UGC8802: A MASSIVE DISK GALAXY IN FORMATION

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ABSTRACT

We report new observations of the galaxy UGC8802 obtained through the GALEX Arecibo SDSS Survey (GASS), which show this galaxy to be in a remarkable evolutionary state. UGC8802 (GASS35981) is a disk galaxy with stellar mass $M_*$ = $2 \times 10^{10} M_\odot$, which appears to contain an additional $2.1 \times 10^{10} M_\odot$ of H I gas. New millimeter observations with the IRAM 30 m telescope indicate a molecular gas mass only a tenth this large. Using deep long-slit spectroscopy, we examine the spatially resolved star formation rate (SFR) and metallicity profiles of GASS35981 for clues to its history. We find that the star formation surface density in this galaxy is low ($\Sigma_{\text{SFR}} = 0.003 M_\odot$ yr$^{-1}$ kpc$^{-2}$) and that the star formation is spread remarkably evenly across the galaxy. The low molecular gas masses measured in our three IRAM pointings are largely consistent with the total star formation measured within the same apertures. Our MMT long-slit spectrum reveals a sharp drop in metallicity in the outer disk of GASS35981. The ratio of current SFR to existing stellar mass surface density in the outer disk is extremely high, implying that all the stars must have formed within the past $\sim$1 Gyr. At current SFRs, however, GASS35981 will not consume its H I reservoir for another 5–7 Gyr. Despite its exceptionally large gas fraction for a galaxy this massive, GASS35981 has a regular rotation curve and exhibits no sign of a recent interaction or merger. We speculate that GASS35981 may have acquired its gas directly from the intergalactic medium, and that GASS35981 and other similar galaxies identified in the GASS survey may provide rare local glimpses of gas accretion processes that were more common during the prime epoch of disk galaxy formation at $z \sim 1$.

Key words: galaxies: evolution – galaxies: individual (UGC8802) – galaxies: kinematics and dynamics – galaxies: star formation – galaxies: stellar content

Online-only material: color figures

1. INTRODUCTION

One of the largest gaps in our understanding of how galaxies form and evolve is the question of how gas—the raw material for star formation—flows into and out of galaxies, and how these flows regulate star formation in these systems. Although LCDM simulations make specific predictions for how structure in the dark matter assembles through hierarchical clustering, the assembly of the visible, baryonic components of galaxies is still a subject of considerable controversy.

The currently favored theoretical picture is that cold gas flows along filaments into the centers of assembling dark matter halos at high redshifts ($z > 2$), and this process can build massive galaxies rapidly at early times (e.g., Genel et al. 2008; Dekel et al. 2009). At lower redshift, massive spiral galaxies are thought to accrete gas much more slowly, at a rate of less than a few solar masses per year, from a surrounding hot corona (Maller & Bullock 2004; Kaufmann et al. 2006; Peek et al. 2008; Binney et al. 2009). Gas may also continue to accrete through major or minor mergers with other galaxies, although this is not believed to be the primary way in which ongoing star formation in local spiral galaxies is fueled at present (Sancisi et al. 2008). Outflows, whether from star formation or active galactic nucleus (AGN)-related feedback mechanisms, are another piece of the puzzle, and their role in shutting down star formation, limiting the efficiency with which stars are able to form, or even providing fuel for ongoing star formation in the form of recycled wind material (Oppenheimer et al. 2010) is similarly debated.

In order to learn more about cold gas in nearby galaxies, we are carrying out the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010). GASS is designed to measure the neutral hydrogen content of a representative sample of $\sim$1000 galaxies uniformly selected from the Sloan Digital Sky Survey (SDSS) spectroscopic and GALEX imaging surveys, with stellar masses in the range $10^{10}$–$10^{11.5} M_\odot$ and redshifts in the range $0.025 < z < 0.05$. As GASS observations are designed to detect H I down to a gas-fraction limit of 1.5%, the full GASS sample will be the first H I survey able to place meaningful, unbiased constraints on the atomic gas reservoirs that may contribute to future growth in massive galaxies.

We are also pursuing a companion project on the IRAM 30 m telescope, COLD GASS, which will obtain accurate and homogeneous molecular gas masses for a subset of $\sim$300 galaxies from the GASS sample. These data will allow us to characterize the balance between atomic and molecular gas in the galaxies in our sample, and understand the physical processes that

8 http://www.mpa-garching.mpg.de/GASS
9 http://www.mpa-garching.mpg.de/COLD_GASS
determine how the condensed baryons are partitioned into stars, \( \text{H} \text{I} \) and \( \text{H}_2 \) in the local universe.

In this paper, we report on UGC8802, an extraordinary galaxy blindly selected for inclusion in the GASS sample (under the catalog name GASS35981, used hereafter), which contains a reservoir of \( \text{H} \text{I} > 10^{10} M_\odot \), at least equal in mass to the galaxy’s entire stellar content. This galaxy contains less than one-tenth of this mass in \( \text{H}_2 \) and also has a rather modest star formation rate (SFR). We describe the spectroscopic follow-up that enables us to conclude that the outer disk of this galaxy is currently forming from gas that has likely accreted from the external environment. In the following, we adopt a standard \( \Lambda \text{CDM} \) cosmology with \( \Omega_\text{m} = 0.3 \) and \( \Omega_\Lambda = 0.7 \).

