INTENSE STAR FORMATION AND FEEDBACK AT HIGH REDSHIFT: SPATIALLY RESOLVED PROPERTIES OF THE $z = 2.6$ SUBMILLIMETER GALAXY SMM J14011+0252

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ABSTRACT

We present a detailed analysis of the spatially resolved properties of the lensed submillimeter galaxy (SMG) SMM J14011+0252 at $z = 2.56$, combining deep near-infrared integral-field data obtained with SPIFFI on the VLT with other multiwavelength data sets. As previously discussed by other authors, the broad characteristics of SMM J14011+0252 in particular and submillimeter galaxies in general are in agreement with what is expected for the early evolution of local massive spheroidal galaxies. From continuum and line flux, velocity, and dispersion maps, we measure the kinematics, star formation rates, gas densities, and extinction for individual subcomponents. The star formation intensity is similar to low-redshift “maximal starbursts,” while the line fluxes and the dynamics of the emission line gas provide direct evidence for a starburst-driven wind with physical properties very similar to local superwinds. We also find circumstantial evidence for “self-regulated” star formation within J1. The relative velocity of the bluer companion J2 yields a dynamical mass estimate for J1 within $\sim 20$ kpc of $M_{dyn} \sim 1 \times 10^{11} M_{\odot}$. The relative metallicity of J2 is 0.4 dex lower than in J1n/J1s, suggesting different star formation histories. Spectral energy distribution fitting of the continuum peak J1c confirms and substantiates previous suggestions that this component is a $z = 0.25$ interloper. When removing J1c, the stellar continuum and H$\alpha$ line emission appear well aligned spatially in two individual components, J1n and J1s, and coincide with two kinematically distinct regions in the velocity map, which might well indicate a merging system. This highlights the close similarity between SMGs and ultraluminous infrared galaxies (ULIRGs), which are often merger-driven maximal starbursts, and suggests that the intrinsic mechanisms of star formation and related feedback are in fact similar to low-redshift strongly star-forming systems.

Subject headings: galaxies: evolution — galaxies: kinematics and dynamics

1. INTRODUCTION

Half of the stars in the local universe formed at $z \gtrsim 1$ or by about half the age of the universe (e.g., Rudnick et al. 2003 and references therein). However, in spite of our knowledge of when this star formation occurred, our understanding of the physical processes triggering and governing it is still rudimentary. In particular, does the physics of star formation depend on redshift? For example, Goldader et al. (2002) hypothesize that the intense star formation observed in some high-redshift galaxies might require a more efficient mode of forming stars, without triggering by major mergers. Erb et al. (2006), on the other hand, find that star formation in galaxies at $z \sim 2$ is less efficient because they drive very efficient winds and energy into galaxy halos and the intergalactic medium (IGM) and thus lose significant amounts of mass. Both hypotheses illustrate the need for detailed studies of star formation at high redshift, to investigate whether low-redshift star-forming galaxies observed at high spectral and physical resolution can be good analogs of star formation at high redshift.

“Superwinds”—vigorous outflows of hot gas due to the thermalized ejecta of supernovae and massive stars in starburst galaxies—are inexorably linked to star formation. While winds likely play a fundamental role in galaxy formation and evolution (e.g., Heckman et al. 1990; Lehnert & Heckman 1996a) and contribute significantly to the metal content of the IGM (e.g., Bouché et al. 2005), the direct observational evidence for the ubiquity of winds in star-forming galaxies at high redshift is still rather limited. It is mainly based on blue line asymmetries and offsets of rest-frame UV interstellar absorption lines relative to optical emission lines (e.g., Pettini et al. 2001) and on the evolution of the mass-metallicity relationship at high redshift (Erb et al. 2006) in UV-selected galaxy populations.

Submillimeter galaxies (SMGs) at $z \sim 2$ are the sites of particularly vigorous star formation, with star formation rates of $\sim 100 – 1000 M_{\odot} \text{yr}^{-1}$, and thus provide an excellent opportunity to investigate the properties of extreme star formation at high redshift (Blain et al. 2002 and references therein).

