

## Dartmouth College Dartmouth Digital Commons

---

Open Dartmouth: Faculty Open Access Articles

---

8-20-2012

# High-Velocity Outflows Without Agn Feedback: Eddington-Limited Star Formation in Compact Massive Galaxies

Aleksandar M. Diamond-Stanic  
*University of California - San Diego*


John Moustakas  
*University of California - San Diego*

Christy A. Tremonti  
*University of Wisconsin-Madison*

Alison L. Coil  
*University of California - San Diego*

Ryan C. Hickox  
*Dartmouth College*

Follow this and additional works at: <https://digitalcommons.dartmouth.edu/facoa>

 Part of the [External Galaxies Commons](#), and the [Stars, Interstellar Medium and the Galaxy Commons](#)

---

### Recommended Citation

Diamond-Stanic, Aleksandar M.; Moustakas, John; Tremonti, Christy A.; Coil, Alison L.; and Hickox, Ryan C., "High-Velocity Outflows Without Agn Feedback: Eddington-Limited Star Formation in Compact Massive Galaxies" (2012). *Open Dartmouth: Faculty Open Access Articles*. 1787.

<https://digitalcommons.dartmouth.edu/facoa/1787>

This Article is brought to you for free and open access by Dartmouth Digital Commons. It has been accepted for inclusion in Open Dartmouth: Faculty Open Access Articles by an authorized administrator of Dartmouth Digital Commons. For more information, please contact [dartmouthdigitalcommons@groups.dartmouth.edu](mailto:dartmouthdigitalcommons@groups.dartmouth.edu).

## HIGH-VELOCITY OUTFLOWS WITHOUT AGN FEEDBACK: EDDINGTON-LIMITED STAR FORMATION IN COMPACT MASSIVE GALAXIES

ALEKSANDAR M. DIAMOND-STANIC<sup>1,6</sup>, JOHN MOUSTAKAS<sup>1</sup>, CHRISTY A. TREMONTI<sup>2</sup>, ALISON L. COIL<sup>1</sup>, RYAN C. HICKOX<sup>3</sup>,  
ADAY R. ROBAINA<sup>4</sup>, GREGORY H. RUDNICK<sup>5</sup>, AND PAUL H. SELL<sup>2</sup>

<sup>1</sup> Center for Astrophysics and Space Sciences, University of California, San Diego, La Jolla, CA 92093, USA; [aleks@ucsd.edu](mailto:aleks@ucsd.edu)

<sup>2</sup> Department of Astronomy, University of Wisconsin-Madison, Madison, WI 53706, USA

<sup>3</sup> Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, USA

<sup>4</sup> Institut de Ciències del Cosmos, University of Barcelona, 08028 Barcelona, Spain

<sup>5</sup> Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA

Received 2012 May 9; accepted 2012 July 18; published 2012 August 1

### ABSTRACT

We present the discovery of compact, obscured star formation in galaxies at  $z \sim 0.6$  that exhibit  $\gtrsim 1000 \text{ km s}^{-1}$  outflows. Using optical morphologies from the *Hubble Space Telescope* and infrared photometry from the *Wide-field Infrared Survey Explorer*, we estimate star formation rate (SFR) surface densities that approach  $\Sigma_{\text{SFR}} \approx 3000 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ , comparable to the Eddington limit from radiation pressure on dust grains. We argue that feedback associated with a compact starburst in the form of radiation pressure from massive stars and ram pressure from supernovae and stellar winds is sufficient to produce the high-velocity outflows we observe, without the need to invoke feedback from an active galactic nucleus.

*Key words:* galaxies: evolution – galaxies: ISM – galaxies: kinematics and dynamics – galaxies: starburst

*Online-only material:* color figures

### 1. INTRODUCTION

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

Galactic winds are ubiquitous in star-forming galaxies at all redshifts and generally exhibit outflow velocities in the 100–500  $\text{km s}^{-1}$  range, which can be attributed to the stellar processes described above (Heckman et al. 2000; Shapley et al. 2003; Martin 2005; Rupke et al. 2005; Weiner et al. 2009; Rubin et al. 2010). Outflows with significantly higher velocities ( $|v| > 1000 \text{ km s}^{-1}$ ) were discovered by Tremonti et al. (2007) in a sample of massive ( $M_{*} \approx 10^{11} M_{\odot}$ ) post-starburst galaxies at  $z \sim 0.6$ , and it was suggested that a more energetic source such as feedback from an accreting supermassive black hole (Silk & Rees 1998; Di Matteo et al. 2005) may be responsible for launching the winds (see Fabian 2012, for a recent review).

However, it is 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 (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 starbursts with compact nuclei and argued that

such velocities could be explained by a wind launched from  $r_0 \sim 100 \text{ pc}$  and driven by feedback from massive stars and supernovae.

