THE SINS/zC-SINF SURVEY of z ~ 2 GALAXY KINEMATICS: OUTFLOW PROPERTIES*

SARAH F. NEWMAN1, REINHARD GENZEL2,3, NATASCHA M. FORSTER-SCHREIBER4, CHIARA MANTINI5, SIMON J. LILLY6, ALVIO RENZINI5, NICOLAS BOUCHÉ7,8, ANDREAS BURKERT9, PETER BUSCHKAMP2, C. MARCELLA CAROLLO6, GIOVANNI CRESCI10, RIC DAVIES1, FRANK EISENHAUER2, SHY GENEL11, ERIN K. S. HICKS12, JARON KURK2, DIETER LUTZ2, THORSTEN NAAB13, YINGHIE PENG14, AMIEL STERNBERG14, LINDA J. TACCONI12, DANIELA VERNANI15, STIJN WUYTS2, AND GIANNI ZAMORANI15

1 Department of Astronomy, Campbell Hall, University of California, Berkeley, CA 94720, USA; sfnewman@berkeley.edu
2 Max-Planck-Institut für extraterrestrische Physik (MPE), Giessenbachstr.1, D-85748 Garching, Germany
3 Department of Physics, Le Conte Hall, University of California, Berkeley, CA 94720, USA
4 Space Sciences Research Group, Northrop Grumman Aerospace Systems, Redondo Beach, CA 90278, USA
5 Osservatorio Astronomico di Padova, Vicolo dellOsservatorio 5, Padova, I-35122, Italy
6 Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse; UPS-OMP; IRAP; 14, avenue Edouard Belin, F-31400 Toulouse, France
7 Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse; UPS-OMP; IRAP; 14, avenue Edouard Belin, F-31400 Toulouse, France
8 CNRS; IRAP; 14, avenue Edouard Belin, F-31400 Toulouse, France
9 Department of Physics, Universität-Sternwarte Ludwig-Maximilians-Universität (USM), Scheinerstr. 1, München, D-81679, Germany
10 Istituto Nazionale di AstrofisicaOsservatorio Astronomico di Arcetri, Largo Enrico Fermi 5, I-50125 Firenze, Italy
11 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138 USA
12 Department of Astronomy, University of Washington, Box 351580, U.W., Seattle, WA 98195-1580, USA
13 Max-Planck Institute for Astrophysics, Karl Schwarzschildstrasse 1, D-85748 Garching, Germany
14 School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
15 INAF Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy

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ABSTRACT

Using SINFONI Hα, [N ii], and [S ii] AO data of 27 z ~ 2 star-forming galaxies (SFGs) from the SINS and zC-SINF surveys, we explore the dependence of outflow strength (via the broad flux fraction) on various galaxy parameters. For galaxies that have evidence for strong outflows, we find that the broad emission is spatially extended to at least the half-light radius (≈ a few kpc). Decomposition of the [S ii] doublet into broad and narrow components suggests that this outflowing gas probably has a density of ~10–100 cm\(^{-3}\), less than that of the star-forming gas (600 cm\(^{-3}\)). There is a strong correlation of the Hα broad flux fraction with the star formation surface density of the galaxy, with an apparent threshold for strong outflows occurring at 1 M\(_{\odot}\) yr\(^{-1}\) kpc\(^{-2}\). Above this threshold, we find that SFGs with log m\(_{\ast}\) > 10 have similar or perhaps greater wind mass-loading factors (\(\eta = M_{\text{out}}/\text{SFR}\)) and faster outflow velocities than lower mass SFGs, suggesting that the majority of outflowing gas at z ~ 2 may derive from high-mass SFGs. The mass-loading factor is also correlated with the star formation rate (SFR), galaxy size, and inclination, such that smaller, more star-forming, and face-on galaxies launch more powerful outflows. We propose that the observed threshold for strong outflows and the observed mass loading of these winds can be explained by a simple model wherein break-out of winds is governed by pressure balance in the disk.

