

## **The Extreme Outer Regions of Disk Galaxies: Star Formation and Metal Abundances**

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**Abstract.** The extreme outer regions of disk galaxies, lying at or beyond the classical optical radius defined by  $R_{25}$ , present an opportunity to study star formation and chemical evolution under unique physical conditions, possibly reminiscent of those which existed during the early stages of disk evolution. We present here some of the first results from a large study to measure star formation rates and metallicities in the extreme outer limits of a sample of nearby spiral galaxies. Despite their low gas column densities, massive star formation is often observed in these outer parts, but at an azimuthally-averaged rate much lower than that seen in the inner disk. Gas-phase O/H abundances of roughly 10% solar characterize the gas at  $1.5\text{--}2 R_{25}$ . The implications of our results for star formation ‘laws’ and models of disk evolution are discussed.

### **1. Introduction**

Distinguishing between competing models of disk galaxy formation and evolution requires observational constraints on the radial variations of the present star formation rate, the star formation history, and the gas-phase chemical abundance. Unfortunately, most observational studies to date have focused only on 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 HI disks which extend to typically  $\gtrsim 1.5\text{--}2 R_{25}$ , and in some rare cases to  $\gtrsim 3 R_{25}$ . Knowledge of the star formation rates and metallicities in these optically-faint, extreme outer reaches of disks is of particular importance for a variety of reasons. First of all, the predictions of various star formation laws and chemical evolution models often diverge most strongly in the outer parts of galaxies (eg. Prantzos & Aubert 1995, Tosi 1996), hence observational constraints are needed as far out in the disk as possible. Furthermore, the outer regions of disk galaxies provide a unique opportunity to study star formation and chemical evolution under the extreme

physical conditions of low gas surface density (yet high gas fraction), low metallicity and long dynamical times; similar conditions are also inferred for many high-redshift damped Lyman- $\alpha$  systems (eg. Pettini et al 1997), and low surface brightness galaxies (Pickering et al 1997).

We have carried out a large observational project to study the extreme outer disks of a sample of nearby spiral galaxies. Results are presented here for three galaxies (NGC 628, NGC 1058 and NGC 6946) studied so far which exhibit recent massive star formation at particularly large radii (and which perhaps not surprisingly have unusually large HI-to-optical sizes). A full discussion of these results is provided in Ferguson et al (1998a, 1998b).

## 2. Observations

Deep wide-field H $\alpha$  images were obtained to map the distribution of recent star formation, using the KPNO 0.9 m and the Lowell 1.8 m telescopes (deep BVR images were also obtained to study the extent and morphology of the underlying stellar disks, but these data will not be discussed here). In Figure 1, we show a continuum-subtracted H $\alpha$  images of one of the galaxies, NGC 6946. Radial H $\alpha$  surface brightness profiles were constructed via elliptical aperture photometry on the H $\alpha$  images.

Long-slit spectroscopy in the range 3700–7000Å was carried out for a small sample ( $\sim 10$ ) of our newly-discovered outer disk HII regions, in order to obtain metallicities. Oxygen and nitrogen abundances were derived via well-established ‘semi-empirical’ methods, based on the inter-relationship between metallicity and the intensities of the strong lines, [OII]  $\lambda 3727$  and [OIII]  $\lambda \lambda 4959, 5007$ , via the parameter  $R_{23}$ . We adopted the particular calibrations proposed by McGaugh (1991) and Thurston et al (1996) to derive O/H and N/O respectively.

## 3. Star Formation Beyond the Optical Edge of Disk Galaxies

### 3.1. Morphology

Our deep images reveal the discovery of massive star formation out to the extent of our imagery ( $\gtrsim 2 R_{25}$ ) in all three galaxies. The inner and outer disk HII regions appear strikingly different, in that star formation in the outer disk occurs in smaller, fainter and more isolated HII regions. The brightest outer disk HII regions detected here have diameters of 150–500 pc and H $\alpha$  luminosities of only  $1\text{--}80 \times 10^{37}$  erg s $^{-1}$  (for reference, the Orion nebula has  $L_{H\alpha} \sim 10^{37}$  erg s $^{-1}$ ). These luminosities imply enclosed ionizing populations of 0.2–20 equivalent O5V stars. Establishing whether the populations of inner and outer disk HII regions are actually intrinsically different, perhaps reflecting different modes of star formation, or if they only appear that way due to poor statistical sampling of the HII region luminosity function in the outer disk (ie. fewer HII regions, hence fewer luminous ones) is an important issue that we will address in the future.