The $z = 2.57$ SMG SMM J14011+0252 (Ivison et al. 2001; Frayer et al. 1999) is perhaps the best-studied SMG across all wave bands, because it has a relatively bright multiwavelength continuum, rest-frame optical emission lines with rather large equivalent widths, and moreover is moderately gravitationally lensed ($M \lesssim 5$) by the $z = 0.25$ galaxy cluster A1835 (see Ivison et al. 2001, 2000; Barger et al. 1999; Fabian et al. 2000; Smail et al. 2000, 2002, 2005; Downes & Solomon 2003; Tecza et al. 2004; Swinbank et al. 2004; Motohara et al. 2005). Ivison et al. (2000) gave the first detailed description of the source properties and estimated a

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Using the flat $\Omega_{\Lambda} = 0.7$ cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ leads to $D_L = 21.04$ Gpc and $D_A = 1.66$ Gpc at $z = 2.565$. The size scale is 8.03 kpc arcsec$^{-1}$. The age of the universe for this redshift and cosmological model is 2.5 Gyr.
far-infrared (FIR) luminosity of \( L_{\text{FIR}} \sim 6 \times 10^{12} L_\odot \) and a star formation rate of \( \text{SFR} = 1260 \pm 3900 M_\odot \, \text{yr}^{-1} \) (for a magnification of 3; see also Ivison et al. 2001). Tecza et al. (2004, hereafter Paper I) reanalyzed the FIR data given in Ivison et al. (2000), estimating \( L_{\text{FIR}} \sim 2.3 \times 10^{13} M_\odot \, \text{yr}^{-1} \) for the star formation rate and \( M_\odot \) for the gravitational lens. The differences are mainly due to different assumptions regarding the modeling of the spectral energy distributions in the far-infrared and different initial mass functions for the star formation rates. Since the values used in Paper I are better matched to the assumptions made in our paper, below we use the values of Paper I.

Many SMGs show evidence for optically evident active galactic nuclei (AGNs) through their rest-frame optical line ratios (Takata et al. 2006). Swinbank et al. (2005) interpret the broad recombination line profiles in some SMGs as likely originating from nuclear broad-line regions. Deep photometry of SMM J14011+0252 covers X-ray to radio wavelengths, and long-slit spectroscopy has been previously taken in the rest-frame UV and optical range. None of these data have revealed evidence for an AGN in this source. All these arguments make SMM J14011+0252 an ideal target for studying the properties of strongly star-forming galaxies in the early universe.

The relationship between the molecular gas and the other components of SMM J14011+0252, however, has led to controversy in the literature. Frayer et al. (1999) reported the first detection of CO(3–2) emission, and Ivison et al. (2001) emphasized a good alignment of the CO(3–2) emission with the faint red component J1n, indicating that this is the location of the intense submillimeter emission and the starburst (see Fig. 1 for the labeling). This view was later challenged by Downes & Solomon (2003), who found a different alignment of their CO(7–6) and CO(3–2) data sets with the rest-frame UV data, placing the CO emission significantly outside the optical emission of J1. The CO emission is marginally resolved spatially (\( 2^\prime < 0.4^\prime \); Downes & Solomon 2003), and its line width of FWHM = 190 \pm 10 km s\(^{-1}\) corresponds to a dynamical mass of \( 3 \times 10^{10} M_\odot \) (Greve et al. 2005, not correcting for inclination). We note that this mass estimate is less than the estimate of the total molecular mass of SMM J14011+0252 (Frayer et al. 1999; Downes & Solomon 2003).

High-resolution Hubble Space Telescope (HST) F702W imaging shows that SMM J14011+0252 has a complex morphology in the rest-frame UV, which does not become more regular in rest-frame optical wave bands (Ivison et al. 2000). Based on rest-frame UV spectroscopy, Ivison et al. (2000) were the first to argue that the nearby blue component J2 is at a very similar but not identical redshift and is a physically related component of J1. The nature of the bright UV-optical continuum peak J1c remained more mysterious: Downes & Solomon (2003) proposed that J1c might be a member galaxy of the foreground cluster A1835 along the line of sight and suggested that several blue features of J1 were in fact multiple images caused by strong lensing through a foreground source J1c. Smail et al. (2005) and Swinbank et al. (2004) agree with the interpretation that J1c is a foreground source but favor a lower magnification factor \( M \sim 3–5 \), which would not lead to multiple images or strong differential lensing. They argue that absorption lines seen in the spectrum of Barger et al. (1999) can be identified as rest-frame optical absorption lines at \( z \sim 0.25 \) and highlight the nearly spherical morphology of J1c, both of which seem unlikely if it is a lensed galaxy at \( z = 2.57 \).

