

# IN THE CRUCIBLE: MASSIVE COMPACT GALAXIES WITH HIGH-VELOCITY OUTFLOWS AND EDDINGTON-LIMITED STAR FORMATION

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## ABSTRACT

Based on infrared photometry from the Wide-field Infrared Survey Explorer (WISE) and optical morphologies from the Hubble Space Telescope (HST), we present the discovery of compact, obscured star formation in galaxies that exhibit  $\gtrsim 1000 \text{ km s}^{-1}$  outflows. The implied star formation rate (SFR) surface densities approach  $\Sigma_{\text{SFR}} = 5000 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ , and we argue that feedback associated with this starburst event is a likely mechanism for launching the high-velocity outflows.

*Subject headings:* keywords

## 1. INTRODUCTION

The central regions of elliptical galaxies are thought to form in compact starbursts (e.g., Kormendy et al. 2009; Hopkins et al. 2009). Feedback associated with such starbursts can produce outflows driven by thermal energy from supernova explosions (e.g., Chevalier & Clegg 1985), stellar winds (e.g., Leitherer et al. 1992), and momentum input from both supernova ram pressure and radiation pressure on dust grains (e.g., Murray et al. 2005). It has been argued that such feedback imposes a limit on the maximum star-formation rate surface density ( $\Sigma_{\text{SFR}}$ ) for starbursts (e.g., Lehnert & Heckman 1996; Meurer et al. 1997; Murray et al. 2005; Thompson et al. 2005) and the maximum stellar surface density for elliptical galaxies and star clusters (e.g., Hopkins et al. 2010).

Galactic winds are ubiquitous in star-forming galaxies at all redshifts and generally exhibit outflow velocities in the  $100\text{--}500 \text{ km s}^{-1}$  range (e.g., Heckman et al. 2000; Shapley et al. 2003; Martin 2005; Rupke et al. 2005; Weiner et al. 2009; Rubin et al. 2010; Steidel et al. 2010). Thus, the discovery of  $|v| > 1000 \text{ km s}^{-1}$  outflows in a sample of massive ( $M_{*} \approx 10^{11} \text{ M}_{\odot}$ ) post-starburst galaxies at  $z \sim 0.6$  by Tremonti et al. (2007) suggested that a more energetic source, such as feedback from an accreting supermassive black hole (e.g., Silk & Rees 1998; Di Matteo et al. 2005; Debuhr et al. 2012), could have been responsible for launching the winds.

However, it also plausible that feedback from a compact starburst could expel gas with such large velocities. Indeed, there is evidence for a positive correlation between outflow velocity and starburst luminosity (e.g., Martin 2005; Rupke et al. 2005; Tremonti et al. 2007), albeit with significant scatter. Furthermore, Heckman et al. (2011) recently found outflows with maximum velocities reaching  $-1500 \text{ km s}^{-1}$  in a sample of local star-

bursts with compact nuclei, and argued that such velocities could be explained by feedback from massive stars.

In this Letter, we present results for a sample of massive galaxies at  $z \sim 0.6$  that exhibit  $|v| \gtrsim 1000 \text{ km s}^{-1}$  outflows, expanding on the sample from Tremonti et al. (2007). We seek to test whether the energetic outflows in these galaxies could have been driven by feedback from starbursts with very large star-formation rate (SFR) surface densities ( $\Sigma_{\text{SFR}}$ ). Our analysis combines galaxy sizes obtained with the Hubble Space Telescope (HST) with star-formation rates and stellar masses estimated from WISE, Spitzer, SDSS, and GALEX photometry.