Key words: cosmology: observations – galaxies: evolution – galaxies: high-redshift – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

Most high-z star-forming galaxies (SFGs) from rest-UV/ optical samples show evidence for powerful galactic outflows, as indicated by UV absorption spectroscopy (Pettini et al. 2000; Shapley et al. 2003; Steidel et al. 2010; Weiner et al. 2009; Kornei et al. 2012) and broad Hα emission-line profiles (Shapiro et al. 2009; Genzel et al. 2011; Newman et al. 2012). This “star formation feedback” may be an essential ingredient in the evolution of high-z SFGs, particularly between z ~ 1 and 3, at the peak of the star formation rate (SFR) density (Hopkins & Beacom 2006). However, little is yet known about how galaxy parameters determine the prevalence and strength of these outflows.

Current theoretical models suggest that outflows could be driven by energy or momentum feedback (e.g., Murray et al. 2005). In the simple momentum-driven wind scenario of Oppenheimer & Davé (2006, 2008), the mass-loading parameter of the wind primarily depends on the circular velocity of the disk \(v_c\), \(\eta \propto v_j^{-1} \propto M_{\text{baryon}}^{-1/2}\), if the wind outflow velocity is near the escape velocity (Murray et al. 2005). Hopkins et al. (2012) have recently carried out high-resolution smoothed particle hydrodynamic simulations of isolated galaxies with different types of input feedback, including that from supernovae (SNe), stellar winds, expanding H II regions, and radiation pressure, and find an overall scaling of \(\eta \propto v_j^{-1} \Sigma_{\text{gas}}^{-1/2}\) and \(\eta \sim 1\) for the parameters of typical high-z massive SFGs and with energy-driven winds. The scaling with \(v_j^{-1}\) is consistent with that found by Oppenheimer & Davé (2006, 2008), yet the dependence on \(\Sigma_{\text{gas}}^{-1/2}\) is contrary to the findings of Chen et al. (2010), who found a positive correlation of the Na D equivalent width (EW) with \(\Sigma_{\text{SFR}}\) from Sloan Digital Sky Survey (SDSS) data of ~100,000 galaxies, where Na D EW is used here as a proxy for the mass loading (\(\eta\)).

In this paper, we analyze the outflow properties of 27 z ~ 2 SFGs, discussed in more detail in N. M. Förster Schreiber et al. (2012, in preparation) and based on new high-quality Hα emission-line SINFONI/Very Large Telescope (VLT) integral field (IFU) spectroscopy with adaptive optics (AO) (Eisenhauer

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et al. 2003; Bonnet et al. 2004). We adopt a Λ cold dark matter cosmology with Ω_m = 0.27, Ω_b = 0.046, and H_0 = 70 km s^{-1} Mpc^{-1} (Komatsu et al. 2011), and a Chabrier (2003) initial stellar mass function (IMF).

2. OBSERVATIONS, DATA REDUCTION, AND ANALYSIS TECHNIQUES

The galaxy sample discussed here (see Table 1) is described in Mancini et al. (2011) and N. M. Förster Schreiber et al. (2012, in preparation). Our 27 z ~ 2–2.5 SFGs are drawn from the SINS and zC-SINF surveys of Hα+[N II] integral field spectroscopy with SINFONI on the ESO VLT (Förster Schreiber et al. 2009; Mancini et al. 2011; N. M. Förster Schreiber et al. 2012, in preparation). They were selected either for their U_0R colors satisfying the “BX” criteria (Steidel et al. 2004; Adelberger et al. 2004; Erb et al. 2006; Law et al. 2009) or based on K-band imaging via the “BzK” criterion for 1.4 < z < 2.5 SFGs (Daddi et al. 2004). They sample the z ~ 2 star-forming “main sequence” for stellar masses between 10^{10.5} and 10^{11.5} M_☉. Our sample includes 25 galaxies observed with an AO mode with a sufficient signal-to-noise ratio (S/N) for analysis (0.05 pixels, typical full width at half maximum (FWHM) 0.02–0.25), in addition to two galaxies observed in seeing limited mode that have very extended disks and thus are well resolved with 0.125 pixels and FWHM ~ 0.5. The data are of high quality (~6 h average integration time per galaxy, with a range from 2 to 22 h, and a total integration time for the entire sample of 180 h) and were reduced with our standard data reduction methods and analysis tools (Schreiber et al. 2004; Davies 2007; Förster Schreiber et al. 2009; Mancini et al. 2011).

