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THE RADIAL DISTRIBUTION OF OXYGEN IN DISK GALAXIES

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ABSTRACT

The shape of the oxygen abundance profile is examined for seven nearby spiral galaxies in which at least 15 H II regions have been observed. The radial abundance profile for three of these galaxies has a distinct change in slope. The others show no deviation from a single scale-length exponential. This behavior is explained within the framework of the star-forming viscous disk model of galaxy evolution. A prediction is made that radial abundance profiles of noninteracting unbarred spiral galaxies change slope at the radius where the rotation curve changes from linearly rising to flat. For barred and interacting galaxies the situation is complicated by additional mixing mechanisms of the interstellar medium.

Subject headings: galaxies: abundances — galaxies: evolution — H II regions

1. INTRODUCTION

The mean oxygen abundance of H II regions decreases with increasing galactocentric radius (see Dinerstein 1990 for a recent review of this field). The primary evidence for the existence of abundance gradients across disk galaxies is the observed radial variation of emission-line ratios of H II regions (Searle 1971). However, there are only a few galaxies for which emission-line ratios have been measured for more than 10 H II regions. Therefore, although the abundance gradient is evident, the full complexity of the radial dependence (i.e., the radial abundance profile) has not been determined. A single scale-length exponential is typically accepted as an adequate description of the profile.

Recent technological advances have greatly increased the number of H II regions observed per galaxy. There now exist measurements of line ratios for more than 30 H II regions in NGC 2997 (Walsh & Roy 1989, hereafter WR89), M33 (Zaritsky, Elston, & Hill 1989, hereafter ZEH89), and M101 and NGC 2403 (Zaritsky, Elston, & Hill 1990, hereafter ZEH90) from observations with the first generation of multiobject spectrographs. There now also exist extensive data on M101 (Scowen, Dufour, & Hester 1992, hereafter SDH) and NGC 628 and NGC 6946 (Belley & Roy 1992) from narrowband imaging. With these data we can now begin to search for deviations from the simple model of the single scale-length exponential radial abundance profile.

Vílchez et al. (1988) first noticed that the abundance gradient in M33 steepens in the inner region of the disk; however, they only had measurements for a few H II regions in the "inner" disk. The steepening of the gradient in M33 was confirmed with the larger data base of ZEH89. A similar steepening was noticed in the abundance gradient of M101 by ZEH90 and was confirmed by SDH. However, the abundance gradients of other well-observed galaxies, NGC 628, NGC 2403, NGC 2997, and NGC 6946, are adequately fitted by a single scale-length exponential (Belley & Roy 1992; ZEH90; this work). No conjectures for the apparently different shapes of abundance profiles were investigated in any of those studies, although Scowen (1991) suggested that the bend might arise at the corotation radius or at the position of an orbital resonance. In § 2 of this *Letter*, I present evidence that the change in slope of the gradient occurs near the radius at which the rotation curve either flattens or turns over. In § 3 I proceed to discuss why such behavior may be expected within the framework of the star-forming viscous disk models.

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2. THE SHAPE OF THE ABUNDANCE PROFILE

For values of the oxygen abundance common to spiral disks, the abundance can be estimated to an accuracy of about 0.1 dex by using the line flux ratio of [O II] $\lambda\lambda$3736, 3729 + [O III] $\lambda\lambda$4959, 5007 to Hβ ($\equiv R_{23}$; Edmunds & Pagel 1984). The line ratio [O III]/Hβ ($\equiv R_3$) can also be used, although with some loss of precision (see ZEH90 for a discussion). The focus of the present discussion will be on the line ratios, which are directly observable. The conversion of line ratios to abundances will be discussed at the end of this section. The values of [O III]/Hβ, or R_{23} when available, and rotational velocities are plotted against radius in Figure 1. The values of [O III]/Hβ are adopted from ZEH89 for M33 and from ZEH90 for NGC 2403 and M101. The values of R_{23} are adopted from Walsh & Roy (1989) for NGC 2997 and from Garnett & Shields (1987) for M81. The rotation curves are fitted curves to data from ZEH89 for M33, from ZEH90 for M101, from Rots (1975) for M81, from Begeman (1987) for NGC 2403, and from Milliard & Marcelin (1981) for NGC 2997.