The outer disk star formation appears remarkably organized, with the HII regions delineating narrow spiral arms. Our deep broad-band images reveal the existence of faint ( $B \sim 26\text{--}28$  mag/arcsec $^2$ ) stellar arms in all three galaxies, associated with these HII arms, and inspection of published HI maps also reveals

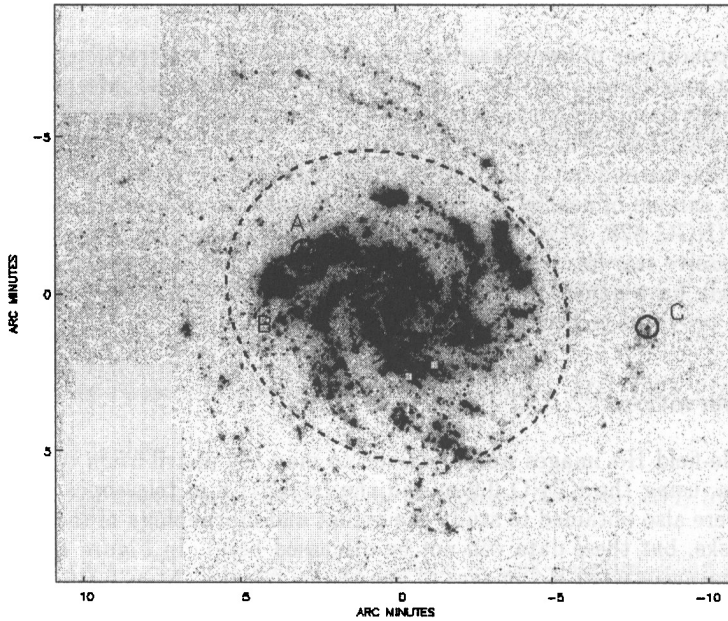


Figure 1. An  $H\alpha$  continuum-subtracted image of NGC 6946. The marked HII regions indicate those for which metallicities have been obtained.  $R_{25}$  is marked in each case by the large dashed circle.

similar structures in the underlying neutral gas (eg. Shostak & van der Kruit 1984; Dickey et al 1990; Kamphuis 1993). The relationship between the inner and outer spiral structure remains unclear, as indeed is the dynamics underlying the outer arms.

### 3.2. Star Formation Rates

The radial variation of the massive star formation rate per unit area across the disk is traced by the azimuthally-averaged  $H\alpha$  surface brightness ( $\Sigma_{H\alpha}$ ) distribution. Since most models for star formation invoke dependences on some form of the gas density, it is informative to plot  $\Sigma_{H\alpha}$  against various components of the interstellar gas (Figure 2). Different components of the gas are seen to correlate in very different ways with the star formation rate. While a roughly linear correlation is seen between  $\Sigma_{H\alpha}$  and  $\Sigma_{CO}$  (except for NGC 1058, where the relation is somewhat steeper), a very complicated non-linear behaviour is seen between  $\Sigma_{H\alpha}$  and  $\Sigma_{HI}$ . Abrupt steepenings are seen at low total gas column densities in all cases, where they occur at azimuthally-averaged total gas surface densities of  $5\text{--}10 M_{\odot}/\text{pc}^2$  or  $6\text{--}10 \times 10^{20} \text{ cm}^{-2}$ . Inspection of Figure 2 indicates that the location of the steepenings is approximately coincident with the radius where the disk undergoes the transition from being dominated by (warm) molecular to atomic gas, suggesting that a high covering factor of the molecular phase might be a requisite for significant star formation (eg. Elmegreen & Parravano 1994).

The existence of abrupt declines in  $\Sigma_{H\alpha}$  at low gas surface densities make it impossible to describe the observations with a single-component Schmidt law,