## 2. ANALYSIS

### 2.1. Morphologies and Sizes

Our sample derives from 29 galaxies targeted for HST/WFC3 imaging in programs 12019 and 12272 (PI: C. Tremonti). Using the F814W filter on the UVIS channel, which has  $0.04''$  pixels and  $\text{FWHM} = 0.074''$ , we obtained  $4 \times 10 \text{ min}$  exposures in a single orbit for each galaxy. The dithered images were processed with MultiDrizzle<sup>7</sup> to produce science mosaics with  $0.02''$  pixels. For each galaxy, we use GALFIT (Peng et al. 2002, 2010) to model the two-dimensional surface brightness profile with a single Sersic component, using stars in the images to construct the model point-spread function (PSF). The Sersic index ( $n$ ) and effective radius ( $r_e$ ) are free parameters in the model. In cases where the best-fit model returns  $n > 4$ , we also fit an  $n = 4$  de Vaucouleurs model (de Vaucouleurs 1948), yielding a larger  $r_e$  value (due to the covariance between  $n$  and  $r_e$ ), and we use these larger effective radii in our analysis.

For this paper, we are most interested in the galaxies with the largest  $\Sigma_{\text{SFR}}$  values, which also have the smallest effective radii. We show the HST images for three high- $\Sigma_{\text{SFR}}$  galaxies in Figure 1. In all three cases, the single-component model GALFIT accounts for  $> 85\%$  of the total flux. The residuals show diffuse emission that is consistent with these systems being late-stage galaxy mergers after final coalescence, although we defer a detailed comparison of the observed morphologies with expectations from merger simulations to future work.

For the most compact galaxy (J0905+5759,  $r_e =$

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<sup>7</sup> <http://stsdas.stsci.edu/multidrizzle/>

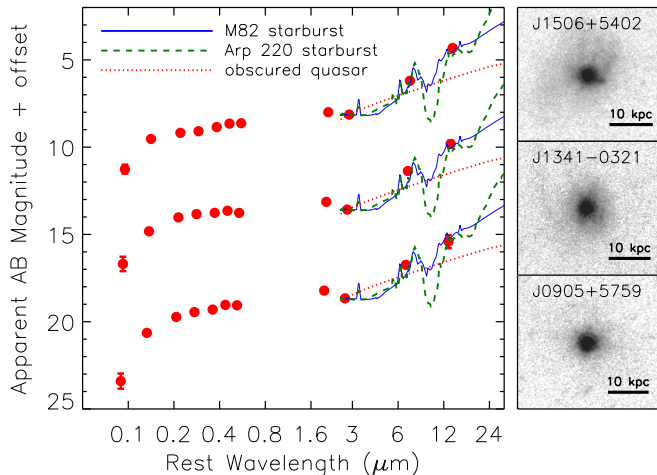


FIG. 1.— Left: Observed UV-IR SEDs ( $\lambda_{\text{rest}} = 0.1\text{--}15\ \mu\text{m}$ ) for three galaxies with large SFR surface densities ( $\Sigma_{\text{SFR}} > 3000\ \text{M}_{\odot}\ \text{yr}^{-1}\ \text{kpc}^{-2}$ ). We show stellar population fits to the  $\lambda_{\text{rest}} = 0.1\text{--}3\ \mu\text{m}$  emission (black solid line) and three templates for dust emission (M82 starburst, Arp 220 starburst, and obscured quasar; Polletta et al. 2007). The starburst templates provide reasonable fits to the  $\lambda_{\text{obs}} = 12$  and  $22\ \mu\text{m}$  WISE photometry, while the quasar template does not. Right: HST/WFC3 F814W images (probing  $\lambda_{\text{rest}} \approx 5000\ \text{\AA}$ ) showing that these galaxies are dominated by a compact nucleus.

$0.013''$  or  $100\ \text{pc}$ ), we also show the observed one-dimensional surface brightness profile in the bottom-right panel of Figure 2.1. We compare to the profiles of six stars in the same image, the best-fit de Vaucouleurs model, and a de Vaucouleurs model with a larger effective radius ( $r_e = 0.04''$ , the native WFC3/UVIS pixel size, which corresponds to a physical scale of  $290\ \text{pc}$ ). This comparison illustrates that this galaxy, while only marginally resolved with an effective radius that is  $\sim 20\%$  of the image FWHM, is clearly more extended than a point source.