Stellar masses and ages are derived from spectral energy distribution (SED) modeling in Förster Schreiber et al. (2009) and Mancini et al. (2011), assuming constant or exponentially declining star formation histories with Bruzual & Charlot (2003) tracks. The SFRs are derived from the SED modeling and from Hα (SFR = L_{Hα}/2.1 × 10^{35} erg s^{-1}; Kennicutt 1998; corrected for a Chabrier 2003 IMF) with a Calzetti et al. (2000) reddening law with A_V, gas = 2.3 × A_H, SED. Half-light radii (R_{1/2}) were computed from the cumulative Hα flux profile determined after fitting a 2D exponential (Sersic n = 1) to the data. We calculate molecular gas masses (M_{gas}) and surface densities (Σ_{gas} = 0.5 × M_{gas}/(π R_{1/2}^2)) from the Hα-derived SFRs using the molecular gas to star formation surface density relation with M_{gas}(M_☉) = 5.8 × 10^{9} × SFR (M_☉ yr^{-1}) (L. J. Tacconi et al. 2012). We also generate position–velocity (pv) data by extracting the spectra along the major galaxy axis for each shifted cube with a slit that is wide enough to cover most of the minor axis emission. The data are then re-added and re-sampled onto a normalized spatialized scale of 0.07 × R_{1/2} (FWHM ~ 0.3 × R_{1/2}) and a spectral scale of 40 km s^{-1} pixel^{-1} (~90 km s^{-1} FWHM).

3. OUTFLOW PROPERTIES IN z ~ 2 SFGs

We ascertain that the outflows are driven by the star formation activity and not by an active galactic nucleus (AGN) as we have excluded any known AGN from our sample, we find that the
broad emission is extended and not concentrated toward the kinematic or morphological center (see Section 3.1), and we measure [N ii]/Hα ratios that are compatible with the expected metallicity based on the $z \sim 2$ mass-metallicity relation (Erb et al. 2006) and are too low to be consistent with the presence of an AGN. In two cases, we trace the origin of the outflows to individual giant star-forming clumps embedded in the disk (Genzel et al. 2011; Newman et al. 2012). We note that Genzel et al. (2011) suggest that the bright emission coming from a clump in one of our galaxies (ZC407302) could be due to AGN activity if this clump is an external minor merger, rather than a star-forming clump formed within the disk. However, there is no other evidence that this galaxy contains an AGN.

3.1. Outflows are Spatially Extended

The broad emission (FWHM $\sim 450$ km s$^{-1}$) is spatially extended over the half-light radii ($R_{1/2}$), which corresponds to a few kpc in the small galaxies and up to 6 kpc in the larger disks. This is demonstrated in the lower panel of Figure 1, where we show a co-added pv diagram of the line emission (large-scale velocity gradients removed) along the morphological major axis for the galaxies. Broad emission is detected at least out to $R_{1/2}$, and its width between $0.5 \times R_{1/2}$ and $R_{1/2}$ (FWHM $= 423 \pm 19$ km s$^{-1}$) is nearly as broad as within $0.5 \times R_{1/2}$ (FWHM $= 475 \pm 12$ km s$^{-1}$). The upper panel of Figure 1 shows that the emission in the outer regions of the galaxies is almost as broad as in the inner regions, and implies a constant or decreasing mass loading with increasing galactocentric radius.