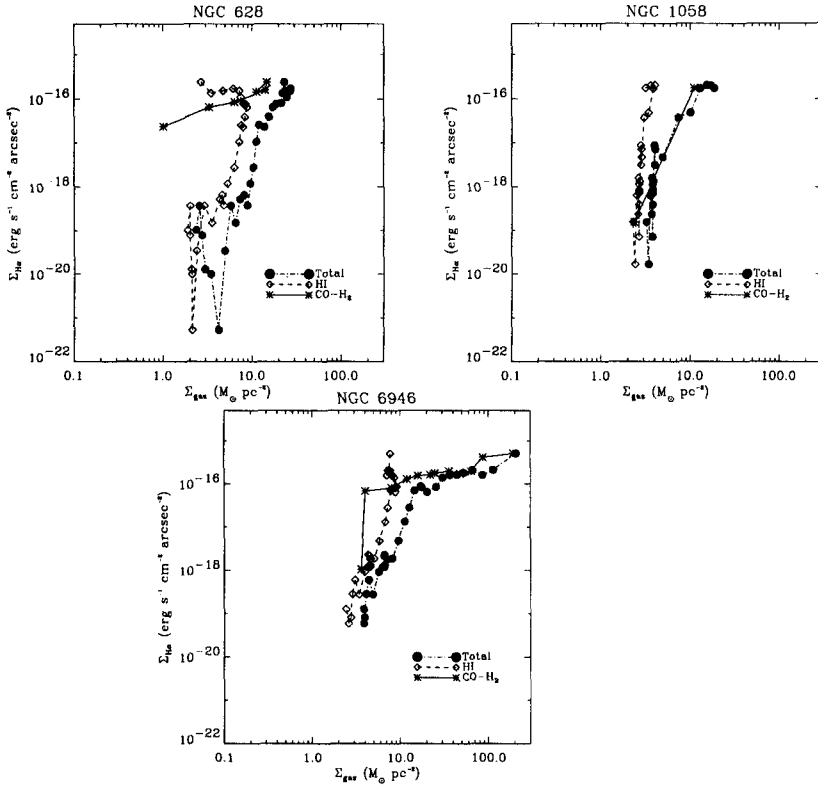


Figure 2. The variation of the deprojected, azimuthally-averaged  $H\alpha$  surface brightness,  $\Sigma_{H\alpha}$ , versus various components of gas surface density,  $\Sigma_{gas}$  (both quantities have been determined as a function of galactocentric radius in a series of elliptical annuli). The total gas surface density is the sum of the  $\Sigma_{CO}$  and  $\Sigma_{HI}$ , corrected for heavy elements.

with a dependence on total gas surface density alone. These steepenings are due almost entirely to sharp declines in the *covering factor* of star formation however, and not to changes in the rate at which stars form locally (see Ferguson et al 1998b). In other words, whenever star formation occurs, it occurs with roughly the same local intensity in both the inner and outer disks.

#### 4. What Drives Star Formation at Low Gas Surface Densities?

The instability driving star formation may well be gravitational; in this case the Toomre-Q criterion (Toomre 1964) yields a critical gas surface density above which one expects local instability to axisymmetric perturbations. For an infinitely thin, one component isothermal gas disk, the critical gas surface density above which self-gravity overcomes shear and pressure is given by

$$\Sigma_{crit} = \frac{\alpha\sigma\kappa}{\pi G} \tag{1}$$

where  $\alpha$  is a constant of order unity,  $\sigma$  is the velocity dispersion of the gas and  $\kappa$  is the epicyclic frequency<sup>1</sup>. Following Kennicutt (1989), we adopt  $\alpha = 0.67$ .

We have used published gas data (rotation curves and velocity dispersions) to calculate the radial variation of  $\Sigma_{crit}$  for each galaxy. Both NGC628 and NGC1058 have low inclinations, which means that the amplitudes and shapes of the rotation curves are somewhat uncertain (but, on the other hand, the radial variation of the velocity dispersions are known with good accuracy). For these two galaxies, we have normalised the rotation curves using the Shostak (1978) relation between  $M_B$  and the maximum rotation velocity, and assumed that the curves remain flat in the outer regions. Two estimates of the critical gas density were made, one assuming a constant gas velocity dispersion ( $6 \text{ km s}^{-1}$  for consistency with Kennicutt 1989) and the other including the radial variation determined directly from the HI observations.