In an earlier paper (Paper I), we presented an initial analysis of deep near-infrared integral field spectroscopy of SMM J14011+0252 obtained with SPIFFI (Spectrograph for Infrared Faint Field Imaging) on the Very Large Telescope (VLT), concentrating on the integrated properties of the source, such as the high gas-phase oxygen abundance \( (12 + \log O/H = 9.0) \), measured with R23) and large mass, and put these results into a broader perspective of mass assembly in the early universe within hierarchical structure formation models. We now complement these findings with a detailed analysis of the spatially resolved properties of this source, and we in particular discuss the implications for star formation and related feedback in massive galaxies at high redshift.

2. SPIFFI AND COMPLEMENTARY DATA SETS

SMM J14011+0252 was observed in the J, H, and K bands with the integral field spectrometer SPIFFI (Eisenhauer et al. 2003) at the ESO VLT in spring 2003, with individual exposure times of 300 s in H and 600 s in J and K. Total exposure times were 340 minutes in K, 95 minutes in H, and 60 minutes in J. We used the 0.25\( ^\prime \) pixel scale and obtained spectral resolutions of \( R = \lambda/\Delta \lambda \sim 1500 \) in the J band, \( \sim 2000 \) in the H band, and \( \sim 2400 \) in the K band.

The data were calibrated using the UKIRT faint standard F135 and agree to within a few percent with the magnitudes previously published for SMM J14011+0252 (Ivison et al. 2000). The seeing disk has FWHM = 0.6\( ^\prime\prime \times 0.4\prime\prime \) in right ascension and declination, respectively, and was measured from the standard star. The data reduction has been described elsewhere (Nesvadba et al. 2006). The main difference between the data reduction in this paper and in Paper I is improved sky subtraction allowing us to investigate the spatially resolved properties of SMM J14011+0252 more robustly. The previous reduction algorithm led to an effective over-subtraction of the sky background near bright emission lines. As a result, the data quality in individual frames was improved through the new reduction, which yielded a more accurate alignment of the individual frames, which led to better data quality in the combined data set and better spatial resolution. This has no significant impact.

Fig. 1.— Contours showing the distribution of the CO(3–2) line emission superimposed on the F702W WFPC2 broadband continuum image (gray scale). The CO(3–2) map is from D. Downes (2006, private communication), and the labels on the WFPC2 image designate the regions of SMM J14011+0252 following the scheme of Motohara et al. (2005). “J1n” refers to the diffuse extended region north of J1c (see also Fig. 2). North is up and east is to the left. The astrometry used for this overlay was derived from identifying six radio sources in the FORS F-band image (see text for details).
on the integrated spectrum discussed in Paper I but does change the mapping of kinematics and emission line morphologies by improving the signal-to-noise ratio (S/N) of the low surface brightness line emitting regions.

In addition, before and since the publication of Paper I, a large number of complementary data sets had and have (now) become available to supplement and refine the interpretation of the SPIFFI data and the overall nature of the source. Ivison et al. (2001) obtained high-resolution optical imaging of the A1835 field through the F702W ($\approx R_{702}$) filter of the WFPC2 on board the HST. The reduced image was kindly provided by R. Ivison. He also kindly shared his 1.4 GHz continuum map of A1835 with us, which was obtained with the NRAO Very Large Array (VLA; Ivison et al. 2001). D. Downes kindly provided us with his CO(3–2) and 242 GHz continuum maps of SMM J14011+0252 obtained with the IRAM Plateau de Bure Interferometer (PdBI; Downes & Solomon 2003).

Deep ISAAC J-, H-, and K-band images are available from the ESO archive and were reduced as described in Bremer et al. (2004). A deep VLT FORS1 F-band image of the field of A1835 was obtained, reduced, and described in Lehner et al. (2005). A. Barger kindly provided the rest-frame UV spectra taken with the Low Resolution Imaging Spectrometer (LRIS) on the Keck 10 m telescope and published in Barger et al. (1999). Finally, R. Pello and A. Hempel graciously shared their F850LP ($\approx Z_{850}$) ACS image of SMM J14011+0252 J1 and J2 before the data were publicly available.