2. OBSERVATIONS

GASS35981 (also SDSS J135308.36+354250.5, in addition to UGC8802), was selected for inclusion in the GASS parent sample because it has photometry from both SDSS and GALEX, is located in a region of sky accessible to Arecibo, and has stellar mass of \( M_\star = 2 \times 10^{10} M_\odot \) and redshift of \( z = 0.0411 \) that fit into our targeted range. GASS35981 has pre-existing \( \text{H} \text{I} \) observations available from the Cornell \( \text{H} \text{I} \) Digital Archive (Springob et al. 2005). The mass of \( \text{H} \text{I} \) in GASS35981 is estimated from the line flux to be \( 2.1 \times 10^{10} M_\odot \), and the rest-frame velocity width of the \( \text{H} \text{I} \) line is \( W_\text{50} = 360 \pm 25 \text{ km s}^{-1} \) (Figure 1). We display the \( \text{H} \text{I} \) archive spectrum in Figure 1. We note that there is no evidence for contamination from possible companion galaxies within the 3.5 Arecibo beam: one nearby galaxy has a spectroscopic redshift of 0.14, and two additional faint companions have SDSS photometric redshifts consistent with \( z = 0.14 \).

The lower panel of Figure 1 shows that GASS35981 (blue star) lies near the extreme end of \( \text{H} \text{I} \) fractions observed by GASS. Indeed, its gas fraction is comparable to the highest values measured for all galaxies in this stellar mass range (e.g., Giovanelli et al. 2007). Indeed, even in \( \text{H} \text{I} \)-selected samples, which are biased toward objects like GASS35981, galaxies in this stellar mass range (\( M_\star > 10^{10} M_\odot \)) with such high gas fractions are quite uncommon (e.g., the ”\( \text{H} \text{I} \) Giants” described by García-Appadoo et al. 2009).

It is also clear that GASS35981 lies significantly above the best-fit ”gas fundamental plane” (dotted line) relating stellar mass surface density, \( \text{NUV}–r \) color, and gas fraction, as described in Catinella et al. (2010). Because this galaxy was an interesting outlier and a presumed easy target, GASS35981 was selected for inclusion in our initial COLD GASS pilot program to obtain molecular gas measurements with the IRAM 30 m telescope.

Observations of GASS35981 in the \( J = 1-0 \) rotational transition of CO were made at 3 mm with the IRAM 30 m telescope, in three different pointings: one at the galaxy center, and one each to the north and south, one beamwidth (22") away along the galaxy major axis. Data were taken in 2009 June and August, using the WILMA and 4 MHz backends simultaneously to record the data, and the CLASS\(^{10} \) software to process them. Individual scans were examined, and a linear baseline subtracted from each of them. After rejection of scans with unstable baselines due to, e.g., poor atmospheric conditions, the data were combined and binned to a spectral resolution of 21 km s\(^{-1} \).

The CO line is detected in the central pointing with \( S/N = 5.8 \), for an integrated line flux of \( T_a^* = 0.43 \pm 0.07 \text{ K km s}^{-1} \) within a 400 km s\(^{-1} \) wide window. We set upper limits at 0.29 and 0.43 K km s\(^{-1} \) for the north and south offset pointing, respectively. Adopting a conversion factor of \( X_{\text{CO}} = 4.4 M_\odot / L' \) (where \( L' \) has units of K km s\(^{-1} \) pc\(^2\)), these fluxes correspond to an \( \text{H}_2 \) mass of \( 8.8 \times 10^{8} M_\odot \) in the central 22" pointing, and upper limits of 5.9 and \( 8.8 \times 10^{8} M_\odot \) in the offset pointings. Using an aperture correction for the 22" beam of the IRAM telescope based on resolved CO maps of nearby galaxies, we estimate a total \( \text{H}_2 \) mass of \( 1.45 \times 10^{9} M_\odot \) for the galaxy, based on the detection in the central pointing. Following the prescription of Springob et al. (2005), we measure a line width of \( W_50 = 335 \pm 20 \text{ km s}^{-1} \). This corresponds to a rest-frame width of 321 km s\(^{-1} \). The spectra of all three pointings are shown in Figure 2.

Follow-up long-slit spectroscopy of GASS35981 was obtained on 2009 November 20, using the Blue Channel Spectrograph on the 6.5 m MMT telescope on Mt. Hopkins, Arizona. The spectrum was obtained with a slit of width 1.25 oriented to P.A. = 13:4 on the sky, such that the slit runs along the major axis of the galaxy, as indicated in the second panel of Figure 3. GASS35981 was observed in 2 \( \times 600 \) s exposures with the 500 line grating. The spectrum covers a wavelength range of \( \sim 3900–7000 \) Å at a spectral resolution of \( \sim 4 \) Å FWHM.