For such a compact source, there is significant uncertainty in our  $r_e$  measurement given uncertainties in the model PSF. To quantify this uncertainty, we used TinyTim to generate a model PSF that is artificially narrower than the stars in the image (convolving the output of tiny2 with a  $\text{FWHM} = 0.04''$  Gaussian, whereas the image FWHM is  $0.074''$ ) and found that this increased the effective radius in the GALFIT model by a factor of two. We also fit a two-component PSF+Sersic model, but found that the Sersic component dominates the fit, yielding a similar effective radius. Furthermore, the spectrum of the galaxy shows no evidence for an AGN contribution to the  $I$ -band continuum (see Figure 3), so there is no clear motivation for including an unresolved, point-source component in the model. We conclude that this galaxy is quite compact and that our  $r_e$  estimate of  $100\ \text{pc}$ , while uncertain, is likely accurate within a factor of two.

## 2.2. Star Formation Rates and Stellar Masses

We gathered photometry from the All-Sky Release of the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010), the Seventh Data Release of the Sloan Digital Sky Survey (SDSS, Abazajian et al. 2009), and

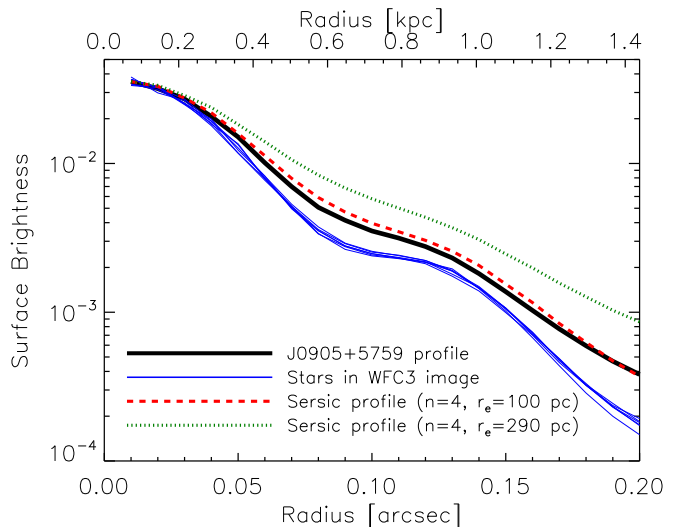


FIG. 2.— One-dimensional surface brightness profile for J0905+5759, which has the smallest effective radius in the sample. The observed profile is shown as the solid black line, and the profiles of six stars in the same image are shown in blue. The best-fit de Vaucouleurs profile with  $r_e = 100\ \text{pc}$  is shown as a dashed red line, and for comparison a broader profile with  $r_e = 0.04'' = 290\ \text{pc}$  is shown as the dotted green line. This galaxy is quite compact, but is more extended than a point source.

General Release 6 from the Galaxy Evolution Explorer (GALEX, Martin et al. 2005). We also obtained  $5 \times 30$  sec dithered exposures at  $3.6\ \mu\text{m}$  and  $4.5\ \mu\text{m}$  for all sources with the Infrared Array Camera (Fazio et al. 2004) on the Spitzer Space Telescope (Werner et al. 2004) as part of General Observer program 60145 (PI: C. Tremonti). We used the post-basic calibrated data to perform aperture photometry on all sources, and we also used the APEX<sup>8</sup> point-source extraction software for photometry of sources in crowded fields. All the photometry was corrected for Galactic extinction based on the Schlegel et al. (1998) dust maps. We show spectral energy distributions (SEDs) for the three high- $\Sigma_{\text{SFR}}$  galaxies in Figure 1.