In this Letter, we measure sizes and SFRs for a sample of massive galaxies at  $z \sim 0.6$  that exhibit  $\gtrsim 1000 \text{ km s}^{-1}$  outflows, expanding on the initial study by 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 SFR surface densities. Our analysis combines galaxy sizes measured with the *Hubble Space Telescope* (*HST*) with SFRs and stellar masses estimated from *Wide-field Infrared Survey Explorer* (*WISE*), *Spitzer Space Telescope*, Sloan Digital Sky Survey (SDSS), and *Galaxy Evolution Explorer* (*GALEX*) photometry.

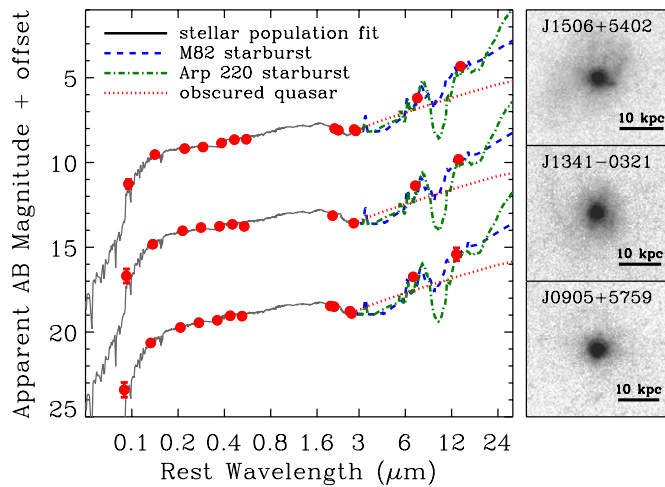
### 2. ANALYSIS

#### 2.1. Morphologies and Sizes

We observed 29 galaxies with *HST* (programs 12019 and 12272) selected from a parent sample of  $\sim 10^3$  galaxies at  $0.35 < z < 1.0$  with post-starburst spectral features: B- or A-star-dominated stellar continua and moderately weak nebular emission ( $\text{EW}([\text{O II}]) < 20 \text{ \AA}$ ; see C. Tremonti et al. 2012, in preparation for more details). The galaxies targeted with *HST* were those with the youngest derived post-burst ages,  $t_{\text{burst}} \lesssim 300 \text{ Myr}$ . Therefore, this sample has bluer  $U - B$  colors and stronger emission lines than typical post-starburst samples (Coil et al. 2011). Our subsequent UV-IR spectral energy distribution (SED) analysis (see Section 2.2) reveals significant ongoing star formation ( $\text{SFR} > 50 M_{\odot} \text{ yr}^{-1}$ ) in the 14/29 galaxies with *WISE* 22  $\mu\text{m}$  detections, calling into question the post-starburst nature of roughly half of the *HST* sample.

Using the F814W filter on the WFC3/UVIS channel, which has 0".04 pixels, we obtained  $4 \times 10$  minute exposures in a single orbit for each galaxy. The dithered images were processed with

<sup>6</sup> Center for Galaxy Evolution Fellow.



**Figure 1.** Left: observed UV-IR SEDs ( $\lambda_{\text{rest}} = 0.1\text{--}15\ \mu\text{m}$ ) for three galaxies with the largest SFR surface densities ( $\Sigma_{\text{SFR}} \approx 3000\ M_{\odot}\ \text{yr}^{-1}\ \text{kpc}^{-2}$ ). The top two SEDs are offset by 5 and 10 mag, respectively. 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, blue dashed line; Arp 220 starburst, green dot-dashed line; obscured quasar, red dotted line; Polletta et al. 2007) scaled to match the  $\lambda_{\text{obs}} = 4.6\ \mu\text{m}$  band. 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.

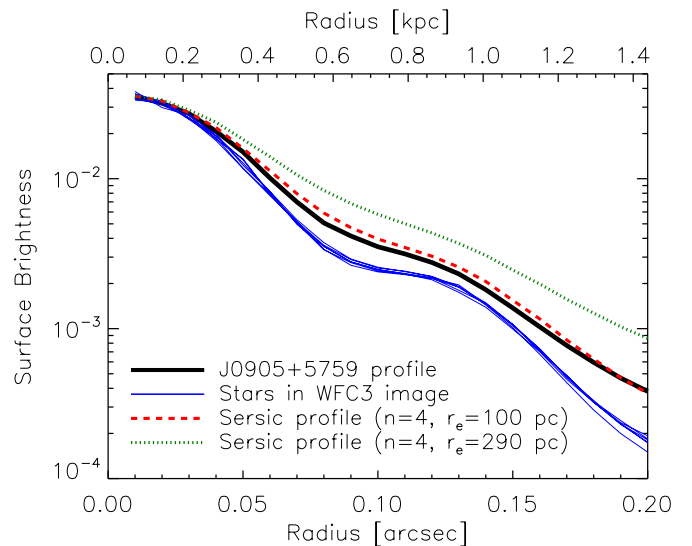
(A color version of this figure is available in the online journal.)