\(^{10} \) http://www.iram.fr/IRAMFR/GILDAS
To measure the radial velocity as a function of radius in two ways: (1) by cross-correlating each spectrum against galaxy templates to determine the velocity, and (2) by fitting directly to the centroids of the Hα emission line. The method utilizing Hα allows us to extend our rotation curves to larger radii. The two methods yield consistent curves at radii where we can fit templates and measure emission line centroids. The resulting rotation curve is plotted in Figure 4, not corrected in any way for the inclination of the galaxy. The solid line plotted over the measured curve is the best-fitting rotation curve of the form

\[ V(R) = V_{\text{MAX}} R / (R^2 + R_{s}^{-2})^{1/2} + \Delta V \] (Böhme et al. 2004; Moran et al. 2007), where \( R \) is the radius, \( a \) and \( R_{s} \) are free parameters that govern the shape of the rotation curve and its turnover, and \( \Delta V \) is the offset of the galaxy’s central velocity from the redshift obtained from the SDSS spectrum (also left as a free parameter). We measure a circular velocity for GASS35981 of

\[ W = 321 \pm 10 \, \text{km} \, \text{s}^{-1} \] (a). This is consistent with the value obtained from the CO spectrum.

Table 1 summarizes some of the basic properties of GASS35981, including the masses and line widths of the various components. The agreement between CO and Hα widths is not surprising because at the radius of the IRAM beam (11 arcsec), the optical velocity has already reached its maximum value. It is interesting, however, that the rest-frame H I velocity width, \( W = 360 \pm 25 \, \text{km} \, \text{s}^{-1} \), appears to be somewhat larger than the estimates from both CO and Hα. Since the optical rotation curve of GASS35981 is flat, one might have expected a better agreement between the H I and Hα widths.

13 We note that the velocity widths are not deprojected to edge-on (the galaxy’s inclination is 63°/25 from face-on, estimated as \( \cos(i) = b/a = 0.45 \).
Even though the significance of the difference is marginal (smaller than 2σ), it is interesting to comment on possible causes of the effect. Based on a statistical analysis of a large data set with both Hα and H i spectroscopy, Catinella et al. (2007) find a systematic difference between optical and H i velocities of normal spiral galaxies with flat rotation curves of a factor 1.06 (see their Figure 6). After applying a 6.5 km s\(^{-1}\) turbulent motion correction (as in Catinella et al. 2007), and accounting for such a scaling factor, the H i width of GASS35981 is 333 km s\(^{-1}\), which is in slightly better agreement with the optical rotation curve and CO line width. The residual difference might be explained by uncertain statistical and turbulent motion corrections, or it might provide evidence for accretion of H i at large radii. It is interesting that the H i profile shown in Figure 1 is noticeably asymmetric. We will come back to this point in the final discussion.

3.2. Spatial Binning of the Spectrum

We now correct each row in the unbinned two-dimensional spectrum to a common rest frame using the rotation curve in Figure 4. This procedure is necessary if we wish to obtain accurate measurements of spectral lines. We then re-bin the spectrum to a slightly higher targeted S/N of ∼8. To each side, the two bins at highest radii are chosen by hand, because there is no clear detection of the stellar continuum this far out. As can be seen in Figure 3, nebular emission is still clearly detected in these regions, so we choose the binning to correspond to clear transitions between the bright or faint knots of Hα. We end up with a total of 12 radial bins, and we mark the limits of each region overlapping our slit. Note that the X-axis arcsecond scale applies to all four panels of this figure.

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### Table 1

| Property | Value       | Property | Value       |
|----------|-------------|----------|-------------|
| M\(_{\text{bul}}\)\(^{a}\) | 2.0 ± 0.3 \times 10^{10} M\(_{\odot}\) | W\(_{\text{H}\alpha}\) | 318 ± 10 km s\(^{-1}\) |
| M\(_{\text{H}\alpha}\)\(^{a}\) | 2.1 ± 0.4 \times 10^{10} M\(_{\odot}\) | W\(_{\text{H}\alpha}\)\(^{b}\) | 360 ± 25 km s\(^{-1}\) |
| M\(_{\text{CO}}\) | 1.4 ± 0.2 \times 10^{9} M\(_{\odot}\) | W\(_{\text{CO}}\) | 321 ± 19 km s\(^{-1}\) |
| M\(_{\text{f}}\) | −21.2       | M\(_{\text{NUV}}\) | −18.7       |
| R\(_{25}\)\(^{c}\) | 24 kpc      | R\(_{\text{d}}\)\(^{d}\) | 9.8 kpc      |
| z        | 0.0411      | SFR\(_{\text{dust}}\) | 3.7 ± 0.3 M\(_{\odot}\) |

**Notes.**

\(^{a}\) Springob et al. (2005).
\(^{b}\) Rest-frame line width.
\(^{c}\) SDSS r-band isophotal major axis radius (25 mag arcsec\(^{-2}\)).
\(^{d}\) SDSS r-band Petrosian half-light radius.