The 10 galaxies used in this co-add (BX455, BX513, BX543, BX599, SA12-6339, ZC404221, ZC407306, ZC407302, ZC412369, and ZC415876) are selected such that they have noticeable broad line wings without the need for stacking and an absence of OH residuals near Hα. All but one have $R_{1/2} < 3$ kpc, and all have $\Sigma_{\text{SFR}} > 1 M_\odot \text{yr}^{-1} \text{kpc}^{-2}$. However, their stellar masses and SFRs span the ranges seen in our full sample. We note that although most of the galaxies from this stack are small (with $R_{1/2} < 3$ kpc), we also observe broad emission from stacks of larger galaxies that also have $\Sigma_{\text{SFR}} > 1 M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ (see next section).

3.2. The Broad Flux Fraction is Strongly Dependent on the SF Surface Density

We explored the dependence of the broad flux fraction on galaxy properties by dividing the entire sample into two bins each (low/high) by SFR, stellar mass, size, inclination, and star formation surface density. We then co-added the spectra in each of the bins and computed the ratio of the broad-to-narrow Hα emission. The results are summarized in Table 2.

The star formation surface density has the largest effect on the broad flux fraction, such that galaxies with $\Sigma_{\text{SFR}} > 1 M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ drive the strongest outflows, which confirms and strengthens a similar finding in Genzel et al. (2011). This result is also consistent with what was observed in $z \sim 0$ SFGs by Chen et al. (2010), where they found a strong correlation between Na D absorption EW (from SDSS data of ~100,000 galaxies) and $\Sigma_{\text{SFR}}$.

In Figure 2, we see the dependence of the broad Hα flux fraction on $\Sigma_{\text{SFR}}$ from five $\Sigma_{\text{SFR}}$-binned points as well as three massive star-forming clumps. The trend seen in Figure 2 can be well described as a “threshold” for outflows. All of the data

**Figure 1.** Lower panel: co-added (pv) diagram for the 10 sources with the best evidence for broad emission, with the vertical (spatial) axis normalized to $R_{1/2}$. The black contours show the unnormalized stack, while the colors have been normalized according to the peak Hα flux for each spatial row. The broad emission in light blue ($>200$–$300$ km s$^{-1}$ from the systemic velocity) is spatially extended (vertical axis) out to at least $R_{1/2}$. Upper panel: spectra from the inner ($R < 0.5 \times R_{1/2}$, blue, solid line) and outer ($0.5 \times R_{1/2} < R < R_{1/2}$, red, dashed line) regions of the galaxies, with the broad fitted components shown by the blue dotted line (inner) and red dash-dotted line (outer). The inner and outer region spectra have $F_{\text{broad}}/F_{\text{narrow}} = 1.31 \pm 0.075$ and 1.13 $\pm$ 0.12, with broad-to-narrow component velocity shifts of $-41 \pm 5$ km s$^{-1}$ and $-33 \pm 9$ km s$^{-1}$, respectively. The inset shows the entire Hα line for the inner spectrum (black) with the broad component (blue, dashed) and narrow component (red, dash-dotted) overplotted.

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


Table 2

| Property         | F_{broad}/F_{narrow} (Ha) | FWHM_{broad} (km s^{-1}) | ΔF_{broad−narrow} (km s^{-1}) | Significance of Difference | Dividing Value |
|------------------|---------------------------|--------------------------|-------------------------------|---------------------------|---------------|
|                  | High Bin                  | Low Bin                  | High Bin                      | Low Bin                   |               |
| SFR              | 0.65 ± 0.074              | 0.50 ± 0.041             | 510 ± 12                      | 423 ± 47                  |               |
| R_{1/2}          | 0.50 ± 0.054              | 0.76 ± 0.082             | 503 ± 15                      | 432 ± 19                  |               |
| Σ_{SFR}          | 0.77 ± 0.027              | 0.16 ± 0.030             | 500 ± 16                      | 423 ± 75                  |               |
| Inclination      | 0.47 ± 0.055              | 0.77 ± 0.091             | 510 ± 44                      | 514 ± 12                  |               |
| m_{s1}           | 0.63 ± 0.056              | 0.41 ± 0.042             | 528 ± 13                      | 423 ± 45                  |               |
| m_{s2}           | 0.23 ± 0.21               | 0.12 ± 0.040             | 423 ± 66                      | 423 ± 80                  |               |
| m_{s3}           | 0.85 ± 0.097              | 0.71 ± 0.10              | 520 ± 11                      | 428 ± 30                  |               |