MultiDrizzle<sup>7</sup> to produce science mosaics with  $0''.02$  pixels. For each galaxy, we use GALFIT (Peng et al. 2002) to model the two-dimensional surface brightness profile with a single Sérsic component (characterized by Sérsic index  $n$  and effective radius  $r_e$ ), using stars in the images to construct the model point-spread function (PSF). In cases where the best-fit model returns  $n > 4$ , we also fit an  $n = 4$  de Vaucouleurs model, yielding a larger  $r_e$  value (due to the covariance between  $n$  and  $r_e$ ); we use these larger effective radii in our analysis.

In this Letter, we highlight the galaxies with the smallest  $r_e$  and largest  $\Sigma_{\text{SFR}}$  values because such extreme starbursts could conceivably produce the high-velocity outflows we observe (see Section 3). We show *HST* images for the three highest  $\Sigma_{\text{SFR}}$  galaxies in Figure 1. In all three cases, the single-component GALFIT model accounts for  $>85\%$  of the total flux. The residuals show diffuse emission that is consistent with these systems being late-stage galaxy mergers, although we defer a detailed study of the merger stage to future work.

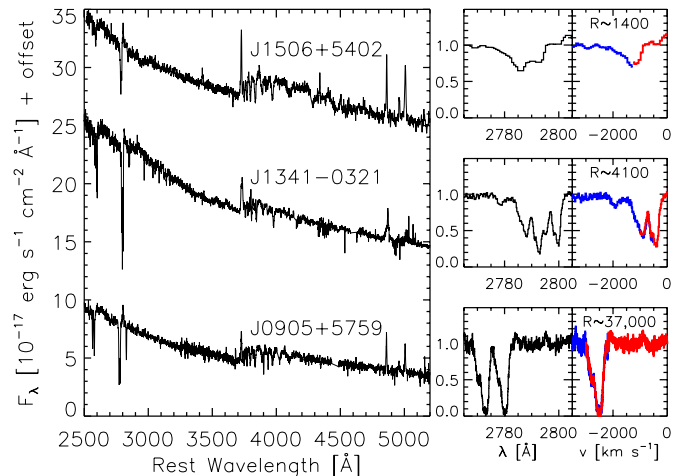
For the most compact galaxy (J0905+5759,  $r_e = 0''.013$  or 100 pc), we also show the observed one-dimensional surface brightness profile in Figure 2. We compare to the profiles of six stars in the same image, the best-fit de Vaucouleurs model, and a de Vaucouleurs model with  $r_e = 0''.04$  (the native WFC3/UVIS pixel size, which corresponds to a physical scale of 290 pc). This comparison illustrates that this galaxy, while only marginally resolved with an  $r_e$  that is  $\sim 20\%$  of the image FWHM, is clearly more extended than a point source.

For such a compact source, there is uncertainty in our  $r_e$  measurement given uncertainties in the model PSF. To quantify this, we used TinyTim to generate a model PSF that is narrower than the stars in the image (convolving with an FWHM =  $0''.04$  Gaussian, whereas the image FWHM is  $0''.074$ ) and found that this increased the  $r_e$  in the GALFIT model by a factor of two. We also fit a two-component PSF+Sérsic model, but found that



**Figure 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, normalized to the same central surface brightness. The best-fit de Vaucouleurs profile with  $r_e = 100$  pc is shown as a dashed red line, and for comparison a broader profile with  $r_e = 0''.04 = 290$  pc is shown as the dotted green line. This galaxy is quite compact, but is more extended than a point source.

(A color version of this figure is available in the online journal.)



**Figure 3.** Spectra covering  $\lambda_{\text{rest}} = 2500\text{--}5200\ \text{\AA}$  for the three galaxies shown in Figure 1. For clarity the top two spectra are offset by +10 and +20 units. These spectra are dominated by the light of a young stellar population but have relatively weak nebular emission lines ([O II]  $\lambda 3727$ , H $\beta$   $\lambda 4861$ , [O III]  $\lambda 5007$ ) and strong Mg II  $\lambda\lambda 2796, 2803$  absorption arising from the interstellar medium. The absence of broad Mg II or H $\beta$  emission lines rules out a significant contribution to the optical continuum light from an AGN. The panels on the right highlight the region around the Mg II doublet 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.