3.3. Continuum and Emission Line Fitting

We employ a modified version of the technique of Brinchmann et al. (2004) to measure the strengths of key emission and absorption lines as a function of radius across GASS35981. The spectrum from each of our 12 spatial positions is first fit to a linear combination of templates drawn from Bruzual & Charlot (2003) single stellar population (SSP)
models, masking regions of the spectrum occupied by common emission lines. Best-fit model spectra are generated individually for both a low- and high-metallicity set of Bruzual & Charlot models (0.02 Z⊙ and Z⊙, respectively), and we retain the one with lowest reduced χ² of the fit. Near the center of the galaxy, these fits unambiguously favor the solar-metallicity model. Low-metallicity templates provide a slightly better fit in each of the two outermost bins where we can measure the stellar continuum (R ∼ 15 kpc on each side). However, we caution that the S/N in the continuum is <5 here, and so the best-fitting metallicity is unlikely to be a reliable indicator. The results of an example fit are shown in Figure 5.

Next, we subtract the best-fitting stellar continuum model from the measured spectrum, creating an emission-line-only spectrum where the Balmer emission lines can be measured free of contamination from the underlying stellar absorption. In the two outermost bins, only nebular emission is detected and no continuum fitting is possible. In these cases, we fit a low-order polynomial to the spectrum to correct for small imperfections in our sky subtraction, which arise when coadding across a large portion of the slit. We then measure emission lines using the polynomial-subtracted spectrum.

We fit a Gaussian function to the emission lines, with the width of the Gaussian constrained to a single value for all lines in a given spectrum. The positions of the line centroids are constrained to their rest wavelengths. The only free parameters in the fit are the amplitude of each line and an overall velocity offset term. For each line, we also recalculate the continuum level in a small region within 50 Å of each fitted line, and subtract this small residual from the template fits to further refine the measured emission line flux. In addition to the Balmer lines Hα, Hβ, and Hγ, we use to estimate dust extinction and SFR (see below), we also measure the forbidden lines [O iii] 5007, [N ii] 6548 and 6584, and [S ii] 6717 and 6731 to measure metallicity across the galaxy.

We limit our analysis of stellar absorption features to the D4000n index, which measures the strength of the 4000 Å break. This index is an indicator of stellar population age (see, e.g., Kauffmann et al. 2003). We use D4000n values measured from the best-fitting absorption line templates, rather than from the spectrum itself. The two agree well for spectral bins with high S/N. We choose the model measurement as we expect it to yield a more reliable estimate in bins where S/N in the continuum is only ∼3–5, because the model fit utilizes information from the entire spectrum.

We estimate the dust extinction within the nebular gas by calculating the Balmer decrement, which we define as the ratio of Hα/Hβ to the case B recombination ratio of 2.87 (Osterbrock 1989). We adopt the formula $A_V = 1.9655R_V \log (Hα/Hβ/2.87)$, where we assume $R_V = 3.1$ and adopt the Calzetti (2001) extinction curve. We further refine the estimates of $A_V$ by comparing to the Hγ line, which is only strong enough to be measured in emission in a few cases. However, even as an upper limit $H_V$ provides a useful constraint. If, after correcting all three lines for dust based on our original $A_V$ estimate, the ratios $Hγ/Hα$ and/or $Hγ/Hβ$ are inconsistent with the expected values of 0.474 and 0.166, respectively, we adjust $A_V$ upward or downward—staying within the 1σ errors on the original measurement—to improve the agreement with these values as far as possible.

We note that all SFRs reported below have been calculated after correcting fluxes for extinction using the Balmer decrement. Likewise, our equivalent widths (EWs) have been corrected for dust using our measured Balmer decrements and assuming $E(B−V)$ of the stellar light is ∼0.44 $E(B−V)$ of the gas, as in Calzetti (2001).
3.4. Colors and Star Formation Rates from the Photometry

We measure the UV/optical color profiles of GASS35981 using SDSS and GALEX photometry in two ways. First, we measure fluxes in a 5′ wide strip running along the major axis of the galaxy. Our chosen aperture lies on top of, but is wider than the spectroscopic slit. To ensure that the fluxes measured using the SDSS images are well matched to those measured from the GALEX images, we convolve the SDSS images with a Gaussian of FWHM 4.5′′ (the size of the GALEX point-spread function, PSF). The resulting color profile is displayed in the bottom panel of Figure 3.

For more precise comparison to the spectroscopy (but at the expense of lower S/N in lower surface brightness regions), we also measured colors through apertures with widths identical to the slit segments containing each of our 12 spectral bins. These apertures are smaller than the GALEX PSF, so we scale the SDSS u-band flux measured in the smaller apertures by the ratio of FUV or NUV to u measured in the wider aperture at the same position along the slit. We use these measurements to estimate SFR and stellar mass surface densities by fitting the full UV through optical spectral energy distributions (SEDs) to population synthesis models as described in J. Wang et al. (2010, in preparation). Our method is very similar to that described in Salim et al. (2007).