Notes. The high/low bins for SFR, m_{s1}, Σ_{SFR}, R_{1/2}, and inclination are divided above and below the value(s) shown in column 9 and have roughly an equal number of galaxies in each bin. The spectrum from each stack was fit constraining the narrow FWHM to between 190 and 210 km s^{-1}, so that the broad component was not fit as a very broad narrow component, and allowing the relative velocities of the two components and the broad line width (FWHM) to vary. The best-fit broad FWHM and the relative velocities for each bin are shown in columns 4–7. For the m_{s1} bins, (1) is for all galaxies, (2) is for galaxies with Σ_{SFR} < 1 M_{⊙} yr^{-1} kpc^{-2}, and (3) is for galaxies with Σ_{SFR} > 1 M_{⊙} yr^{-1} kpc^{-2}.

3.3. Local Electron Density of the Outflow

We estimate the ratio of the [S II] doublet in the broad and narrow components for a stack of the galaxy spectra, in order to constrain the star-forming gas and wind densities. The 14 galaxies used in this stack are selected such that they do not have strong OH sky features close to the location of the [S II] lines and have noticeable broad Hα components. We follow the fitting method described earlier in the text, except here we allow the amplitudes of the broad and narrow components in all nebular lines to vary, as opposed to, for instance, setting [N II]/Hα (broad) equal to [N II]/Hα (narrow). The reduced χ^2 of the fit in the region of the Hα line is 1.71 and in the region of the [S II] lines is 0.97, while an imposed one-component

![Figure 2](image-url)
fit yields reduced $\chi^2$ values of 26.1 and 1.24, respectively, highlighting the challenges of attempting such a measurement.

For the narrow component, we find $F([\text{S} \text{ii}])_{6716}$/$F([\text{S} \text{ii}])_{6731} = 0.99 \pm 0.27$, and for the broad component, we find that the ratio is $1.43 \pm 0.40$, corresponding to electron densities of 600 (+1000/−450) and 10 (+590/−10) $\text{cm}^{-3}$, respectively (Osterbrock 1989). The errors come from the fit uncertainties. Although our estimate is uncertain, the inferred local gas density in the outflow could be more than an order of magnitude less than the density of the star-forming regions (traced by the narrow component), consistent with a diffuse outflow. In Newman et al. (2012), we assumed a mass outflow density of 100 $\text{cm}^{-3}$, based on two different outflow geometries and estimates of outflow density from local starburst galaxies (see, e.g., Heckman et al. 1990). Thus, we assume that these two values are upper and lower limits and take an average, resulting in a wind density of 50 $\text{cm}^{-3}$. Figure 3 shows the co-added spectrum along with the best fit.

A comparison of the narrow and broad $[\text{N} \text{ii}]/H\alpha$ ratios (0.17 ± 0.017 and 0.31 ± 0.028, respectively) with those of Newman et al. (2012) in the clump and wind regions of ZC406690 shows that the narrow $[\text{N} \text{ii}]/H\alpha$ ratio is quite similar to the clump value and the broad ratio is very similar to that of the wind regions, which are affected by shocks. Therefore, not only does the broad $[\text{S} \text{ii}]$ ratio tell us about the density in the wind, but the broad $[\text{N} \text{ii}]/H\alpha$ value provides further evidence that the broad component derives from outflows.