For M33, M81, and M101, the line ratios systematically deviate from an exponential fit (a straight line in the semilog plots provided). I proceed to fit a model that describes the inner and outer regions with independent single scale-length exponentials. To quantitatively and systematically determine where the slope of the profile changes (i.e., the radius at which different scale-length exponentials are to be fitted), the following prescription was used. The galactocentric radius of one of the observed H II regions was chosen to define the demarcation between the inner and outer radial zones. Linear least-squares fits were calculated for the line ratios in both the inner and outer zones, and χ^2 was evaluated. The process was repeated with each observed H II region in the galaxy, except for the innermost and outermost three regions, as the demarcation point. The model that minimized χ^2 defined the boundary between the inner and outer zones. If the improvement in χ^2 realized with the "double" exponential was insignificant

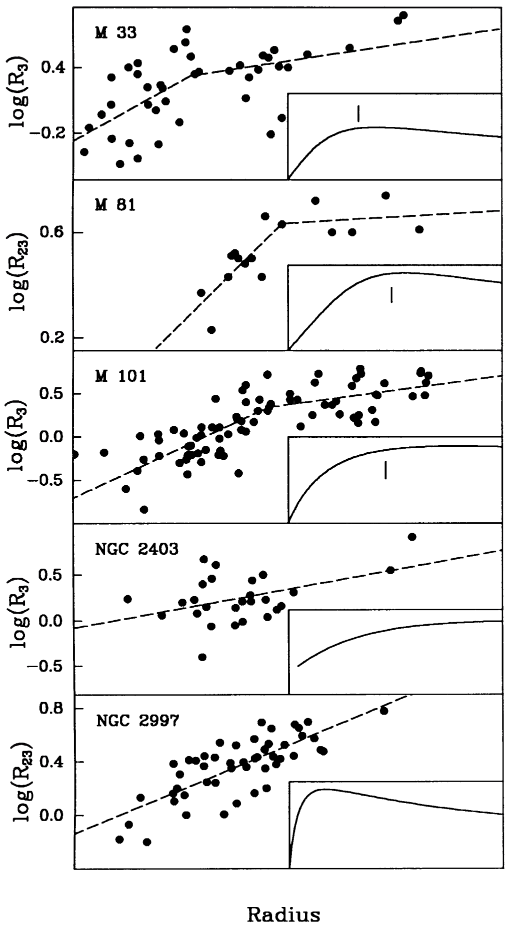

FIG. 1.—Logarithm of the line flux ratio, either R_3 or R_{23}, plotted as a function of deprojected galactocentric radius in the upper panels. Data are from published studies cited in the text. The derivation of the fits (*dashed lines*) is described in the text. Fitted rotation curves are plotted in the inset panels for the same range of radii. Radial scales vary between plots for different galaxies, but all begin at $R = 0$. They end at 35′, 13′.5, 12′, 8′.5, and 8′ for M83, M81, M101, NGC 2403, and NGC 2997, respectively. The small vertical bars mark the radius chosen as the boundary between inner and outer zones.

("significant" was defined to be at least a factor of 10 increase in the probability of randomly obtaining the observed χ^2), then a single-exponential fit was adopted. Using this technique, I examined M33, M81, M101, NGC 628, NGC 2403, NGC 2997, and NGC 6946. In accordance with a visual examination of the data, M33, M81, and M101 are fitted better by two exponentials; the others are not. The fits are shown in Figure 1 for the five galaxies that are unbarred and have well-determined rotation curves. For M33, M81, and M101, the adopted boundary between the inner and outer zones is marked in the inset panels of Figure 1 by a vertical line and coincides with the radius at which the rotation curve initially reaches between 95% and 100% of its maximum amplitude.