(A color version of this figure is available in the online journal.)

the Sérsic component dominates the fit, yielding a similar  $r_e$ . Furthermore, the spectrum of the galaxy shows no evidence for an active galactic nucleus (AGN) contribution to the optical continuum (see Figure 3), so there is no clear motivation for including an unresolved, point-source component in the model. We conclude that our  $r_e$  estimate is accurate within a factor of two.

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

## 2.2. Star Formation Rates and Stellar Masses

We gathered photometry from the *WISE* All-Sky Release, the SDSS Seventh Data Release, and *GALEX* General Release 6. We also obtained  $5 \times 30$  s dithered exposures at  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$  for all sources with the Infrared Array Camera on the *Spitzer Space Telescope* as part of GO program 60145. We used the post-basic-calibrated data to perform aperture photometry on all sources and point-source photometry on sources in crowded fields. We show SEDs for the three highest  $\Sigma_{\text{SFR}}$  galaxies in Figure 1.

We estimate IR-based SFRs 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 14/25 galaxies with  $22 \mu\text{m}$  detections, this yields SFRs that agree with those obtained from the Rujopakarn et al. (2011b) method based on  $24 \mu\text{m}$  luminosity with a scatter of 0.05 dex. Several authors have shown that the shape of the IR SED for star-forming galaxies depends on  $\Sigma_{\text{SFR}}$  (Rujopakarn et al. 2011a; Elbaz et al. 2011), with more compact starbursts having larger total-IR (8–1000  $\mu\text{m}$ ) to mid-IR (8–24  $\mu\text{m}$ ) ratios, characteristic of the most luminous galaxies in the local universe (Rieke et al. 2009). If we used the most luminous local templates for the 8/25 sources with SFRs in the ULIRG regime ( $\text{SFR}_{\text{IR}} > 100 M_{\odot} \text{yr}^{-1}$ ), we would obtain SFRs that are larger by 0.5 dex than the values we adopt for this Letter.

We also estimate SFRs and stellar masses based on stellar population fits to the  $\lambda_{\text{rest}} = 0.1\text{--}3 \mu\text{m}$  SEDs using the method of Moustakas et al. (2011). For the 14/25 galaxies with  $\text{SFR}_{\text{IR}} > 50 M_{\odot} \text{yr}^{-1}$ , there is agreement between these UV-based SFR estimates and  $\text{SFR}_{\text{IR}}$  with a scatter of 0.32 dex. For a Small Magellanic Cloud dust law, we find a median attenuation of  $A_V = 0.4$  mag. The observed  $H\beta$  luminosities, uncorrected for dust extinction, are typically factors of 10–20 $\times$  smaller than expected from the UV and IR SFRs. This can be reconciled by either strong differential dust attenuation (i.e.,  $A_V \approx 2\text{--}3$  mag for the line-emitting region), escaping ionizing photons from matter-bounded H II regions, or a recently quenched starburst ( $t > 5$  Myr) with a small ratio of ionizing ( $\lambda < 912 \text{\AA}$ ) to non-ionizing UV photons.

## 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 a young ( $t < 50$  Myr) stellar population. We highlight the interstellar medium 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 SFRs ( $\text{SFR} \approx 200 M_{\odot}$ ) for the three galaxies described above imply extremely large SFR surface densities ( $\Sigma_{\text{SFR}} \approx 3000 M_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$ ). To place these galaxies in context, we plot  $\Sigma_{\text{SFR}}$  versus stellar mass for the 25/29 galaxies detected by *WISE* in Figure 4.