We estimate IR-based star-formation rates for the 25/29 galaxies with WISE 12 or  $22\ \mu\text{m}$  detections by fitting Chary & Elbaz (2001) templates to their 12 and  $22\ \mu\text{m}$  fluxes. For the 14/29 galaxies with  $22\ \mu\text{m}$  detections, this yields SFRs that agree with those obtained from the Rujopakarn et al. (2012) method based on  $24\ \mu\text{m}$  luminosity with a scatter of  $0.05\ \text{dex}$ . We note that several authors have shown that the shape of the IR SED for star-forming galaxies depends on the surface density of star formation (e.g., Rujopakarn et al. 2011; Elbaz et al. 2011), with more compact starbursts having larger total-IR ( $8\text{--}1000\ \mu\text{m}$ ) to mid-IR ( $8\text{--}24\ \mu\text{m}$ ) ratios. The extreme  $\Sigma_{\text{SFR}}$  values of our sample imply large total-IR to mid-IR ratios, characteristic of the most luminous galaxies in the local universe (e.g., Chary & Elbaz 2001; Dale & Helou 2002; Rieke et al. 2009). If we used the most luminous local templates for the 8/29 sources with SFRs in the ULIRG regime ( $\text{SFR}_{\text{IR}} > 200\ \text{M}_{\odot}\ \text{yr}^{-1}$ ), we would obtain SFRs that are larger by  $0.5\ \text{dex}$  than the values we adopt for this paper.

We also estimate star-formation rates and stellar masses based on stellar population fits to the  $\lambda_{\text{rest}} = 0.1\text{--}$

<sup>8</sup> <http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysis/tools/tools/n>

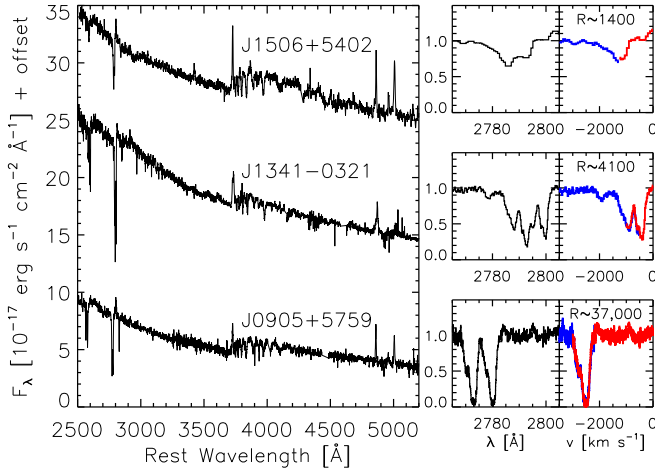


FIG. 3.— Spectra covering  $\lambda_{\text{rest}} = 2500\text{--}5200 \text{ \AA}$  for the three galaxies shown in Figure 1. These spectra are dominated by light from the young stellar population and exhibit [O II]  $\lambda 3727$ , H $\beta$   $\lambda 4861$ , and [O III]  $\lambda 5007$  emission lines. The panels on the right highlight the Mg II  $\lambda\lambda 2796, 2803$  spectral region in both wavelength and velocity space to illustrate the outflow kinematics. The spectrum in the bottom panel has sufficient spectral resolution (FWHM  $\approx 8 \text{ km s}^{-1}$ ) to resolve the intrinsic shape of the absorption-line profile, revealing that the gas near the centroid velocity ( $v = -2470 \text{ km s}^{-1}$ ) covers the entire galaxy.

$3 \mu\text{m}$  SEDs using the method of Moustakas et al. (2011). For galaxies with  $\text{SFR}_{\text{IR}} > 50 \text{ M}_{\odot} \text{ yr}^{-1}$ , there is agreement between these UV-based SFR estimates and  $\text{SFR}_{\text{IR}}$  with a scatter of 0.32 dex. For an SMC dust law, we find a median attenuation of  $A_V = 0.4 \text{ mag}$ .