3. ABSOLUTE ASTROMETRY

Various possible and disparate alignments have been proposed for SMM J14011+0252 in the literature (see Downes & Solomon 2003; Ivison et al. 2001). The position of both the radio and millimeter interferometric positions relative to the rest-frame optical and UV have been especially problematic.

We obtained new and more robust astrometry for the field of SMM J14011+0252 using ISAAC K-band and FORS V-band imaging of A1835 (Lehnert et al. 2005). We identified six radio sources in the V-band image at magnitudes brighter than 17.5 mJy (the V-band image has a 5σ limit of 27.8 mJy). Of these six sources, three were point sources at the resolution of the data (seeing FWHM $\approx 0.7''-0.8''$) and three were extended. Given their high S/N, the uncertainty in the position is very small ($\leq 0.08''$). The depth and field of view of this image are greater than in previously available optical/near-infrared data. The radio sources are spread over the roughly $6'\times 6'$ field of view of the V-band image. A comparison of the radio source and optical positions suggests that the best alignment has an rms scatter of $0.04'' \times 0.08''$ ($\sim 10$ times less than the absolute positional uncertainty in each band). Such a good alignment suggests both that the position in each frame can be accurately determined and that the relative distortion in both the radio map and V-band image are insignificant compared to the total relative positional uncertainties over the entire field of view of the V-band image. All other optical/NIR data can be referenced to the V-band image to very high accuracy given the large number of sources that we used for the relative alignment (several dozen point or pointlike sources). The VLA radio and PdBI millimeter maps share the "radio" coordinate frame. We estimate a total absolute uncertainty of $0.33'' \times 0.34''$ ($\leq 1.5$ SPIFFI pixels) in right ascension and declination of the optical and near-infrared data relative to the CO position, including an absolute astrometric uncertainty in the CO map of $0.3''$ (following Downes & Solomon 2003) and a fiducial uncertainty of $0.14''$ (the pixel size of the ISAAC data, which is certainly an overestimate of the true uncertainty, since the relative alignment is better than a pixel). The relative uncertainty between the VLA map and the optical/near-infrared data is smaller (by a factor of 4–8).

The aligned K-band ISAAC image was used to put the SPIFFI cubes into the common frame, based on the positions of J1 and J2 and assuming a pixel scale of 0.25'' for the SPIFFI data. J1 and J2 have S/N $> 15$ and 6 in the SPIFFI continuum image in the central pixel, respectively, and S/N $> 30$ and 11 in the ISAAC K-band image, respectively. The alignment is limited by the uncertainty of the peak position in J1c and J2, which is much smaller than a single pixel in either data set ($0.25''$ for SPIFFI or 0.14'' for ISAAC).

Our new astrometric alignment rules out previous claims that the CO emission might be significantly offset from the UV and optical positions and is an independent confirmation of the initial alignment of Ivison et al. (2001) based on some new data sets. The position of the CO data is shown in Figure 1 as contours overlaid on the HST R$_{702}$ image, and in Figure 2 with respect to the ISAAC J – K color image. Within the uncertainty of 0.33'' the CO emitter can be identified with either J1n or J1c. The redder colors and stronger star formation (§ 5.1) favor J1n as the more likely source of CO line emission. We summarize the positions of the individual components in SMM J14011+0252 relative to the radio frame in Table 1. At any rate, this calibration firmly places the CO and radio emission within the isophotes of J1 in the HST (Ivison et al. 2000) and ground-based images (Ivison et al. 2000; Bremer et al. 2004; Lehner et al. 2005).

4. RESULTS AND ANALYSIS

4.1. Continuum Morphology and Colors

The rest-frame optical and UV continuum and Hα emission line morphology of the J1 complex have been described elsewhere (see, e.g., Ivison et al. 2000; Tecza et al. 2004; Motohara et al. 2005; Smail et al. 2005). Overall, our data are consistent with these
previous descriptions, but deeper and more detailed in several aspects. We label individual components in Figures 1–3.

Continuum emission is centered on J1c and varies strongly with wavelength. At short wavelengths the extended emission becomes relatively stronger. In Figure 2 we show the J-band color distribution derived from the ISAAC data. The K-band data were convolved with a two-dimensional Gaussian disk to have the same resolution as the J-band data. K-band fluxes are corrected for the equivalent width measured with SPIFFI. Line contamination is <0.2 mag in J1n and insignificant in J1s.