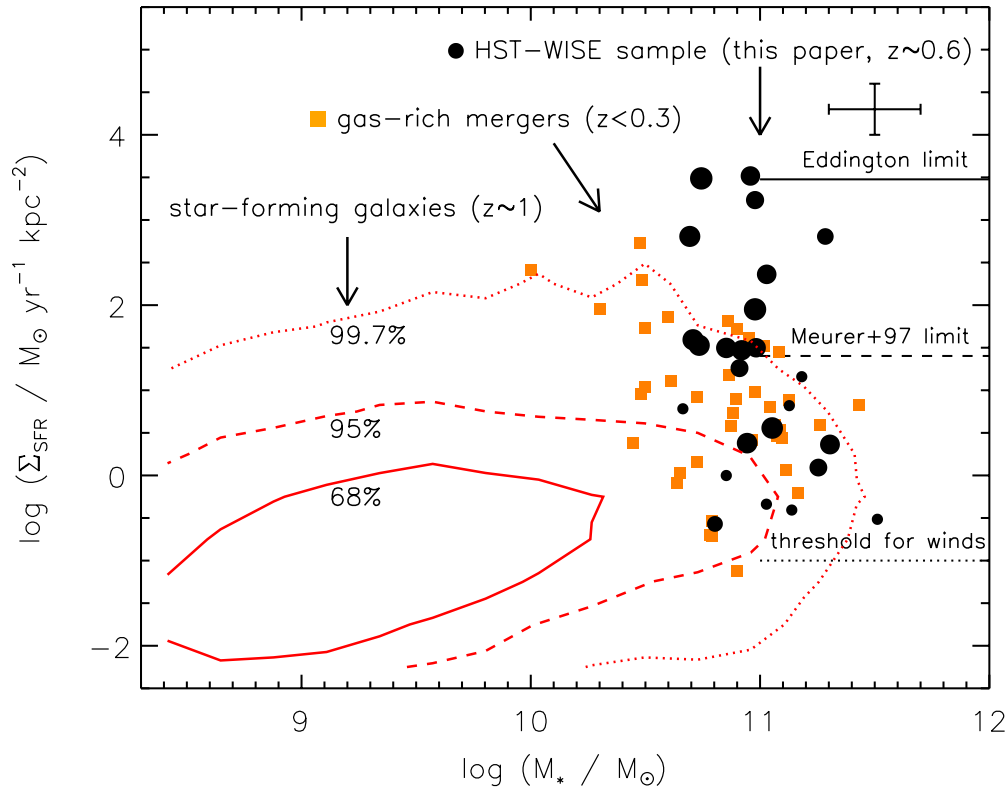
We include comparison samples of  $\sim 10^5$  star-forming galaxies at  $0.5 < z < 1.5$  from Wuyts et al. (2011) and gas-rich mergers at  $z < 0.3$  including 32 ULIRGs from Veilleux et al. (2006), six Lyman break analogs with dominant central objects from Overzier et al. (2009), and the local compact starburst Arp 220 (Kennicutt 1998; Rodríguez Zaurín et al. 2008). We also mark the empirical threshold for launching winds ( $\Sigma_{\text{SFR}} \approx 0.1 M_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$ ; Heckman 2002); the 90th percentile limit for the surface brightness of starbursts over a wide range in redshift measured using UV,  $H\alpha$ , far-IR, and radio continuum emission ( $\Sigma_{\text{SFR}} \approx 25 M_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$  for a Chabrier initial mass function; Meurer et al. 1997); and the theoretical limit for a starburst limited by feedback from radiation pressure ( $\Sigma_{\text{SFR}} \approx 3000 M_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$ ; 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 (Figure 1) and optical spectra (Figure 3) for our sample indicate that their  $\lambda_{\text{rest}} = 0.1\text{--}15 \mu\text{m}$  emission is dominated by star formation, it is worthwhile to consider the level of ongoing AGN activity and its effect on our measurements. We observed 12/29 galaxies with the *Chandra X-ray Observatory* (proposal ID 11700896, see P. Sell et al. 2012, in preparation for more details), including the 3/29 galaxies with significant [Ne v]  $\lambda 3426$  detections (an indication of AGN activity; Gilli et al. 2010) and the most luminous [O III]  $\lambda 5007$  sources in the sample. Of these 12 galaxies, only 2 were detected with  $>4$  X-ray counts and upper limits for the remainder imply  $L_X \lesssim 10^{43} \text{ erg s}^{-1}$ . The two significant detections were for galaxies hosting optical broad-line AGNs; neither was detected at  $22 \mu\text{m}$  by *WISE* or shows evidence for an outflow, and both have  $\Sigma_{\text{SFR}} < 10 M_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$ . For the most luminous [O III] source, J1506+5402, the observed [O III]/X-ray ratio implies X-ray absorption by a factor of  $\sim 10$  (Heckman et al. 2005). However, even if the X-ray attenuation were a factor of 100, typical for local Compton-thick AGNs (Diamond-Stanic et al. 2009), the expected mid-IR AGN contribution (Gandhi et al. 2009) would still be  $\lesssim 30\%$  of the observed mid-IR luminosity. Only 1/29 galaxies has *WISE* mid-IR colors that would identify it as an AGN candidate (Stern et al. 2012), and this particular galaxy has  $\Sigma_{\text{SFR}} < 50 M_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$ . We conclude that the bolometric output of the galaxies in our sample is dominated by star formation and that our results regarding large  $\Sigma_{\text{SFR}}$  values are not affected by AGN contamination.