To optimize the fits, we constrain the internal extinction of the galaxies in the library of models to be consistent with the measured Balmer-decrement values for this galaxy. Assuming that the attenuation of the starlight is 0.44 times the extinction measured in nebular gas (Calzetti 2001), we obtain $\tau_\text{e} = 0.5$ averaged over our 12 spectral bins, with a dispersion of ±0.25. We use this as a prior in our parameter estimation.

4. RESULTS

In this section, we analyze SFRs, stellar population ages, and metallicities of the nebular gas as a function of position in GASS35981. We show that star formation is spread fairly evenly across the disk of the galaxy, but the ratio of current star formation to stellar mass surface density in the outskirts of the galaxy is very high. This suggests the outer disk has been formed recently. We then show that the modest H2 content implied by the CO observations matches expectations from the SFR profile of the galaxy. We also examine the metallicity profiles, finding a sharp drop in metallicity that corroborates our conclusion that stars in the outer disk were formed recently.

4.1. Star Formation in GASS35981

After correcting Hα luminosities for dust, we measure SFRs using the equation in Meurer et al. (2009): $\text{SFR} (M_\odot \text{yr}^{-1}) = L_{\text{H}\alpha} / (6.93 \times 10^{33} \text{W})$, corrected to a Kroupa (2001) initial mass function (IMF). Then, by dividing by the area of the galaxy covered by each portion of the slit (1.25 × 0.3′′, where $N$ is the number of individual rows that went into each coadded spectrum), we estimate the SFR surface density as a function of position across GASS35981. This is shown in Figure 6, left, from which it is clear that the SFR surface density is remarkably uniform across the galaxy. This result is confirmed by the SFR surface densities estimated from the photometry alone (Section 3.3), overplotted as red circles on Figure 6, which match the values estimated using the spectroscopy very well. The SFR surface density profile of GASS35981 is quite different to those of “normal” spiral galaxies of the same stellar mass. Figure 2 of Bigiel et al. (2008) shows that in spirals where H2 dominates in the central regions, $\Sigma_{\text{SFR}}$ decreases from 0.01–0.1 $M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ near the galaxy centers to less than 0.001 $M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ near the edges of the optical disk. The SFR surface density profile of GASS35981 is much more similar to those of H2-dominated dwarf irregular galaxies (Figure 3 of Bigiel et al.), but these galaxies have considerably smaller stellar masses.

In the right panel of Figure 6, we plot EW(Hα) as a function of position along the slit. Since the EW is the ratio of emission line flux to the underlying continuum, it is an excellent proxy for ratio of current star formation to past-averaged star formation (i.e., pre-existing stellar mass), conventionally referred to as the $b$-parameter. The exact relation between the two depends on the past SFH of the galaxy. An empirical relation between the two quantities can be derived for galaxies in the SDSS using the SFRs, stellar masses, and Hα EWs published in the SDSS MPA/JHU value added catalogs. The $b$-parameter is estimated from the SFRs and stellar masses using the formulation described in Brinchmann et al. (2004). We use this relation to transform between EQW(Hα), which is plotted on the left axis of Figure 6, to $b$, which is plotted on the right axis of the same figure.
We see in Figure 7 that $D4000_n$ appears to decrease from $\sim 1.7$ in the center of the galaxy to $1.3-1.4$ beyond $\sim 10$ kpc. For a simple SSP model from Bruzual & Charlot (2003), $D4000_n = 1.3$ indicates a stellar population age of 500 Myr, while $D4000_n = 1.7$ occurs at an age of $\sim 3$ Gyr. These characteristic timescales grow larger for more realistic extended SFHs; this will be discussed further in Section 5. The S/N of our spectrum is not high enough to measure $D4000_n$ at very large radii, but the fact that such young ages are implied for $R = 10$ kpc is suggestive that the outer disk may be even younger.

### 4.1.1. Analysis of the CO Measurements

Given the order of magnitude difference between the measured H\textsc{i} mass and the measured molecular gas mass, it is important to determine whether the latter is consistent with the derived SFR. Bigiel et al. (2008) show that SFR surface density is directly proportional to H\textsc{2} mass surface density according to the relation $\Sigma_{SFR} = 10^{-3.1} \Sigma_{H_2}$ (in units of $M_\odot$ yr$^{-1}$ kpc$^{-2}$ and $M_\odot$ pc$^{-2}$, respectively). This relation holds over a large range in $\Sigma_{H_2}$ (3–50 $M_\odot$ yr$^{-1}$ pc$^{-2}$) and does not appear to vary as a function of any larger scale property of the galaxies in the sample.