3.4. Mass Loading of High-z Galactic Outflows

We assume the simplified outflow model of Genzel et al. (2011) and Newman et al. (2012) for a warm ionized outflow with a radially constant outflow velocity and mass-loss rate, to convert the $F_{\text{broad}}/F_{\text{narrow}}$ ratio in Figure 2 into a mass-loading factor $\eta \equiv M_{\text{out}}/\text{SFR}$,

\[
M_{\text{out}} = M_\odot \times \frac{v_{\text{out}}}{R_{\text{out}}} = \frac{1.36 n_\text{H}}{\gamma_{\text{H} \alpha} n_e} \left( L_{\text{H} \alpha} \times \frac{F_{\text{broad}}}{F_{\text{total}}} \right) \frac{v_{\text{out}}}{R_{\text{out}}} \quad (1)
\]

where $M_{\text{out}}$ is the mass outflow rate, $M_\odot$ is the instantaneous mass in the outflow, $v_{\text{out}}$ is the average velocity of the outflow, $R_{\text{out}}$ is the radial extent, $n_\text{H}$ is the atomic mass, $\gamma_{H\alpha}$ is the $H\alpha$ emissivity at $T_e = 10^4 \text{ K}$ ($\gamma_{H\alpha} = 3.56 \times 10^{-25} \text{ erg cm}^2 \text{ s}^{-1}$), $n_e$ is the local electron density in the outflow, $L_{H\alpha}$ is the total extinction-corrected $H\alpha$ luminosity, and $F_{\text{broad}}/F_{\text{total}}$ is the fraction of the total flux in the broad component. We assume $v_{\text{out}} = 400 \text{ km s}^{-1}$ (see Section 4) and $R_{\text{out}} = 3 \text{ kpc}$. The latter is based on the spatial offset of outflowing gas from a massive star-forming clump described in Newman et al. (2012), and from the finding in Section 3.1 that the broad emission is extended to several kpc from the galaxy center. The emission-line-based estimate is independent of the collimation of the outflow. We adopt $n_e = 50 \text{ cm}^{-3}$ as the average local electron density, derived in the previous section.

The inferred mass-loading factors corresponding to the broad flux fraction are shown on the rightmost $y$-axis in Figure 2. The mass-loading factors for galaxies below the $\Sigma_{\text{SFR}}$ threshold are $\sim 0.5$ and above the threshold are $\sim 2$, albeit with an overall absolute uncertainty of at least a factor of three. Despite the uncertainties, a mass-loading factor of two is consistent with observations of both local starbursts (Heckman et al. 1990; Veilleux et al. 2005; Chen et al. 2010) and high-z SFGs (Pettini et al. 2000; Weiner et al. 2009; Steidel et al. 2010; Genzel et al. 2011; Bouché et al. 2012), as well as theoretical predictions (Murray et al. 2005; Davé et al. 2011; Hopkins et al. 2012).

4. WHY DO THE OUTFLOWS DEPEND SO STRONGLY ON $\Sigma_{\text{SFR}}$?

We propose that the strong dependence of $\eta$ on $\Sigma_{\text{SFR}}$ discussed in Section 3.4 is mainly caused by the threshold that governs when star formation feedback can break out of the dense gas layer in the disk.

Following Ostriker & Shetty (2011) (see Equations (1) and (7)), in a baryon dominated galactic disk in pressure equilibrium, the weight of the disk balances the pressure generated from star formation feedback in the form of SNe, stellar winds, $H\text{ii}$ regions, cosmic rays, and radiation from the star-forming
layer. If that pressure exceeds the weight of the disk, then a momentum-driven outflow is launched perpendicular to the galactic plane, with a threshold $\Sigma_{\text{SFR}} (M_\odot \text{yr}^{-1} \text{kpc}^{-2})$ of

$$\Sigma_{\text{SFR, th}} = \frac{\pi G f_g}{2 (P_{\text{tot}}/m_*)} d_2 = 0.9 \times \frac{f_g 0.5 \times \Sigma_{\text{d,500}}}{(P_{\text{tot}}/m_*)_{1000}},$$

