of 10%–15% solar. Despite the many uncertainties involved, both NGC 628 and NGC 1058 have metallicities that lie within a factor of 2 of the closed-box model predictions, thus suggesting that the role of gas flows in the evolution of their outer disks is similar to that for the solar neighborhood. The outer disk of NGC 6946, on the other hand, does not appear to fit this picture. In the future, we plan to investigate the predictions of the simple model in more detail, including study of the radial variation in the derived effective yield.

7.4. Comparison with High-Redshift Damped Lyα Systems

Much recent attention has been focused on uncovering the nature of the damped Lyα systems (DLAs) that cause absorption in the spectra of high-redshift quasars. While there remains much debate on this topic, follow-up imaging and spectroscopy of these systems lend support for the idea that at least some of them are young disk galaxies (e.g., Wolfe 1988; Briggs et al. 1989; Djorgovski et al. 1996). The distribution of impact parameters for these systems is not well defined; however, in the particular case of Djorgovski et al. (1996), an impact parameter of 18 kpc is inferred that clearly places the line of sight in the outer parts of what appears to be a large disk galaxy at \( z = 3.15 \). How do the chemical abundances measured in the DLAs compare with those measured in the extended parts of local disk galaxies? There have been many recent efforts to measure the gas-phase chemical abundances in DLA systems (e.g., Pettini et al. 1994, 1997; Pettini, Lipman, & Hunstead 1995; Wolfe et al. 1995; Lu et al. 1996; Lu, Sargent, & Barlow 1998); studies have generally found them to exhibit a wide range of low metallicities, ranging from less than 0.01 of the solar value to 0.1 solar, and showing a trend of increasing metallicity with decreasing redshift, albeit with considerable scatter at all redshifts (e.g., Lu et al. 1996; Pettini et al. 1997). Pettini et al. (1997) calculate a column-density-weighted mean metallicity of 1/13 solar for their sample of 34 DLAs (0.7 < \( z < 3.4 \)), using the Zn lines, which should be relatively unaffected by depletion onto dust. This comparison suggests an intriguing similarity in the mean chemical enrichment level of DLA systems and present-day outer galactic disks, with DLA systems being only slightly more metal-poor.

Figure 13 shows a plot of nitrogen-to-oxygen abundance as a function of O/H for our present sample of H II regions, as well as those inner disk regions from MRS. We have indicated where I Zw 18, the most metal-poor gas-rich object known in the local universe, falls on this diagram (Skillman & Kennicutt 1993). Also shown are a set of N/Si measurements for a sample of high-redshift DLA systems from Lu, Sargent, & Barlow (1998). (Note that we have not shown the error bars for these data, but only the upper and lower limits.) The dashed lines indicate the expectations for a pure secondary and primary + secondary origins for nitrogen from Vila-Costas & Edmunds (1993). The extreme outer disk H II regions are consistent with a combination of both primary and secondary production of nitrogen.

\[ \text{Fig. 13.—Variation of log (N/O) vs. 12 + log (O/H) for our sample of H II regions, as well as the inner disk H II regions measured by MRS. Typical uncertainties in our measurements are indicated by the error bars in the bottom left. The location of the Sun in this diagram is indicated by a five-pointed star. We also plot values for the most metal-poor object known in the local universe, I Zw 18 (Skillman & Kennicutt 1993), as well as the N/Si and Si/H measurements for a sample of high-redshift DLA systems from Lu, Sargent, & Barlow (1998). (Note that we have not shown the error bars for these data, but only the upper and lower limits.) The dashed lines indicate the expectations for a pure secondary and primary + secondary origins for nitrogen from Vila-Costas & Edmunds (1993). The extreme outer disk H II regions are consistent with a combination of both primary and secondary production of nitrogen.} \]

\[ \text{\footnote{Note that the average H I column for this sample of DLA systems is \( \sim 10^{21} \text{ cm}^{-2} \), which is several times higher than the typical H I column, where our sample of outer H II regions reside (a few times } 10^{19} \text{ cm}^{-2}).} \]
DLA systems in the Lu et al. sample are considerably more metal-poor than present-day outer galactic disks, others are only slightly displaced from outer disks in terms of O/H and almost identical in terms of N/O. The long dynamical timescales (\(\sim 10^8 - 10^9\) yr) that characterize the extreme outer disks imply that they evolve at a very slow rate, but nonetheless, we would expect them to have been more metal-poor in the past than at the present epoch. We therefore conclude that while, on average, DLA systems tend to be slightly more metal-poor than outer galactic disks at present, the two were very likely indistinguishable at long look-back times.