I propose that the line ratios of H II regions in NGC 2403 and NGC 2997 are adequately fitted by a single exponential because only radii interior or exterior to the rotation curve turnover are well sampled. One can argue that a change in slope might be present but not detected in NGC 2403 because of the large scatter in excitation. However, a single exponential clearly provides an adequate fit to the data for NGC 2997. Although not shown in Figure 1, the line ratios for NGC 628 and NGC 6949 are also adequately fitted by a single exponential (Belley & Roy 1992; this work). Unfortunately, neither of these two galaxies is suitable for this study. Because NGC 628 is nearly face-on, its rotation curve is difficult to measure. NGC 6946 has a central bar (Ball et al. 1985), so the material in the inner disk is unlikely to be in circular orbit. As the subsequent discussion will illustrate, radial gas flows, such as those produced by bars (cf. Belley & Roy 1992), might negate any steepening of the abundance gradient in the inner region and so are not included in simple models. I conclude that although the present sample is small, it does support the hypothesis that the rotation curve and the abundance profile are related. Clearly, confirmation awaits further observations. Regardless of whether a relationship exists between the abundance profile and rotation curve, I stress that the radial distribution of [O III/Hβ] and R_{23} in many galaxies is poorly fitted by a single exponential. If so, then there are two questions that remain to be addressed: (1) Is [O III]/Hβ a reliable abundance diagnostic? (2) Is the bend in the line-ratio gradient indicating that the slope of the abundance gradient is changing or that the conversion between the line ratios and abundance is strongly nonlinear?

To address the first question, note that R_{23} is generally accepted as a reliable abundance indicator (most recently shown by McGaugh 1991). Even so, one must be cautious because basic uncertainties remain and the calibration of the line ratio for oxygen abundances greater than solar has not been confirmed. Whether [O III]/Hβ is an accurate abundance indicator remains a topic of controversy. Therefore, there is justifiably some concern that the effect discussed above, for those galaxies for which only [O III]/Hβ was observed, may not be produced by a corresponding change in the distribution of oxygen. Inarguably, observing both [O II] and [O III] enables one to estimate the ionization parameter, U, and hence produce a more reliable estimate of the abundance. However, if the value of U varies only slightly among the regions observed, then observations of [O III]/Hβ will be adequate to trace the overall oxygen distribution. Empirically, a similar conclusion can be reached if the observed values of [O II] + [O III] and [O III] are strongly correlated. In Figure 2, R_{23} is plotted against [O III]/Hβ, where values are taken from a variety of observations presented in the literature (references identified in the figure legend). If the *entire* scatter present in the correlation is real and due to additional information contained in the [O II] line, then the improvement in the precision obtained by observing the [O II] lines is roughly 0.09 dex for H II regions with log ([O III]/Hβ) > −0.5 (true for ~95% of the observed H II regions in giant spirals; ZEH90). Since the observational errors are estimated to be of order 0.1 dex, the omission of the [O II] measurement is not critical to determining the global distribution of oxygen in the disks of giant spiral galaxies. In addition, the decrease in precision due to the omission of [O II] can be compensated for by observing many H II regions. Abundance gradients measured using [O III]/Hβ observations of many H II regions per galaxy are in excellent agreement with those obtained using R_{23} (ZEH90).