J – K colors (corresponding to roughly U – R at rest frame) are different in J1n and J1s, with J – K ≈ 1.6 in J1s. J-band emission in J1n is relatively faint. We replaced the J-band flux with the 3σ limit where we detected K- but no J-band emission, so that the measured J – K ≈ 2.0 in J1n is in fact a lower bound to the J – K color in J1n.

The red area in J1s coincides spatially with the bright knots J1a and J1b in the HST F702W image. We also identify these knots in the ISAAC K-band image. Comparison of the seeing-matched ISAAC and HST data sets indicates that the prominence of these knots in the HST data compared to the ground-based images is in large part due to the smaller point-spread function (PSF) in the F702W image and does not reflect intrinsic variations in size with wavelength or strong line contamination. Unresolved blue knots superimposed on J1n in Figure 3, however, should also appear at longer wavelength in spite of the lower resolution. We do not observe them, but the low surface brightness region becomes more prominent in J1n. This indicates that these color variations reflect intrinsic variations in the morphology of J1n.

4.1.1. Line Ratio Diagnostics: Ionizing Source and Gas Densities

Line emission in J1 reaches the highest surface brightnesses in the areas of J1n and J1s and is generally lower in J1c, as expected for a foreground galaxy. To differentiate between J1n and J1s, we assign all spatial pixels to J1n and J1s if they are at least 2 SPIFFI pixels (0.5″, roughly corresponding to the seeing disk) north or south from J1c, respectively. The spectral range of our observations includes all strong optical emission lines between the [O II] λλ3726, 3729 and the [S II] λλ6717, 6731 doublets. We use emission line ratios, namely, [O II]/Hβ, [N II]/Hα, and [S II]/Hα, to constrain the ionizing source (e.g., Baldwin et al. 1981). All line ratios in the two-dimensional diagnostic diagrams are within the region of H II regions for all components. J1n falls on the dividing line between H II regions and LINERs (Ostebrock 1989), similar to many other high-redshift sources showing high excitation (Erb et al. 2006; van Dokkum et al. 2005). This indicates that the bulk of the line emission in J1n and J1s arises from gas photoionized by hot massive stars and supports earlier X-ray measurements (Fabian et al. 2000) and that the far-infrared emission from this system is powered by the starburst, without a measurable AGN component.

The Hα emission lines in J1n and J1s have a relative spectral shift of Δλ/λ ≈ 61 ± 9 km s⁻¹, significant at the level of ~6σ. [N II]/Hα ratios are 0.52 ± 0.03 and 0.43 ± 0.02 in the integrated
spectra of J1n and J1s, respectively. Line widths (and 1 σ scatter of individual line width measurements) are FWHM = 198 ± 32 km s\(^{-1}\) in J1n and are marginally narrower in J1s (FWHM = 157 ± 35 km s\(^{-1}\)) with large scatter across both components. We summarize the emission line properties in Table 2.

We calculate the extinction in the two regions from the observable Hα/Hβ ratios (see Table 2), the Balmer decrement, and a Galactic extinction law, as described in Paper I, and extract the Hβ line emission from the same regions as Hα. For J1n and J1s, we find \(E(B-V)\) = 1.6 and 1.3, respectively.

The [O\textsc{ii}] \(\lambda\lambda3726, 3729\) and [S\textsc{ii}] \(\lambda\lambda6717, 6731\) doublets are faint but spectrally resolved and have sufficient signal-to-noise ratios in the integrated spectrum to robustly measure the ratios of the two components, \(R_{[S\textsc{ii}]} = I(6717)/I(6731) = 1.25 \pm 0.18\) and \(R_{[O\textsc{ii}]} = I(3726)/I(3729) = 1.07 \pm 0.21\) for [S\textsc{ii}] and [O\textsc{ii}], respectively (see Table 2). For densities between 100 and 10\(^4\) cm\(^{-3}\) and a given temperature, the ratio of the two components yields the electron densities. Assuming a “canononical” temperature \(T = 10^4\) K for H\textsc{ii} regions (Osterbrock 1989), our best-fit density estimate \(N_e \approx 400\) cm\(^{-3}\) (with favored values between \(\approx 180\) and 900 cm\(^{-3}\); see Fig. 4).