### 2.3. Outflow Kinematics and Covering Factors

We present  $\lambda_{\text{rest}} = 2500\text{--}5200 \text{ \AA}$  spectroscopy for three high- $\Sigma_{\text{SFR}}$  sources in Figure 3 based on data from MMT/Blue Channel and SDSS (J1506+5402), Magellan/MAGE (J1341-0321), and Keck/LRIS and Keck/HIRES (J0905+5759). The spectra are dominated by light from the young ( $t < 50 \text{ Myr}$ ) stellar population. We highlight the Mg II  $\lambda\lambda 2796, 2803$  absorption lines, which are used to measure outflow velocities. At low spectral resolution (e.g., the top right panel of Figure 3) it is not possible to determine the intrinsic shape of the absorption line profile and therefore the covering factor of the outflowing gas. However, the Keck/HIRES spectrum of J0905+5759 (FWHM  $\approx 8 \text{ km s}^{-1}$ ) reveals that the gas covers the entire continuum source near the velocity centroid ( $v = -2470 \text{ km s}^{-1}$ ) indicating a galaxy-wide outflow.

## 3. DISCUSSION

The compact sizes ( $r_e \approx 100 \text{ pc}$ ) and large star formation rates ( $\text{SFR} \approx 500 \text{ M}_{\odot} \text{ yr}^{-1}$ ) for the galaxies described above implies extremely large star-formation rate surface densities ( $\Sigma_{\text{SFR}} \approx 5000 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ). To place these galaxies in context, we plot their  $\Sigma_{\text{SFR}}$  values as a function of stellar mass in Figure 4. We include comparison samples of  $\sim 10^5$  star-forming galaxies at  $0.5 < z < 1.5$  from Wuyts et al. (2011) and a few dozen gas-rich mergers at  $z < 0.3$  including 32 ULIRGs from Veilleux et al. (2006), five Lyman break analogs with dominant central objects from Overzier et al. (2009), and the local

compact starburst Arp 220 (Scoville et al. 1997; Kennicutt 1998; Rodríguez Zaurín et al. 2008). We also mark the empirical threshold for launching winds ( $\Sigma_{\text{SFR}} \approx 0.1 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ , Heckman 2002), the 90th percentile limit for the surface brightness of starbursts measured using UV, H $\alpha$ , far-IR, and radio continuum emission ( $\Sigma_{\text{SFR}} \approx 45 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  Meurer et al. 1997), and the theoretical limit for a starburst limited by feedback from radiation pressure ( $\Sigma_{\text{SFR}} \approx 2000 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ , Murray et al. 2005; Thompson et al. 2005; Hopkins et al. 2010). The most luminous, compact starbursts in our sample exhibit SFR surface densities that reach the Eddington limit, suggesting that their growth is being regulated by momentum input from massive stars.

### 3.1. Constraints on Ongoing AGN Activity

While the SEDs (see Figure 1) and optical spectra (see Figure 3) for our sample indicate that their bolometric output is dominated by star formation, it is worthwhile to consider the amount of ongoing AGN activity in these systems. The strongest case for detectable AGN emission among the high- $\Sigma_{\text{SFR}}$  galaxies can be made for J1506+5402, which has a weak [Ne V]  $\lambda 3426$  emission line typically associated with AGN activity (e.g., Abel & Satyapal 2008). This galaxy was observed with the Chandra X-ray Observatory (proposal ID 11700896, PI: C. Tremonti) and had four detected counts, corresponding to a  $0.5\text{--}8.0 \text{ keV}$  X-ray luminosity of  $10^{42.7} \text{ erg s}^{-1}$  (see P. Sell et al., in preparation for more details on the 12/29 galaxies with Chandra observations). Using the relationship between  $2\text{--}10 \text{ keV}$  X-ray and  $12.3 \mu\text{m}$  mid-IR luminosity for AGNs from Gandhi et al. (2009), one would expect a source with  $L_X \approx 5 \times 10^{42} \text{ erg s}^{-1}$  to have  $L_{\text{MIR}} \approx 7 \times 10^{42} \text{ erg s}^{-1}$ , which is  $400\times$  smaller than observed luminosity for J1506+5402,  $L_{\text{MIR}} \approx 3 \times 10^{45} \text{ erg s}^{-1}$ . If this source were Compton-thick (e.g., the typical  $2\text{--}10 \text{ keV}$  attenuation for local Compton-thick AGNs is a factor of 100; Diamond-Stanic et al. 2009), then the expected mid-IR AGN contribution could be relevant at the  $\lesssim 30\%$  level, but this would not affect our conclusions that this galaxy is starburst dominated with a  $\Sigma_{\text{SFR}}$  value near the Eddington limit. As is the case for typical ULIRGs (e.g., Farrah et al. 2007), there is certainly evidence for AGN activity in a fraction of our sample, but the bolometric output is dominated by star formation.