The second question is more difficult. If the observed line ratios become less sensitive to abundance variations for values of log [O III]/H$\beta \gtrsim 0.4$ or log $R_{23} \gtrsim 0.6$, then that could produce the flattening observed in the line-ratio radial profiles of M33, M81, and M101, even if the oxygen abundance is well described by a single scale-length exponential. The calibration diagrams of Edmunds & Pagel (1984) and McGaugh (1991)

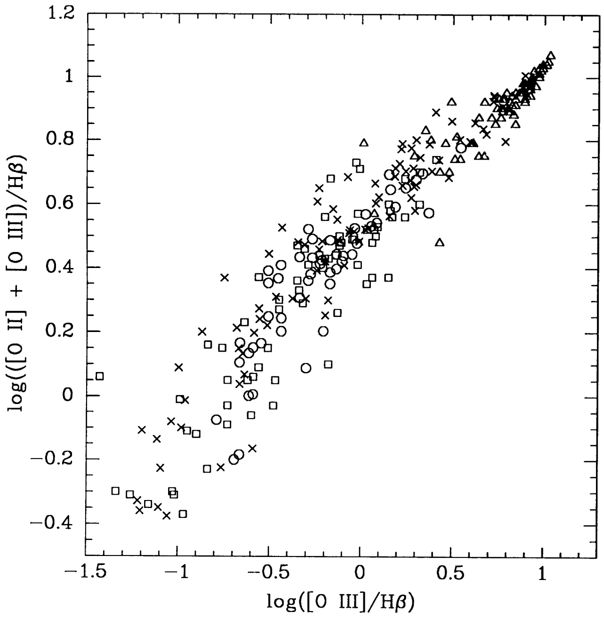

FIG. 2.—([O II] + [O III])/Hβ is plotted against [O III]. The triangles are from data tabulated by McGaugh (1991) from references cited therein. The squares are from data from Oey & Kennicutt (1991). The crosses are from Walsh & Roy (1989), and the circles are from McCall, Rybski, & Shields (1985). The strong correlations suggest that [O III] alone is sufficient to identify *general* trends in [O II] + [O III], which are in turn correlated to the oxygen abundance.

suggest that such an inflection point exists, but at a smaller value of the oxygen abundance than necessary to account for the observed flattening. In support of this assertion, note that when line ratios have been converted to oxygen abundances using available calibrations, the break in the excitation gradient is propagated to the abundance gradient at the same radius (Vílchez et al. 1988; SDH). Unfortunately, there is significant uncertainty both in the data and in the models. Until temperature measurements are available for regions with a wide variety of abundances or the shapes of abundance profiles are measured for many galaxies with different mean abundances, the question will remain unanswered. Given our current calibration of line ratios, the bend in the line-ratio gradient is apparently due to a corresponding change in the radial distribution of oxygen. Despite this uncertainty, I now proceed to discuss the connection between the star-forming viscous disk models and the shape of the abundance profile.

3. STAR-FORMING VISCOUS DISKS

A trademark, if not the defining characteristic, of spiral galaxy disks is the exponential surface luminosity profile. While there are a variety of evolutionary scenarios which result in such profiles, the one of most interest in this context was introduced by Lin & Pringle (1987). They demonstrated that an exponential profile is the natural end product of star-forming viscous disks, provided that one adopts the assumption that the star formation and viscous time scales are comparable. Whether this model describes the origin of the stellar profile is not as relevant to this work as whether the evolution of an existing stable disk with an exponential surface luminosity profile can be described by such a model. To some degree, models of star-forming viscous disks must be applicable to galaxy disks. The model has been furthered by the work of Clarke (1989) and Sommer-Larsen & Yoshii (1989, 1990, hereafter SLY89 and SLY90) in which they examined the resulting chemical abundance profiles. In the latest of these, models that include infall (SLY90), the authors produced model abundance curves that are accurate fits to the observed stellar and gaseous abundances as a function of radius in our own Galaxy, and to the age-metallicity relationship and the metallicity distribution of G dwarfs in the solar neighborhood. These models are a simplification of the much more complicated physical processes involved, but they have had some important successes. Might a connection between the rotation curve and the abundance profile be expected within the framework of star-forming viscous disk models?