### 4.2. Morphology and Kinematics of the Emission Line Gas: Evidence for a Merger?

Figure 1 of Paper I shows the continuum-subtracted Hα line image extracted from the SPIFFI data cube. Hα emission is extended both along and perpendicular to the direction of lensing shear in the two components of SMM J14011+0252, J1 and J2. Hα line emission is detected in J1n and J1s.

The SPIFFI K-band integral-field spectroscopy of J1 is of superb quality and allows us to map the intrinsic kinematics within J1 using the spectral positions of the Hα line cores (fitted with

### Table 2: Emission Lines in J1

| ID (1) | \(\lambda_{\text{ext}}\) (Å) | \(z\) (3) | \(\lambda_{\text{obs}}\) (Å) | FWHM\(_{\text{obs}}\) (km s\(^{-1}\)) | FWHM\(_{\text{int}}\) (km s\(^{-1}\)) | Flux (10\(^{-20}\) W m\(^{-2}\)) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Hα ................. | 6563 | 2.5651 ± 0.00052 | 2.3397 ± 0.00047 | 22 ± 1 | 259 ± 19 | 2.03 ± 0.12 |
| [N\textsc{ii}] ................. | 6583 | 2.5654 ± 0.00053 | 2.3471 ± 0.00048 | 26 ± 2 | 305 ± 32 | 1.05 ± 0.07 |
| [N\textsc{ii}] ................. | 6548 | 2.5658 ± 0.00058 | 2.3349 ± 0.00058 | 31 ± 6 | 377 ± 75 | 0.53 ± 0.04 |
| [S\textsc{ii}] ................. | 6717 | 2.5654 ± 0.00068 | 2.3940 ± 0.00063 | 26 ± 10 | 296 ± 113 | 0.26 ± 0.03 |
| [S\textsc{ii}] ................. | 6731 | 2.5663 ± 0.00093 | 2.4001 ± 0.00087 | 32 ± 18 | 373 ± 209 | 0.29 ± 0.03 |
| [O\textsc{iii}] ................. | 5007 | 2.5652 ± 0.00064 | 1.7851 ± 0.00045 | 14 ± 6 | 188 ± 87 | 0.17 ± 0.02 |
| Hβ ................. | 4861 | 2.5657 ± 0.00061 | 1.7333 ± 0.00041 | 11 ± 5 | 118 ± 58 | 0.13 ± 0.02 |
| [O\textsc{ii}] ................. | 3727 | 2.5656 ± 0.00085 | 1.3289 ± 0.00044 | 16 ± 8 | 349 ± 179 | 0.21 ± 0.03 |

### J1s

| ID (1) | \(\lambda_{\text{ext}}\) (Å) | \(z\) (3) | \(\lambda_{\text{obs}}\) (Å) | FWHM\(_{\text{obs}}\) (km s\(^{-1}\)) | FWHM\(_{\text{int}}\) (km s\(^{-1}\)) | Flux (10\(^{-20}\) W m\(^{-2}\)) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Hα ................. | 6563 | 2.5656 ± 0.00052 | 2.3401 ± 0.00048 | 22 ± 2 | 240 ± 25 | 1.09 ± 0.07 |
| [N\textsc{ii}] ................. | 6583 | 2.5658 ± 0.00056 | 2.3474 ± 0.00051 | 22 ± 4 | 238 ± 51 | 0.47 ± 0.04 |
| [N\textsc{ii}] ................. | 6548 | 2.5667 ± 0.0013 | 2.3354 ± 0.0012 | 66 ± 27 | 835 ± 348 | 0.43 ± 0.03 |
| [S\textsc{ii}] ................. | 6731 | 2.5726 ± 0.00085 | 2.5997 ± 0.00079 | 33 ± 15 | 388 ± 181 | 0.28 ± 0.02 |
| [S\textsc{ii}] ................. | 6731 | 2.5578 ± 0.00066 | 2.3944 ± 0.00062 | 14 ± 9 | 104 ± 68 | 0.14 ± 0.03 |
| Hβ ................. | 4861 | 2.5658 ± 0.00060 | 1.7333 ± 0.00041 | 14 ± 5 | 194 ± 72 | 0.17 ± 0.02 |
| [O\textsc{ii}] ................. | 5007 | 2.5655 ± 0.00069 | 1.7853 ± 0.00043 | 18 ± 7 | 178 ± 102 | 0.11 ± 0.02 |
| [O\textsc{ii}] ................. | 3727 | 2.5669 ± 0.00094 | 1.3294 ± 0.00049 | 23 ± 10 | 506 ± 216 | 0.23 ± 0.02 |