7.5. The Origin of Nitrogen

A major unsolved question is the importance of primary and secondary processes in the production of nitrogen. Nitrogen is believed to be mostly a product of secondary nucleosynthesis, being produced via the CNO cycle; however, it is also thought to have a primary component that can be produced in the earlier helium-burning stages (Renzini & Voli 1981). It is thought that secondary nitrogen is produced by stars of a wide range of masses, whereas primary nitrogen is produced by only intermediate-mass stars \((4 \, M_\odot \leq M \leq 8 \, M_\odot);\) Renzini & Voli 1981); there is evidence, however, that nitrogen produced in massive stars can also be primary (Matteucci 1986). As an example, Laird (1985) finds that [N/Fe] is constant for solar-neighborhood stars with \(-1.8 \leq [\text{Fe/H}] \leq 0.5,\) implying that nitrogen and iron are produced in the same way, by the same stars. Since it is well known that some iron is primary and produced on short timescales by Type II supernovae from the core collapse of massive stars (e.g., Arnett 1995), one then expects that such stars must also contribute to nitrogen production. The simple model for the chemical evolution of galaxies (i.e., closed box) predicts that N/O will be independent of O/H for a primary origin of nitrogen and proportional to O/H for a secondary origin (see Vila-Costas & Edmunds 1993 for a discussion, including the complication of "delayed" primary production).

The timescales for nitrogen production differ in stars of varying mass. If nitrogen is predominantly produced by massive stars, then there should be no time delay between the release of the element with respect to oxygen, and thus one expects the N/O ratio to exhibit only a small amount of scatter. If, on the other hand, most nitrogen comes from intermediate-mass stars, then one expects a time delay of up to a few times \(10^8\) yr between the release of nitrogen and oxygen. This is expected to introduce a large scatter in the N/O ratio at low O/H, decreasing with increasing metallicity as the effects of the time delay become less and less important (see, e.g., Garnett 1990; Pilyugin 1992).

In Figure 13, we have overplotted the expectations for primary and secondary production of nitrogen, as taken from Vila-Costas & Edmunds (1993). At high metallicities, the expected linear trend between O/H and N/O is seen, indicative of the dominant role of secondary nitrogen production. On the other hand, the extreme outer disk H II regions are seen to populate the region bracketed by the pure secondary and primary + secondary curves and thus appear consistent with a combination of primary and secondary production of nitrogen. The spread in N/O at fixed O/H in the outer disk may very well reflect the timescale between "bursts" of star formation, produced perhaps by the passage of a spiral arm. Further measurements, with improved accuracy, are needed to better understand these results.

8. SUMMARY AND FUTURE WORK

We have presented the first results from a systematic study of the physical properties and chemical abundances in a sample of newly discovered, extreme outer disk H II regions. Optical spectra are presented for H II regions in three late-type spirals—NGC 628, NGC 1058, and NGC 6946—all of which are characterized by larger than average H i-to-optical sizes. We have found that the outermost H II regions studied, typically lying at \((1.5 - 2)R_{25}\), have O/H abundances in the range of 9\%–15\% solar and N/O abundances in the range of 20\%–25\% solar. Evidence is also found for diminished dust extinction at large radii, with the outermost H II regions having internal extinctions of \(A_V \sim 0 – 0.2\) mag. Electron densities in the outer disk H II regions are comparable to those found in the inner disk. The outer disk H II regions are observed to span a range in volume-averaged ionization parameter \(<U>\), and no correlation is seen with either galactocentric radius or metallicity.

By combining our sample of outer disk measurements with those for inner disk H II regions published in the literature, we have been able to probe the radial variation of both oxygen and nitrogen-to-oxygen abundances out to unprecedented radii. Single log-linear relationships are found to adequately describe the radial abundance variations, although the derived slopes often differ considerably from those found if only inner disk H II regions are used to define the fit. The small number of H II regions in our sample, together with uncertainties in the calibrations of the semiempirical methods used here to determine abundances, limit our ability to constrain subtle changes in the radial gradient, as well as scatter in the outer disk.

Comparison of our outermost oxygen abundances with the predictions of the simple closed-box model for chemical evolution reveals a general consistency for two of the three galaxies and suggests that the role of gas flows in the evolution of their extreme outer disks is comparable to that in the solar neighborhood. An intriguing similarity is found between both the mean enrichment level and the nitrogen-to-oxygen abundance in outer disks and in some high-redshift DLA systems, implying that outer disks at the present epoch are relatively unevolved systems. While DLA systems tend to be slightly more metal-poor than present-day outer disks, they were very likely indistinguishable at large look-back times. Finally, we have found that the outer disk H II regions in our sample are consistent with a combination of primary and secondary production of nitrogen.

A limitation of the current work is the reliance on semiempirical methods to determine the abundances. A concern is that the outer disk H II regions under study here are physically different from the clusters of OB stars on which the model calibrations are based. A more complete set of photoionization models, extending to H II regions that are ionized by only a few massive stars, would be highly desirable. We are intending to measure the temperature-sensitive line \([\text{O III}] \lambda 4363,\) or at least place strong limits on it, for several of the brightest H II regions in the present sample, in order to compare the "direct" and semiempirical abundance determinations for these objects. We are also continuing to obtain measurements of additional H II regions in...
these galaxies, as well as extending our work to include several other galaxies residing in a range of physical environments (e.g., field and cluster). The new generation of 8 m telescopes will significantly ease the task of measuring abundances for extreme outer disk H II regions, while future Hubble Space Telescope instruments will make it possible to probe outer disk abundances via quasar absorption lines. A larger sample of outer disk abundances will allow study of the detailed nature of the abundance gradient at large radii, as well as the amount of intrinsic scatter at a fixed radius. Ultimately, we will use our measurements of outer disk chemical abundances, along with our measurements of past and present star formation rates, in order to construct self-consistent models of outer disk evolution.

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