### 3.2. The Outflow Launching Mechanism

Are the high-velocity outflows observed in these galaxies produced by a compact starburst? Murray et al. (2011) argued that massive star clusters with large gas surface densities are the ideal launching point for galactic-scale outflows driven by radiation pressure, and that the outflow velocity should scale with escape velocity of the most massive star clusters in a galaxy. For our sample, if one assumes that the spatial extent of the stellar mass is comparable to that of the rest-frame *V*-band light (see Section 3.3), then half of the stellar mass ( $M_* \sim 10^{11} M_{\odot}$ ) will be within the effective radius ( $r_e \sim 100 \text{ pc}$ ). Such a compact stellar population would have an escape velocity comparable to



**Figure 4.** SFR surface densities and stellar masses for the *HST*-WISE sample described in this paper (black circles, symbol size proportional to outflow velocity), along with samples of  $z < 0.3$  gas-rich mergers (orange squares, including ULIRGs, Lyman break analogs, and Arp 220; Kennicutt 1998; Veilleux et al. 2006; Rodríguez Zaurín et al. 2008; Overzier et al. 2009) and  $z \sim 1$  star-forming galaxies (shown with 68%, 95%, and 99.7% contours; Wuyts et al. 2011). We mark the empirical threshold for launching winds (dotted line,  $\Sigma_{\text{SFR}} \approx 0.1 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ; Heckman 2002), the 90th-percentile starburst intensity limit from Meurer et al. (1997) (dashed line,  $\Sigma_{\text{SFR}} \approx 25 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ), and the Eddington limit from radiation pressure on dust grains (solid line,  $\Sigma_{\text{SFR}} \approx 3000 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ; Murray et al. 2005; Thompson et al. 2005; Hopkins et al. 2010). The representative error bar in the top-right portion of the plot corresponds to uncertainties of 0.3 dex in  $\Sigma_{\text{SFR}}$  and 0.2 dex in stellar mass. 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.

(A color version of this figure is available in the online journal.)

the  $\gtrsim 1000 \text{ km s}^{-1}$  outflow velocities we observe:

$$v_{\text{esc}} = \sqrt{2GM_*/r} \\ = 2100 \left( \frac{M_*}{10^{11} M_{\odot}} \right)^{1/2} \left( \frac{r}{200 \text{ pc}} \right)^{-1/2} \text{ km s}^{-1}. \quad (1)$$

This argument, combined with the fact that we observe galaxies with significant dust-obscured star formation and  $\Sigma_{\text{SFR}}$  values near the Eddington limit, suggests that momentum input from massive stars in the form of radiation pressure is a viable mechanism for launching these outflows.

In addition to radiation pressure, we also expect significant momentum flux from stellar winds and supernovae. For example, a starburst with  $\text{SFR} \approx 200 M_{\odot} \text{ yr}^{-1}$  would have radiation pressure  $L_{\text{bol}}/c \approx 3 \times 10^{35} \text{ dyne}$  and ram pressure  $\dot{p} \approx 5\text{--}10 \times 10^{35} \text{ dyne}$  from stellar winds and supernovae (Leitherer et al. 1992, 1999; Veilleux et al. 2005). Furthermore, Heckman et al. (2011) noted that such a large momentum injection ( $\dot{p} \approx 10^{35} \text{ dyne}$ ) from a small initial radius  $r_0 \approx 100 \text{ pc}$  could accelerate a cloud with column density  $N_H \approx 10^{21} \text{ cm}^{-2}$  to a terminal velocity  $v_{\infty} \approx 1800 \text{ km s}^{-1}$ . Thus, the energetics of compact starbursts are sufficient to produce the high-velocity outflows we observe, and it is plausible that both radiation pressure on dust grains and supernova ram pressure contribute to driving the winds.

### 3.3. Placing These Galaxies in Context

It is clear from Figure 4 that the high- $\Sigma_{\text{SFR}}$  galaxies in our sample constitute a rare population, suggesting that they represent an unusual or short-lived phase. Mergers of gas-rich galaxies are a viable mechanism for producing compact starbursts (Mihos & Hernquist 1996), and such gas-rich major mergers are rare at  $z \sim 0.6$  due to the decline in both the gas fraction (Tacconi et al. 2010) and the fractional major merger rate (Lotz et al. 2011) of galaxies since  $z \sim 2$ . Furthermore, our high- $\Sigma_{\text{SFR}}$  galaxies are caught in a particular time interval where there is both vigorous star formation and strong feedback. The length of this phase may be set by the gas consumption timescale or the timescale for feedback to suppress subsequent star formation. Based on the Kennicutt-Schmidt relation (Kennicutt 1998), a compact starburst with  $r_e \approx 100 \text{ pc}$ ,  $\text{SFR} \approx 200 M_{\odot}$ , and  $\Sigma_{\text{SFR}} \approx 3000 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  would have a gas surface density of  $\Sigma_{\text{gas}} \sim 10^{11} M_{\odot} \text{ kpc}^{-2}$  corresponding to  $M_{\text{gas}} \sim 3 \times 10^9 M_{\odot}$  inside 100 pc, which would be consumed on a timescale  $\sim 20 \text{ Myr}$ . This scenario could be tested with CO observations of molecular gas masses and kinematics for these extreme galaxies.