### J2

| ID (1) | \(\lambda_{\text{ext}}\) (Å) | \(z\) (3) | \(\lambda_{\text{obs}}\) (Å) | FWHM\(_{\text{obs}}\) (km s\(^{-1}\)) | FWHM\(_{\text{int}}\) (km s\(^{-1}\)) | Flux (10\(^{-20}\) W m\(^{-2}\)) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| [O\textsc{ii}] ................. | 5007 | 2.5636 ± 0.00057 | 1.7843 ± 0.00040 | 13 ± 3 | <50 | 0.28 ± 0.04 |
| [O\textsc{ii}] ................. | 3727 | 2.5649 ± 0.00007 | 1.3286 ± 0.0003 | 16 ± 5 | <50 | 0.09 ± 0.007 |
| Hβ ................. | 4861 | 0 | 0 | 0 | 0 | <0.09 |
| Hα ................. | 6563 | 2.5635 ± 0.00055 | 2.3387 ± 0.00050 | 14 ± 3 | <50 | 0.31 ± 0.04 |
| [N\textsc{ii}] ................. | 6583 | 2.5628 ± 0.0013 | 2.3545 ± 0.0012 | 24 ± 29 | <50 | 0.07 ± 0.02 |

Notes.—The regions are as defined in Figs. 1–3. Col. (1): Line identification, with wavelength given in col. (2). Col. (2): Rest-frame wavelength. Col. (3): Redshift of the line calculated using the wavelength in col. (2). Col. (4): Observed wavelength. Col. (5): Full width at half-maximum. Col. (6): Intrinsic FWHM corrected for instrumental resolution. Col. (7): Line flux.

![Fig. 4.—Density estimates in SMM J14011+0252 J1 as a function of line ratio](image-url)
Gaussian line profiles) across an area of $1.75'' \times 3.25''$, with uncertainties of $\pm 15$ km s$^{-1}$ (Fig. 5) and a spatial resolution of $0.4'' \times 0.6''$ in right ascension and declination, respectively, corresponding to $\sim 4.4 \times 5.4$ seeing disks. Hence, the data set is well resolved spatially. Velocity dispersions of the lines are $\sigma = 55-106$ km s$^{-1}$ (corrected for the instrumental resolution). Velocities vary by 190 km s$^{-1}$ with the steepest overall velocity gradient increasing from northeast to southwest. Although this gradient is continuous, it is not strictly monotonic, and the data suggest velocity shears along two axes, which coincide with the regions of maximum $K$-band surface brightness in the J1c-removed data sets (Fig. 5). The differences in the peak velocities in these two dynamical regions are highly significant ($>3 \sigma$) and are thus not consistent with a single velocity gradient.

The close spatial alignment between star formation (traced by the H$\alpha$ surface brightness), gravitational potential (traced by the velocity map), and stellar population (traced by the $K$-band continuum and $J-K$ color) is intriguing (Fig. 5). This coincidence of the velocity shear, star formation, and $K$-band continuum can be naturally explained if J1n and J1s are a close, likely merging, galaxy pair. Moreover, this hypothesis is supported by our population synthesis fits discussed in $\S$ 4.4, which imply that J1n and J1s are dominated by stellar populations of different ages and extinctions, and they have different velocity dispersions (Fig. 5). At a projected distance of $\sim 12,000$ kpc, the internal dynamics of J1n and J1s appear to be driven by their own gravity. The evidence for this is our finding that both have velocity gradients that align well with their axes of the most extended $K$-band continuum emission. This indicates that the central parts of either components are likely still dominated by their individual potential wells.