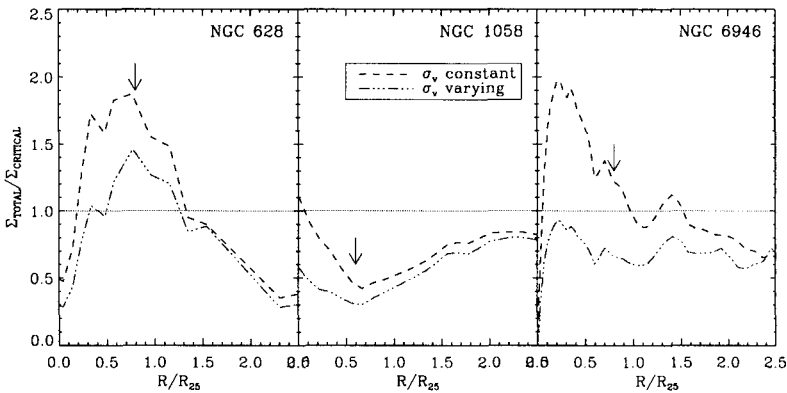


Figure 3. The radial variation of the ratio of the azimuthally-averaged (observed) gas surface density to the critical surface density for gravitational instability, calculated using both a constant velocity dispersion (dashed line) and a radially-varying one (dashed-dotted line). The solid horizontal line indicates the value of the ratio above which instability is expected.

The observed gas surface densities typically lie within a factor of two of the estimated critical densities at all radii, with the agreement often being even better when a radially-varying velocity dispersion is used (eg. NGC 6946, see Figure 3). This general agreement is very encouraging, in view of that fact that many of the input data – eg. rotation curves, gas surface densities, value of  $\alpha$  etc – used to estimate  $\Sigma_{crit}$  have significant uncertainties. It therefore appears that the outer disks of these galaxies lie close enough to the Q-stability limit so that processes such as swing amplification can operate and trigger star formation locally. Realistic uncertainties in the quantities used in this derivation are not likely to change the value of the stability parameter ( $\Sigma/\Sigma_{crit}$ ) by more than a factor of two at any given radius, and hence should not affect our principal conclusion that the gas disks are marginally unstable over a large radial zone.

<sup>1</sup>The epicyclic frequency is defined as  $\kappa = \sqrt{2} \frac{v}{R} \sqrt{1 + \frac{R}{v} \frac{dv}{dR}}$ .

On the other hand, the abrupt decreases in star formation rate at low gas surface density appear uncorrelated with changes in the gravitational stability of the disk (see Figure 3); that is, the locations where  $\Sigma_{H\alpha}$  plummets (indicated by the small arrows in Figure 3) are no more or no less stable than any other location in the disk. Further, while the stability parameter changes by only a factor of a few at most across each disk, the star formation rate per unit area typically changes by a factor of  $10^2$ – $10^3$ ! The sizes of the star formation regions are also difficult to reconcile with the predictions of the gravitational instability model, the theoretically most unstable length being much larger (i.e. a few kiloparsecs). Thus, while local gravitational instability can probably account for the existence of star formation at large radii in these three galaxies, it fails to explain either the rates of star formation or the scales of star formation across the disks.

What alternative explanations are there for the reduced star formation rates seen in the outer disk? It may be that star formation occurs only when the local gas column exceeds some fixed threshold value (eg. Skillman 1987), and perhaps reaching that threshold becomes more difficult at larger radii. Such a local threshold could be related to a critical column density of dust necessary to shield molecular gas from UV radiation. Indeed, Elmegreen & Parravano (1994) argue that the low thermal pressures make it increasingly difficult to sustain a cool molecular phase beyond  $\sim 3$  disk scale-lengths. Comparison of our H $\alpha$  images to HI maps shows star formation down to local HI columns of a few times  $10^{20}$  cm $^{-2}$ , but the HI maps are for the most part low resolution (few kiloparsecs) and better data are needed to test this idea. Yet another explanation for the reduced rates could be an intrinsic correlation between azimuthally-averaged star formation rate and gas *volume* density, combined with a vertical flaring of the gas disk, such that the transformation between gas surface density and volume density varies with galactocentric radius (see also Madore et al 1974). It is well known that gaseous disks exhibit an increase of scaleheight at large radius (eg. Merrifield 1992) whereas the young stars are confined to a thin plane. The combination of an increase in gas scale height with radius with the slow decline of gas surface density could conspire to produce a rapid decline in areal star formation rate between the inner and the outer disks, as is observed. We will investigate the success of these models in more detail in future work.

## 5. Chemical Abundances at Large Radii

Figure 4 presents the derived O/H abundances for the galaxies as a function of the deprojected galactocentric radius, normalised to  $R_{25}$ . The outermost abundances in all cases are  $\sim 10$ – $15\%$  solar, measured at radii in the range  $1.5$ – $2 R_{25}$ . Although these represent some of the lowest abundances ever measured in spiral disks, they indicate that the outermost gas is far from being pristine.