where $G$ is the gravitational constant, $(P_{\text{tot}}/m_*)$ is the characteristic total momentum injection per mass, $d_2$ is the disk surface density, and $f_g$ is the gas fraction, with fiducial values of 1000 km s$^{-1}$ (Ostriker & Shetty 2011; Murray et al. 2005), 500 $M_\odot$ pc$^{-2}$ (Erb et al. 2006; Förster Schreiber et al. 2009), and 0.5 (Tacconi et al. 2010; Daddi et al. 2010), respectively. Here, we have equated the weight of the gas above the disk (see Ostriker & Shetty 2011, Equation (1), with an added dependency on $f_g$ since we only care about infalling gas) with the pressure from star formation feedback (see Ostriker & Shetty 2011, Equation (7)). This is similar to the Eddington limit of momentum-driven winds (Murray et al. 2011), which gives $\Sigma_{\text{SFR, threshold}} \propto v_c^{5/2} R^{-2}$, where $v_c$ is the circular velocity.

The wind has a total momentum outflow rate,

$$\dot{M}_w v_\infty \leq \left( \frac{P_{\text{tot}}}{m_*} \right) \text{SFR},$$

where $v_\infty$ is the outflow velocity at large distances from the midplane, implying a mass-loading factor,

$$\eta = \frac{\dot{M}_w}{\text{SFR}} \leq \frac{(P_{\text{tot}}/m_*)}{v_\infty} = 2.5 \times \frac{(P_{\text{tot}}/m_*)_{1000}}{v_{\infty,400}},$$

with $v_{\infty,400}$ in units of 400 km s$^{-1}$. This velocity is motivated by the observed outflow velocities in both low-$z$ and high-$z$ SFGs (Pettini et al. 2000; Martin 2005; Veilleux et al. 2005; Weiner et al. 2009; Steidel et al. 2010; Genzel et al. 2011) as well as from this work. The adopted value of the characteristic momentum injection is chosen assuming $P_{\text{tot}}/m_*$ from radiation pressure $\sim 200–300$ km s$^{-1}$ (Ostriker & Shetty 2011) and that the direct momentum injection contributions of SNe, stellar winds, H II regions, and radiation pressure are all roughly comparable (Murray et al. 2005, 2010), giving a total $(P_{\text{tot}}/m_*)$ of 1000 km s$^{-1}$. Here, we have assumed that energy-driven winds are unimportant and that the bulk of the ram pressure from SNe does not play a strong role until the gas has been lifted out of the disk (see Murray et al. 2011).

This simple model predicts that for constant $\eta$, the ability of an outflow to break out of the disk strongly depends on the star formation surface density, and this threshold value scales linearly with gas fraction and as the square of the disk surface density. Second, the mass loading of galactic winds above breakout and the threshold star formation surface density for breakout both depend on $(P_{\text{tot}}/m_*)$. Thus, if one of these quantities can be determined for a galaxy of known properties, then the other can be predicted. The model also predicts that it is harder to launch a wind from a more massive galaxy (with larger $v_c^2/R^2$). This final prediction is also acquired by writing the threshold in terms of $m_*$ by assuming (1) the $R_{1/2}$–$m_*$ relation of Ichikawa et al. (2012) $(R_{1/2} \sim m_*^{0.14})$, (2) the SFR–$m_*$ relation for normal SFGs (SFR $= m_*^{0.7}$ $(1+z)/3.2^{2.6}$) (Elbaz et al. 2007; Nöeske et al. 2007), and (3) a constant gas depletion timescale $(t_{\text{depl}} = M_* / \text{SFR} \sim 6.4 \times 10^8$ yr) (L. J. Tacconi et al. 2012, in preparation). We note that the Ichikawa et al. (2012) relation was derived using $K$-band continuum emission, while our $R_{1/2}$ are derived using $H_\alpha$, so there may be some inconsistency. This gives an $m_*$ threshold of $\sim$ few $\times 10^{10} M_\odot$, such that it is easier for outflows to “break out” from galaxies below this threshold.