### 3.2. The Outflow Launching Mechanism

#### 3.3. Momentum Flux from Supernovae and Stellar Winds

Meurer et al. (1997) argued for a limit near  $45 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  (somewhat smaller for a Chabrier IMF) based on the surface brightness of starbursts measured using rest-frame UV, H $\alpha$ , far-IR, and radio continuum emission, such that only 10% of starbursts exceeded this limit. They argued that the momentum flux from supernovae and stellar winds expected at this threshold matches the mean central pressure measured by Heckman et al. (1990) for starburst-driven winds.

There are also relevant arguments about ram pressure driving of high-velocity winds from Heckman et al. (2011).

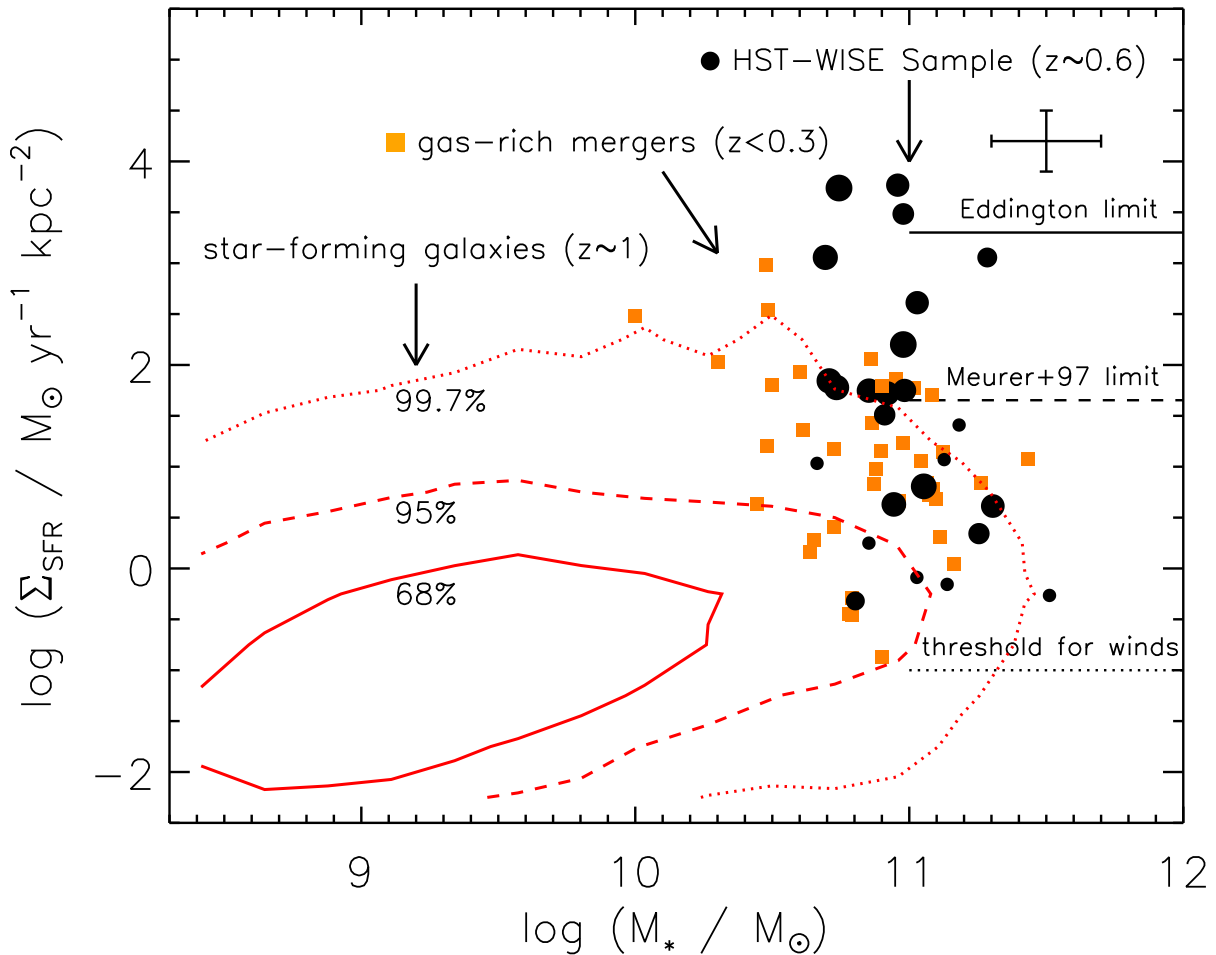


FIG. 4.— SFR surface densities and stellar masses for the HST-WISE sample described in this paper (black circles, with symbol size proportional to outflow velocity), along with samples of gas-rich mergers (orange squares) and star-forming galaxies (shown with 68%, 95%, and 99.7% contours). We mark the empirical threshold for launching winds (dotted line,  $\Sigma_{\text{SFR}} \approx 0.1 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ; Heckman 2002), the 90th-percentile starburst intensity limit from Meurer et al. (1997) (dashed line,  $\Sigma_{\text{SFR}} \approx 45 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ), and the Eddington limit from radiation pressure on dust grains (solid line,  $\Sigma_{\text{SFR}} \approx 2000 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ; Murray et al. 2005; Thompson et al. 2005; Hopkins et al. 2010). Our HST-WISE sample overlaps with the region characterized by gas-rich mergers, and extends to very large SFR surface densities near the Eddington limit, suggesting growth that is limited by momentum injection from massive stars.