When comparing SFR and H\textsc{2} mass for GASS35981, we must carefully account for possible aperture effects, because the SFR surface density is measured through a narrow slit, while the H\textsc{2} masses are estimated in three much larger apertures with FWHM of 22′. However, we have seen that in GASS35981 the SFR surface density appears to be quite uniform across the whole galactic disk. The CO line flux measured in our central pointing corresponds to an average H\textsc{2} surface density across the beam of $\Sigma_{H_2} = 3.6 \pm 0.1 M_\odot$ pc$^{-2}$, under our assumed conversion factor $X_{CO} = 4.4 M_\odot/L_\odot$. Adopting the Bigiel et al. relation between $\Sigma_{H_2}$ and $\Sigma_{SFR}$ yields a predicted SFR surface density $\Sigma_{SFR} = 0.0029 \pm 0.0001 M_\odot$ yr$^{-1}$ kpc$^{-2}$, which is in excellent agreement with the observed $\Sigma_{SFR}$ in this galaxy.

In the two offset pointings where we do not detect any CO, our most stringent upper limit (in the northern pointing) implies that $\Sigma_{H_2} < 2.4 M_\odot$ pc$^{-2}$, and hence $\Sigma_{SFR} < 0.0019$. This is 50% lower than the median $\Sigma_{SFR}$ we measure from our spectra, though from Figure 6 we see that our photometric estimates of $\Sigma_{SFR}$ exhibit a dip in the region covered by the northern pointing, which could explain the low H\textsc{2} mass.

Alternatively, variation in the conversion factor $X_{CO}$ could explain the discrepancy; since below we will present evidence that the metallicity is low in the outer regions of GASS35981 (which implies a lower amount of CO per unit of H\textsc{2}), this possibility seems plausible. We note that Bigiel et al. (2008) neglected variations in $X_{CO}$ in deriving their SFR–H\textsc{2} relation, and so the $\sim 0.3$ dex scatter they measure likely includes a contribution from variations in metallicity/$X_{CO}$. Though the single discrepant point here is too little to draw conclusions from, in a future paper we will examine possible variations in $X_{CO}$ across the COLD GASS sample.

### 4.1.2. Total Star Formation Rate

Finally, we estimate a total SFR for GASS35981 by extrapolating the SFR surface density measured for each spectral bin along the slit to the annulus that spans the same radial range as that portion of the slit, and that extends half-way around the galaxy, where it meets the corresponding annulus extrapolated from the other side of our slit. The aperture corrections are
Figure 8. Top: metallicity of GASS35981 as a function of position along the slit, estimated from the \([\text{N}\,\text{II}]/\text{H}\alpha\) emission line ratio (Pettini & Pagel 2004). Solar metallicity is marked with the dotted line. Bottom: similar metallicity estimates including the ratio of \([\text{O}\,\text{III}]/\text{H}\beta\), also from Pettini & Pagel, as described in the text.

4.2. Metallicity Gradient

We utilize the \([\text{N}\,\text{II}]\) 6584 to \(\text{H}\alpha\) emission line ratio as our primary metallicity indicator. We estimate metallicity from the relation of Pettini & Pagel (2004): \(12+\log(O/H) = 9.37+2.03 \times N_2+1.26 \times N_2^2+0.32 \times N_2^3\), where \(N_2 = \log([\text{N}\,\text{II}]6584/\text{H}\alpha)\). The resulting metallicities are plotted as a function of position across GASS35981 in Figure 8. In the bulge and inner disk of the galaxy \((R < 15 \text{ kpc})\), GASS35981 exhibits near-solar metallicity. However, at large radii, we see a sharp drop in metallicity of \(\sim 0.5 \text{ dex}\), at a radius corresponding to the start of the blue, faint outer disk of the galaxy (Figure 3). This is also the region of the galaxy where the \(b\) parameter exceeds unity.

Sharp breaks to low metallicities are not common in the portion of the larger GASS sample with follow-up MMT spectroscopy that has been analyzed so far. We find an average gradient in \(\log(O/H)\) of \(-0.14 \text{ dex}/r_e\), compared to \(-0.41 \text{ dex}/r_e\) for GASS35981. Less than 10% of the galaxies in our sample exhibit metallicity below \(12+\log(O/H) < 8.5\), and in most of these cases, the low metallicities are seen over the whole galaxy. Only \(\sim 15\%\) of the 62 galaxies analyzed so far have metallicity gradients as strong as GASS35981, and even fewer of these exhibit a sharp drop. We note that there is one well-known local galaxy with a metallicity gradient similar to GASS35981: M101 (van Zee et al. 1998). The importance of this similarity is unclear, however, since the two galaxies differ in other respects (e.g., the distribution of star formation; Kuntz & Snowden 2010).