The basic model is straightforward, and for specific details I refer the reader to the papers by Sommer-Larsen & Yoshii. In outline, the model consists of an axisymmetric disk in which the gaseous disk viscously evolves on a time scale t_v, and which forms stars on a time scale t_s. The stars, once formed by the simple prescription that $\partial\Sigma_s/\partial t = \Sigma_g/t_s$, where Σ_s is the surface density of stars and Σ_g is the surface density of gas, do not disperse radially. By invoking conservation of angular momentum and mass, for the annuli that construct the disk, and by assuming that the angular velocity Ω does not change with time, one can produce the equation that governs the evolution of the surface gas density given by Lin & Pringle (1987):

$$\frac{\partial \Sigma_g}{\partial t} = -\frac{\partial}{R\,\partial R}\left\{\left[\frac{\partial(R^2\Omega)}{\partial R}\right]^{-1}\frac{\partial}{\partial R}\left(\nu\Sigma_g R^3\frac{\partial\Omega}{\partial R}\right)\right\} - \frac{\Sigma_g}{t_s}, \quad (1)$$

where ν is the coefficient of kinematic viscosity. The other principal equation of the model describes the chemical evolution of the disk and is, following SLY89,

$$\frac{\partial}{\partial t}(Z\Sigma_g) = -\frac{\partial}{R\,\partial R}(Z\Sigma_g R u_r) + \frac{\partial}{R\,\partial R}\left(\nu_D \Sigma_g R\frac{\partial Z}{\partial R}\right) - Z\frac{\Sigma_g}{t_s} + y(1-Z)\frac{\Sigma_g}{t_s}, \quad (2)$$

where Z is the mass fraction of heavy elements in the gas, y is the chemical yield, ν_D is the diffusion coefficient, and u_R is the radial velocity of the gas. The radial velocity of the gas is given by

$$u_R = -\frac{\alpha}{2-\alpha}\frac{\nu}{R}\left[\frac{\partial \log \Sigma}{\partial \log R} + \frac{\partial \log \nu}{\partial \log R} + (2-\alpha)\right], \quad (3)$$

where α is the radial power-law dependence of Ω (i.e., $\Omega \propto R^{-\alpha}$). These are the basic equations describing the model. For details relating the various time scales and viscosities I refer the reader to SLY90 and references therein.

In a full treatment of the problem the equations are integrated numerically. However, one can learn the characteristics of the model under various conditions by examining the equations given above. In the context of this *Letter*, the most interesting aspect of the model is the dependence of the radial abundance distribution on α. For flat rotation curves $\alpha = 1$, while for solid-body rotation (linearly rising rotation velocities) $\alpha = 0$. Typical spiral galaxy rotation curves rise linearly in the inner part of the disk and are flat at larger radii. Because there is no radial gas flow when $\alpha = 0$ (eq. [3]), the first term on the right-hand side of equation (2) is eliminated. In addition, because $\alpha = 0$ and $\nu_D = (\alpha\nu)/(2-\alpha)$, $\nu_D = 0$ and the second term on the right-hand side of equation (2) is also eliminated. Finally, because $\alpha = 0$, $\partial\Omega/\partial R = 0$, and so only the second term on the right-hand side of equation (1) is nonzero. When

$\alpha = 0$ (linearly rising), neither equation (1) nor equation (2) contains nonzero terms that remain to connect the evolution of one annulus to that of its neighbors. The independence of annuli arises because when the disk is in solid-body rotation, there is no relative velocity between one annulus and another, and therefore no viscous drag or turbulent diffusion. When $\alpha = 1$, the model includes radial gas flows. Any outflow must consist of relatively enriched gas, since the inner annuli have higher metal abundance (standard models produce negative abundance gradients [cf. SLY89] which agree with observations), while inflow consists of relatively metal-poor gas. A radial outflow of enriched gas increases the abundances in the outer disk and flattens whatever metal abundance gradient would otherwise be present. A radial inflow will also flatten the abundance gradient. These conclusions agree with the results from numerical simulations that exclude radial gas flows and turbulent diffusion (SLY90). This simple argument suggests that the abundance gradient in the inner portion of a galaxy disk, that with a linearly rising rotation curve ($\alpha = 0$), should be steeper than that in the outer portion of the disk, that with a flat rotation curve ($\alpha = 1$). This interpretation also suggests that the change in slope should occur roughly where the rotation curve changes slope.