We have compared the O/H gradients derived from fitting the entire set of datapoints in each galaxy and from fitting only those points lying within the optical disk (see Figure 4). Clearly, the outer disk abundances play a crucial role in defining the abundance gradient across the disk, leading to significantly steeper gradients for NGC 1058 and NGC 6946. Within the limits of the current dataset, it appears that the radial abundance gradients can be adequately described by



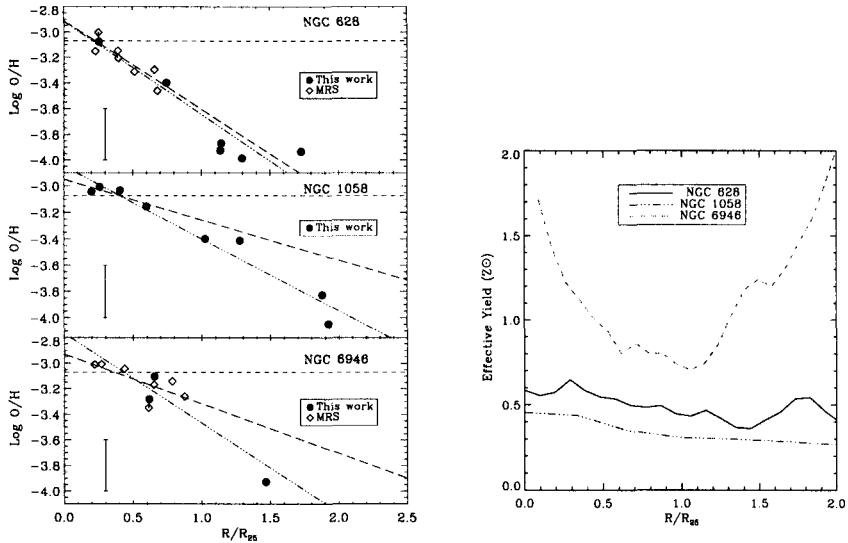


Figure 4. (Left) Radial variation of O/H, expressed in terms of the optical radius. The solar value is indicated by the horizontal dashed line. The dashed-dotted lines indicate fits to all the abundance measurements, whereas the long-dashed lines indicate fits to only the inner disk points. (Right) The radial variation of the effective yield, as derived for the closed box model.

single log-linear relationships. This result would appear to imply a continuity in the star formation (ie. metal production) process from inner to extreme outer disk, whereas our direct observations of the present star formation rate indicate that this is not the case. Gas flows and/or significant pre-enrichment of the disk gas may be required to reconcile these observations.

To assess the importance that gas flows might have had in the evolution of outer galactic disks, we have compared our data with the predictions of the simple ‘closed box’ model (no inflow or outflow from each radial zone). The closed box model can be represented by a simple relation  $Z = -p \ln \mu$  where  $p$  is the yield of the element in question and  $\mu$  is the gas fraction, defined as baryonic mass in gas to the total baryonic mass (stars + gas). We have used our deep B-band surface photometry and published HI and CO maps to calculate the gas fractions. Figure 4 (right) shows the radial variation of the effective yield required to reconcile our observations with the closed box model. Interestingly, both NGC 628 and NGC 1058 are consistent with relatively constant effective yields across their disks, with values similar to that found in the solar neighbourhood ( $0.5 Z_{\odot}$ ; Wyse & Gilmore 1995). In these cases, it would therefore appear that the role of gas flows in the evolution of the disk is similar to that for the solar neighbourhood. On the other hand, NGC 6946 exhibits gas fractions that are too high for the observed metallicity at both small and large radius.

## 6. Conclusions

The first results from our ongoing study of extreme outer galactic disks indicate that, in at least some galaxies, these regions are the sites of ongoing massive star formation and have metallicities which are low, although far from pristine. Observations of star formation in these low gas surface density parts are of particular importance for testing current ideas about the processes which govern large scale formation in galaxies. Our analysis suggests that considerations of gravitational instability alone cannot explain why the rate of star formation drops so abruptly beyond the optical edges of disk galaxies.

The low metallicities in these regions are similar to those measured in some high-redshift damped Lyman- $\alpha$  systems (eg. Pettini et al 1997) and suggest that outer disks are relatively unevolved at the present epoch. Perhaps star formation has only recently begun in these parts, or perhaps the extreme outer disk has been forming stars for a significant period of time, but at a such low rate that little evolution has had the chance to take place. Distinguishing between these two alternatives requires establishing the mean age of the bulk of the outer disk stars, and we are currently investigating this issue via deep HST photometry of resolved stars in the outer parts of galaxies.

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