Considering our full *HST*-WISE sample in Figure 4, we find values of  $\Sigma_{\text{SFR}}$  spanning four orders of magnitude. This could be explained as an evolutionary sequence where the high- $\Sigma_{\text{SFR}}$  galaxies represent the peak of the starburst when the high-velocity outflows are launched, while the lower  $\Sigma_{\text{SFR}}$  galaxies

represent a subsequent, post-starburst phase. It is interesting to note that all 12/25 galaxies above the  $\Sigma_{\text{SFR}} \approx 25 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  limit from Meurer et al. (1997) exhibit outflows (with median centroid velocity  $v = -1500 \text{ km s}^{-1}$ ), while all 7/25 galaxies without detected outflows (the smallest black circles in Figure 4) have  $\Sigma_{\text{SFR}} < 20 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ . If a compact starburst is a requirement for the production of high-velocity outflows, it may be that the sources without outflows have not gone through such a phase (see A. Robaina et al. 2012, in preparation for a discussion of the relationship between galaxy morphology, outflow velocity, and stellar population age in this sample).

Finally, we consider the implications of our results for models of massive galaxy formation. Simulations of major galaxy mergers with large gas fractions ( $f_{\text{gas}} \sim 50\%$ ) can produce  $M_{*} \sim 10^{11} M_{\odot}$  remnants with  $r_e \sim 1 \text{ kpc}$  (Wuyts et al. 2010), but our sample includes galaxies of similar mass that are smaller in the rest-frame  $V$  band by almost an order of magnitude. If the mass in these galaxies follows their  $V$ -band light, it would be extremely challenging for them to grow in size from  $r_e \sim 0.1 \text{ kpc}$  to  $r_e \sim 5 \text{ kpc}$  to reach the local size–mass relation (Shen et al. 2003) in the  $t \sim 6 \text{ Gyr}$  since  $z = 0.6$ . For comparison the compact, quiescent galaxies observed at  $z \sim 2$  (Trujillo et al. 2007; van Dokkum et al. 2008) have  $t \sim 10 \text{ Gyr}$  to grow by a factor of  $\sim 5$ . In this context, it is worth noting that the half-light radius (ignoring dust attenuation) at rest-frame  $V$  band can be a factor of 5–10 smaller than the half-mass radius for a gas-rich merger at final coalescence near the peak of starburst activity (Wuyts et al. 2010). One could test for such size discrepancies and probe the radial dependence of the mass-to-light ratio for these galaxies by measuring sizes at rest-frame near-IR wavelengths.

#### 4. SUMMARY

We have measured large SFR surface densities for galaxies that exhibit  $\gtrsim 1000 \text{ km s}^{-1}$  outflows. The largest  $\Sigma_{\text{SFR}}$  values are comparable to the Eddington limit from radiation pressure on dust grains, and such compact starbursts are expected to have substantial momentum input from massive stars and supernovae. High-velocity outflows have been previously interpreted as a signpost of AGN feedback, but given that feedback from a compact starburst is capable of producing such a signature and is clearly present in this sample, we conclude that the outflows we observe are likely driven by star formation.

We acknowledge useful discussions with and assistance from James Aird, Brandon Kelly, Dusan Keres, David Law, Alexander Mendez, Kate Rubin, Art Wolfe, and Stijn Wuyts. We thank the referee for suggestions that have improved the paper. A.M.D. acknowledges support from the Southern California Center for Galaxy Evolution, a multi-campus research program funded by the University of California Office of Research. Support for HST-GO-12272 was provided by NASA through a grant from STScI. Support for Spitzer-GO-60145 was provided by contract

1419615 from JPL/Caltech. This Letter includes data obtained at the W. M. Keck Observatory.