As a check on our \([\text{N}\,\text{II}]/\text{H}\alpha\) metallicity estimates, we also compute metallicity using \(O3N2 = \log([\text{O}\,\text{III}]5007/\text{H}\beta/([\text{N}\,\text{II}]6584/\text{H}\alpha])\) (Pettini & Pagel 2004), which is plotted in the bottom panel of Figure 8. Though intrinsically more accurate, this indicator provides somewhat poorer constraints for our galaxy, because \(\text{H}\beta\) is not always detected at \(>3\sigma\) in our spectra. We note, however, that metallicities measured in this way are entirely consistent with those from \([\text{N}\,\text{II}]/\text{H}\alpha\), as can be seen by comparing the two panels in Figure 8. We also use \((S\,\text{II}) 6717+\text{[S}\,\text{II}]6731/\text{H}\alpha\) as an additional check, as this line depends on metallicity in much the same way as \([\text{N}\,\text{II}]\) (Dopita et al. 2006). Although it is detected with lower S/N in our spectrum, and is more affected by sky subtraction residuals due to its redder wavelength, the \([\text{S}\,\text{II}]/\text{H}\alpha\) ratio exhibits a similar drop at large radii. This indicates that peculiar nitrogen abundances are not responsible for the effect that we see.

Finally, in Figure 9 we plot metallicity as a function of \(\text{EW(H}\alpha)\). There is clearly a strong correlation: regions of the galaxy with the highest ratio of current to past-averaged SFR are also the most metal-poor. We also overplot the best-fit relation between \(\text{EW(H}\alpha)\) and \([\text{N}\,\text{II}]-based metallicity for star-forming galaxies drawn from the SDSS MPA/JHU value-added catalog. These measurements apply to the region of the galaxies sampled by the \(3\,\text{arcsec}\) diameter SDSS fiber. The relation between SFR and metallicity measured within GASS35981 follows that exhibited by the general population of star-forming galaxies in SDSS. We note, however, that the galaxies with high \(\text{EW(H}\alpha)\) and low metallicities are generally much lower mass systems.

5. DISCUSSION

We have seen that GASS35981 is currently undergoing star formation that is evenly spread across the galaxy. In the outskirts, however, a sharp drop in metallicity and a correspondingly large...
increase in the EW(H\textalpha) suggest that the bulk of the stellar mass in this region has been formed only recently, and out of a low metallicity reservoir of gas.

In this section, we ask how long ago the gas began forming its stars, and we consider the processes that may have delivered the gas to the galaxy.

5.1. A Model Star Formation History

We construct a simple toy model of the galaxy’s SFH in the bulge ($R < 5$ kpc), inner disk ($5 < R < 15$ kpc), and outer disk ($R > 15$ kpc) of the galaxy. Using constraints derived from the galaxy’s current SFR and stellar mass surface density, we build a simple model that is consistent with observations in all three locations.

Our observations show that the current star formation is uniformly distributed across the galaxy, so we postulate that the overall SFH can be modeled by a period of constant star formation of some length that is the same everywhere, superimposed on an older stellar population that dominates at the center and is virtually absent at large radii.

Our model incorporates the following constraints.

1. At $R > 15$ kpc, the metallicity is low and the $b$ parameter is extremely high. Let us assume that this indicates all of the existing stellar mass has been built during the current star formation episode. For the three outer spectral bins with the lowest metallicities, the timescales for forming the entire stellar population at the currently observed SFR range from 0.7 to 2.0 Gyr. We thus adopt 1 Gyr as our reference value.

2. We then subtract the stellar mass formed in the current episode from the observed stellar mass in the bulge and the inner disk, and assign the resulting mass to the old stellar population. In the inner disk, the mass surface density in the old stellar component is $\sim$10 times that in the outer disk, while in the bulge region, this factor is closer to 60. For simplicity, we will concentrate all of the star formation needed to build this mass into a single episode of 1 Gyr length ending at $z = 1$ (7 Gyr in the past).

A simple schematic of this model SFH is shown in Figure 10. We then use Bruzual & Charlot (2003) models to predict $D_{4000}$ in the inner disk and bulge, obtaining values of 1.3 and 1.5, respectively. These values are in good agreement with the measured values of 1.4 and 1.6 in the corresponding radial bins. Thus, through only a simple partition of mass into old and young components, we can reasonably reproduce one of the key spectral features of GASS35981. We note that varying the formation time of the old component or doubling its timescale to 2 Gyr changes the results very little. Likewise, adjusting the length of the more recent star-forming episode within the range 0.7–2 Gyr does not significantly affect our results.

Finally, we can estimate the total fraction of the stellar mass added to the galaxy in the most recent star formation episode and find that it is around 20%. Note, however, that at its current SFR, GASS35981 will not exhaust its H\textsc{i} reservoir for another 5–7 Gyr.

5.2. Was the Gas Captured from Another Galaxy?

We have concluded that a new episode of star formation began approximately 1 Gyr ago in GASS35981. It is tempting to speculate that renewed star formation in this galaxy is connected to the acquisition of its large H\textsc{i} reservoir.

So how did GASS35981 acquire its gas? One possibility is that the gas was accreted as the result of an interaction with another gas-rich system. GASS35981 does have two luminous neighbors at projected distances of 300 kpc and 400 kpc with redshift differences of $\sim$0.4 km s$^{-1}$—i.e., GASS35981 does appear to be a member of a loose group. We do not, however, see any signs of an interaction or merger in either the rotation curve or optical morphology of GASS35981.