The first two predictions are met by the available data. For $z \sim 0$ normal SFGs with $f_g \sim 0.07$ and $\Sigma_{\text{SFR}} \sim 500 M_\odot$ pc$^{-2}$ (Catinella et al. 2010), Equation (4) suggests a critical break-out star formation surface density of $\sim 0.1 M_\odot$ yr$^{-1}$ kpc$^{-2}$. Indeed, winds are only detected in compact star-forming dwarfs and/or starbursts above $\sim 0.1 M_\odot$ yr$^{-1}$ kpc$^{-2}$ (Heckman et al. 1990; Veilleux et al. 2005; Chen et al. 2010, see also Murray et al. 2011). Mass-loading factors for local galaxies with winds are estimated to be around one (Martin et al. 2012).

For the typical high-$z$ SFGs presented in this paper ($f_g \sim 0.5$, $\Sigma_{\text{d}} \sim 500–1000 M_\odot$ pc$^{-2}$), Equation (2) suggests a break-out star formation surface density near or slightly above $1 M_\odot$ yr$^{-1}$ kpc$^{-2}$, in remarkable agreement with our findings in Section 3.2 and Figure 2. Above this threshold, Equation (4) predicts a mass loading of $\sim$2.5, again in good agreement with our observations. We caution that our determination of the mass-loading factor in the previous section is dependent on a simplified model with fairly uncertain parameters, yet the agreement is encouraging.

A positive correlation of $\eta$ with $\Sigma_{\text{SFR}}$ (which was also observed by Chen et al. 2010) is possible evidence against the scenario in which winds are launched by the energy of hot SN bubbles, as in this case where the shorter cooling time of the dense gas suggests $\eta \propto \Sigma_{\text{SFR}}^{1/2}$ (Hopkins et al. 2012), and could support the momentum-driven wind model.

However, the third prediction of the simple model (massive galaxies are less efficient at driving winds) does not appear to be met by our data. For the SFGs in the “wind regime” ($\Sigma_{\text{SFR}} > 1 M_\odot$ yr$^{-1}$ kpc$^{-2}$), we do not see any significant variation of $F_{\text{broad}}/F_{\text{narrow}}$ as a function of $v_c$, which is expected theoretically for momentum-driven winds ($\eta \propto v_c^{-1}$; Murray et al. 2005; Oppenheimer & Davé 2006, 2008; Hopkins et al. 2012).

This finding, as well as the approximate $m_*$ independence of the observed $F_{\text{broad}}/F_{\text{narrow}}$ ratio in our data, surprisingly suggests that massive SFGs have mass-loading factors that are similar to or higher than those of low-mass SFGs. If so, then the volume-averaged outflow rate and metal enrichment of the circumgalactic/intergalactic medium at $z \sim 2$ may be dominated by massive galaxies just around the Schechter mass (log $M_* \sim 10.65$; Peng et al. 2010). Indeed, with a slope $\alpha$ of the main sequence of SFGs (SFR $\propto m_*^{\alpha}$) $\sim 0.7$ or higher, the SFR (and thus the outflow rate, with constant $\eta$) increases faster with $m_*$ than the volume density of SFGs decreases ($D(m_*) \sim m_*^{-0.5}$; Peng et al. 2010). We note that a massive galaxy dominance in the metal enrichment of the intracluster medium (ICM) is demanded by the fact that in clusters $\sim 2/3$ of the metal mass is contained in the ICM, whereas only $\sim 1/3$ is still locked into stars and galaxies (Renzini 1997).

Furthermore, the $z \sim 2$ $m_*$ dependence of the mass–metallicity relation ($Z \sim m_*^{0.24}$; Erb et al. 2006) may be primarily driven by the larger (diluting) gas fractions in low $m_*$ SFGs, besides these galaxies driving winds more effectively ($M_{\text{g}}/m_* = t_{\text{depl}} \times \text{SFR}/m_* \sim m_*^{-0.3}$). In addition, if high-$m_*$ galaxies are indeed ejecting this much mass, then we may have uncovered a mechanism contributing to the quenching of star formation near the Schechter mass (Peng et al. 2010).

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