#### REFERENCES

- Chary, R., & Elbaz, D. 2001, *ApJ*, 556, 562  
 Chevalier, R. A., & Clegg, A. W. 1985, *Nature*, 317, 44  
 Coil, A. L., Weiner, B. J., Holz, D. E., et al. 2011, *ApJ*, 743, 46  
 Diamond-Stanic, A. M., Rieke, G. H., & Rigby, J. R. 2009, *ApJ*, 698, 623  
 Di Matteo, T., Springel, V., & Hernquist, L. 2005, *Nature*, 433, 604  
 Elbaz, D., Dickinson, M., Hwang, H. S., et al. 2011, *A&A*, 533, A119  
 Fabian, A. C. 2012, *Ann. Rev. Astron. Astrophys.*, in press  
 Gandhi, P., Horst, H., Smette, A., et al. 2009, *A&A*, 502, 457  
 Gilli, R., Vignali, C., Mignoli, M., et al. 2010, *A&A*, 519, A92  
 Heckman, T. M. 2002, in ASP Conf. Proc. 254, Extragalactic Gas at Low Redshift, ed. J. S. Mulchaey & J. Stocke (San Francisco, CA: ASP), 292  
 Heckman, T. M., Borthakur, S., Overzier, R., et al. 2011, *ApJ*, 730, 5  
 Heckman, T. M., Lehnert, M. D., Strickland, D. K., & Armus, L. 2000, *ApJS*, 129, 493  
 Heckman, T. M., Ptak, A., Hornschemeier, A., & Kauffmann, G. 2005, *ApJ*, 634, 161  
 Hopkins, P. F., Cox, T. J., Dutta, S. N., et al. 2009, *ApJS*, 181, 135  
 Hopkins, P. F., Murray, N., Quataert, E., & Thompson, T. A. 2010, *MNRAS*, 401, L19  
 Kennicutt, R. C., Jr. 1998, *ApJ*, 498, 541  
 Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, *ApJS*, 182, 216  
 Lehnert, M. D., & Heckman, T. M. 1996, *ApJ*, 472, 546  
 Leitherer, C., Robert, C., & Drissen, L. 1992, *ApJ*, 401, 596  
 Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, *ApJS*, 123, 3  
 Lotz, J. M., Jonsson, P., Cox, T. J., et al. 2011, *ApJ*, 742, 103  
 Martin, C. L. 2005, *ApJ*, 621, 227  
 Meurer, G. R., Heckman, T. M., Lehnert, M. D., Leitherer, C., & Lowenthal, J. 1997, *AJ*, 114, 54  
 Mihos, J. C., & Hernquist, L. 1996, *ApJ*, 464, 641  
 Moustakas, J., Zaritsky, D., Brown, M., et al. 2011, arXiv:1112.3300  
 Murray, N., Ménard, B., & Thompson, T. A. 2011, *ApJ*, 735, 66  
 Murray, N., Quataert, E., & Thompson, T. A. 2005, *ApJ*, 618, 569  
 Overzier, R. A., Heckman, T. M., Tremonti, C., et al. 2009, *ApJ*, 706, 203  
 Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, *AJ*, 124, 266  
 Polletta, M., Tاجر, M., Maraschi, L., et al. 2007, *ApJ*, 663, 81  
 Rieke, G. H., Alonso-Herrero, A., Weiner, B. J., et al. 2009, *ApJ*, 692, 556  
 Rodríguez Zaurín, J., Tadhunter, C. N., & González Delgado, R. M. 2008, *MNRAS*, 384, 875  
 Rubin, K. H. R., Weiner, B. J., Koo, D. C., et al. 2010, *ApJ*, 719, 1503  
 Rujopakarn, W., Rieke, G. H., Eisenstein, D. J., & Juneau, S. 2011a, *ApJ*, 726, 93  
 Rujopakarn, W., Rieke, G. H., Weiner, B. J., et al. 2011b, arXiv:1107.2921  
 Rupke, D. S., Veilleux, S., & Sanders, D. B. 2005, *ApJS*, 160, 115  
 Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, *ApJ*, 588, 65  
 Shen, S., Mo, H. J., White, S. D. M., et al. 2003, *MNRAS*, 343, 978  
 Silk, J., & Rees, M. J. 1998, *A&A*, 331, L1  
 Stern, D., Assef, R. J., Benford, D. J., et al. 2012, *ApJ*, 753, 30  
 Tacconi, L. J., Genzel, R., Neri, R., et al. 2010, *Nature*, 463, 781  
 Thompson, T. A., Quataert, E., & Murray, N. 2005, *ApJ*, 630, 167  
 Tremonti, C. A., Moustakas, J., & Diamond-Stanic, A. M. 2007, *ApJ*, 663, L77  
 Trujillo, I., Conselice, C. J., Bundy, K., et al. 2007, *MNRAS*, 382, 1093  
 van Dokkum, P. G., Franx, M., Kriek, M., et al. 2008, *ApJ*, 677, L5  
 Veilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, *ARA&A*, 43, 769  
 Veilleux, S., Kim, D.-C., Peng, C. Y., et al. 2006, *ApJ*, 643, 707  
 Weiner, B. J., Coil, A. L., Prochaska, J. X., et al. 2009, *ApJ*, 692, 187  
 Wuyts, S., Cox, T. J., Hayward, C. C., et al. 2010, *ApJ*, 722, 1666  
 Wuyts, S., Förster Schreiber, N. M., van der Wel, A., et al. 2011, *ApJ*, 742, 96