Furthermore, a scenario in which GASS35981 is left with $2 \times 10^{10} M_{\odot}$ of H\textsc{i} after an encounter with either of its neighbors seems fairly implausible. Simulations predict that no more than 20% of the gas mass of any donor galaxy should be stripped in an encounter (E. Bournaud 2010, private communication), so we would require a donor galaxy with $>10^{11} M_{\odot}$ of H\textsc{i}! Such an encounter could, however, be responsible for jostling an already-present H\textsc{i} reservoir out of equilibrium, causing it to form stars.

If the gas was not acquired from another passing galaxy, one might speculate that GASS35981 accreted its H\textsc{i} reservoir directly from the surrounding intergalactic medium (IGM) at some point in the past. Since blind H\textsc{i} surveys such as ALFALFA (Giovanelli et al. 2005) and HIPASS (Barnes et al. 2001) do not find dark H\textsc{i} clouds of $10^{10} M_{\odot}$, the gas must have entered GASS35981 from an ionized phase if it entered all at once or over a short timescale. Since its two identified neighbors suggest that GASS35981 resides in a group, the presence of intra-group gas could be fueling an unusually high accretion rate onto GASS35981. Indeed, accretion from the intra-group medium has been speculated to be responsible for a number of other peculiar star-forming systems (e.g., Beaulieu et al. 2010).

Alternatively, the gas reservoir could have been built slowly through multiple accretions of smaller gas clouds or streams, which could be either neutral or ionized. Under this scenario, star formation would need to be suppressed somehow during the buildup of the reservoir. The galaxy formation models of Birnboim et al. (2007) exhibit quiescent, reservoir building periods similar to what would be needed here, but in general they apply to somewhat higher mass galaxies than GASS35981, and also may not be valid at $z \sim 0$. Multiple minor mergers with gas-rich dwarfs could also supply the gas, but it becomes even harder in this case to imagine how the H\textsc{i} could build up over time rather than form stars with each new accretion event.
6. CONCLUSIONS

We have reported on the remarkable galaxy GASS35981, a disk galaxy with stellar mass $M_*=2 \times 10^{10} M_\odot$ which contains an additional $2.1 \times 10^{10} M_\odot$ of H I gas. Millimeter observations indicate a molecular gas mass only a tenth this high. Through follow-up long-slit spectroscopy, plus SED fitting using our UV through optical photometry we have shown the following.

1. Star formation is evenly spread across the galaxy, at a surface density of $\Sigma_{SFR} = 0.003 M_\odot$ yr$^{-1}$ kpc$^{-2}$.

2. The proportion of the stellar mass contributed by the current star formation episode rises toward the outer regions of the galaxy, reaching a peak at $R = 30$ kpc, where the entire disk must have formed in the past Gyr.

3. Interstellar metallicities exhibit a sharp drop at $R > 15$ kpc, coincident with a sharp rise in EW(Hα). This is consistent with recent infall of lower-metallicity gas (Tinsley & Larson 1978).

4. The Hα rotation curve is regular and symmetric, and reveals no signs of a recent interaction or merger that could have deposited the gas and/or triggered the recent star formation episode.

The main conclusion from our observations is that GASS35981 appears to be in the early stages of formation of its outer stellar disk.

We are not able to provide conclusive answers to questions pertaining to the origin and fate of the gas in this galaxy with this data set alone. Scenarios in which the gas was acquired in a recent merging event are disfavored because of the extremely regular kinematics of the disk. The H I mass of GASS35981 is too large to be easily explained by gas transfer from a passing galaxy. We therefore speculate that GASS35981 acquired its gas directly from the IGM. Although our observations show that the stars in the outer disk formed within the last Gyr, this does not mean that the gas was also acquired less than 1 Gyr ago. It is also unclear whether GASS35981 will continue forming stars in its current low-efficiency state, or whether the gas will flow inward toward the bulge, and GASS35981 will eventually develop into a more normal massive spiral galaxy with a star formation surface density that decreases as a function of radius.

Questions concerning the eventual fate of the gas can be addressed using the larger samples that will be provided by the full GASS and COLD GASS surveys in the future. By studying trends in SFR surface density, mean stellar age, metallicity, and stellar mass profiles as a function of atomic and molecular gas content for complete samples of galaxies, we hope to map out evolutionary sequences in disk galaxy formation.

Answers to questions concerning the origin of the gas will likely require a different approach. Our comparison of the H I line width of GASS35981 with its CO line width and Hα rotation curve yield tantalizing hints that the atomic gas may not be in equilibrium with the rest of the galaxy. In addition, the H I spectrum in Figure 1 is clearly asymmetric about the line center. High-resolution H I mapping of GASS35981 will be needed to understand the dynamical state of the gas in more detail. Even so, such observations are unlikely to prove that the H I originated from a more diffuse (and unseen) reservoir of IGM gas. This can only be done if we are able to find tracers of this gas, for example, absorption lines in the spectra of background quasars that arise when the quasar light passes through the circumgalactic medium of the galaxy (Cen & Ostriker 1999). These tracers must then be linked with galaxies like GASS35981.

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