### 3.4. The Eddington Limit from Radiation Pressure on Dust Grains

In models where gaseous outflows are driven by radiation pressure from massive stars, estimates of the maximum  $\Sigma_{\text{SFR}}$  where the outward force from radiation exceeds the inward force of gravity are in the  $\Sigma_{\text{SFR}} \sim 10^3 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  range (e.g., Thompson et al. 2005; Hopkins et al. 2010).

The relative importance of momentum injection versus thermal heating may vary as a function of galaxy mass (e.g., Hopkins et al. 2012), with thermal heating being less efficient in galaxies with larger gas densities and shorter cooling times. Regarding momentum injection, Sharma & Nath (2011) have argued that radiation pressure becomes more important than ram pressure at large SFRs. Massive star clusters with large gas surface densities are the ideal launching point for galactic-scale outflows driven by radiation pressure (e.g., Murray et al. 2011), and the outflow velocities are expected to scale

with escape velocity of the most massive star clusters in a galaxy.

### 3.5. Outflows at the Escape Velocity

The observed  $\gtrsim 1000 \text{ km s}^{-1}$  outflow velocities we observe correspond approximately to the escape velocities for compact regions (i.e., massive star clusters) with the sizes and masses that we’ve measured.

$$v_{\text{esc}} = \sqrt{2GM_{\text{cl}}/r_{\text{cl}}} = 2074 \text{ km s}^{-1} \left( \frac{M_{\text{cl}}}{10^{11} \text{ M}_{\odot}} \right)^{1/2} \left( \frac{r_{\text{cl}}}{200 \text{ pc}} \right)^{-1/2} \quad (1)$$

### 3.6. Placing These Galaxies in Context

They are rare and thus represent an unusual or short-lived phase. Gas consumption time for starbursts. Connection to ellipticals. Conceivable that they could grown in size sufficiently by  $z = 0$ ?

Connection to models. How such large SFRs given the powerful wind?

#### 4. CONCLUSIONS

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