4. DISCUSSION AND CONCLUSION

In this *Letter* I have presented the following hypothesis: that the oxygen abundance gradients in the disks of spiral galaxies flatten noticeably at the radius where the rotation curve changes from linearly rising to flat, and that this effect has a simple physical explanation within the framework of star-forming viscous disk models. The evidence in support of the first part of the previous statement comes from observations of H II regions in the disks of nearby spiral galaxies. All noninteracting, unbarred spiral galaxies that have had a large number of H II regions observed in the portions of the disk that have a linearly rising or flat rotation curve have R_{23} or [O III]/Hβ profiles that change slope at a radius that corresponds to the turnover radius of the rotation curve. Furthermore, no galaxy that has had a large number of regions observed shows any evidence of a change in slope of the line-ratio profile at a radius other than the rotation curve turnover. However, the sample is small, and so this result is not definitive. The behavior of the line ratios was linked to a corresponding change in oxygen abundance, although other possibilities (e.g., errors in the line-ratio calibration, changes in the ionizing spectrum of stars, or systematic changes in the ionization parameter) could not be eliminated. A basic outline of the existing star-forming viscous disk models was presented. A simple argument demonstrated that one might expect the inner disks of spiral galaxies, which have linearly rising rotation curves, to have steeper abundance gradients than the outer disks, which have flat rotation curves. The change in slope of some line-ratio radial profiles, and presumably the abundance profile, strengthens the case for obtaining observations of many H II regions per galaxy. For many galaxies it may be misleading to characterize the abundance profile with a single scale-length exponential.

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REFERENCES

Ball, R., Sargent, A. I., Scoville, N. Z., Lo, K.-Y., & Scott, S. L. 1985, ApJ, 298, L21
Begeman, K. 1987, Ph.D. thesis, Univ. Groningen
Belley, J., & Roy, J.-R. 1992, ApJS, 78, 61
Clarke, C. J. 1989, MNRAS, 238, 283
Dinerstein, H. L. 1990, in The Interstellar Medium in Galaxies, ed. H. A. Thronson, Jr., & J. M. Shull (Dordrecht: Kluwer), 257
Edmunds, M. G., & Pagel, B. E. J. 1984, MNRAS, 211, 507
Garnett, D. R., & Shields, G. A. 1987, ApJ, 317, 82
Lin, D. N. C., & Pringle, J. E. 1987, ApJ, 320, L87
McCall, M. L., Rybski, P. M., & Shields, G. A. 1985, ApJS, 57, 1
McGaugh, S. S. 1991, ApJ, 380, 140
Milliard, B., & Marcelin, M. 1981, A&A, 95, 59
Oey, M. S., & Kennicutt, R. C., Jr. 1991, in preparation
Rots, A. H. 1975, A&A, 45, 43
Scowen, P. A. 1991, PASP, 103, 902
Scowen, P. A., Dufour, R. J., & Hester, J. J. 1992, AJ, submitted (SDH)
Searle, L. 1971, ApJ, 168, 327
Sommer-Larson, J., & Yoshii, Y. 1989, MNRAS, 238, 133 (SLY89)
———. 1990, MNRAS, 243, 468 (SLY90)
Vílchez, J. M., Pagel, B. E. J., Díaz, A. I., Terlevich, E., & Edmunds, M. G. 1988, MNRAS, 235, 633
Walsh, J. R., & Roy, J.-R. 1989, ApJ, 341, 722 (WR89)
Zaritsky, D., Elston, R., & Hill, J. M. 1989, AJ, 97, 97 (ZEH89)
———. 1990, AJ, 99, 1108 (ZEH90)