We have also mapped the [N $\text{ii}$]/H$\alpha$ line ratios (Fig. 6) over most of J1, where both lines are detected at $>5 \sigma$ significance. Ratios are [N $\text{ii}$]/H$\alpha \sim 0.3$–0.4 over most of J1s, in the typical range of metal-rich H $\text{ii}$ regions and galaxy nuclei in the nearby universe. [N $\text{ii}$]/H$\alpha$ ratios peak in J1n, about 0.8$''$ to the north from J1c, and $\sim 0.6$ from the H$\alpha$ peak. The maximum ratio is [N $\text{ii}$]/H$\alpha \sim 0.7$, which is significantly larger than the ratios generally found in H $\text{ii}$ regions (Pettini & Pagel 2004; Osterbrock 1989 and

![Fig. 5.—Map of relative velocities of H$\alpha$ (left) and full width at half-maximum of H$\alpha$ (right). In both plots, contours indicate the $K$-band surface brightness with J1c removed, and the gray diamond indicates the location of J1c. North is up and east to the left in each panel.](image)

![Fig. 6.—Map of the [N $\text{ii}$] $\lambda$6583/H$\alpha$ line ratios for the J1 complex. Contours indicate the distribution of H$\alpha$ line surface brightness. The color-scale bar on the right indicates the values of the [N $\text{ii}$] $\lambda$6583/H$\alpha$ ratios. North is up and east to the left. The black diamond marks the position of J1c.](image)
4.3. Relationship between Gas and Continuum Emission

In both J1n and J1s, the brightest Hα emitting regions are also the regions with the reddest $J-K$ colors. Rest-frame equivalent widths are $\sim 50$–$150$ Å and are positively correlated with $J-K$ color in J1n and J1s, with significances better than $0.01$ or less in non-parametric tests (low values indicate a highly significant correlation; Fig. 3). The positive correlation is a clear indication that the reddening is related to star formation in regions with variable and high extinction rather than the age of the stellar population. If the red colors indicated the age of the stellar population, we would expect that the reddest regions of the galaxy in $J-K$ would be those with the lowest Hα equivalent widths.

In the case of SMM J14011+0252, however, the highest equivalent widths are reached in the reddest areas, indicating that the color is indeed due to variable and high extinction, rather than an age spread in the stellar populations in both J1n and J1s. In addition, where the surface brightness of line emission is intense enough to allow for a robust measure of Hβ, the reddest regions also have high Hα/Hβ ratios. This supports the hypothesis that the color variation is more likely due to reddening than to large differences in ages of the stellar populations. Our finding also implies, however, that significant numbers of Hα photons escape, perhaps a sign of an irregular, clumpy dust distribution. Chapman et al. (2004) reach a similar conclusion based on the differences in structure in high-resolution radio maps compared to high-resolution imaging in the rest-frame UV. It is also possible that a favorably oriented starburst-driven wind (§6) is giving a less obscured view to some of the starburst region.

4.4. Population Synthesis Models and the Role of J1c

As outlined in §1, the nature of the optical and near-infrared continuum peak J1c is difficult to constrain. It has a nearly circular symmetry, which led Smail et al. (2005) to conclude that J1c cannot be gravitationally lensed and is thus not at the redshift of SMM J14011+0252 (and in agreement with Swinbank et al. [2004] that some of absorption lines in the Barger et al. spectrum are coincident with optical absorption lines from a galaxy at $z = 0.25$). Moreover, its smooth, featureless light profile does not appear typical for a strongly star-forming dusty galaxy at high redshift seen in the rest-frame UV. Both arguments, although circumstantial, imply that J1c could be a foreground object along the line of sight that is not physically related to the SMG. Unfortunately, the observed wavelengths of some of the optical absorption lines at the redshift of the foreground cluster A1835 are degenerate with UV absorption lines at the redshift of the SMG (Swinbank et al. 2004; Smail et al. 2005), so the spectrum is not necessarily a unique constraint.

We constructed an azimuthally averaged light profile of J1c from the F850LP ACS image of SMM J14011+0252. To this one-dimensional profile, we fit a Sérsic profile convolved with the PSF (estimated using a nearby star in the ACS image), obtaining a good fit with a Sérsic model of index $n = 1.25 \pm 0.2$ and a half-light radius of $r_e = 0.27'' \pm 0.06''$. The spatial resolution is $\sim 0.11''$. We then subtract this fit from the ACS image. Fit residuals are $\leq 10\%$ in a $0.5''$ box aperture centered on J1c and are likely due to deviations in the core of the PSF from our simple Gaussian model and/or extended emission from the sources J1s and J1n contaminating the fitted light distribution of J1c. The left panel of Figure 7 shows the J1c-removed F850LP ACS image.

We estimate the impact of J1c in each wave band by convolving our best-fit Sérsic model from the ACS image with the PSF appropriate for each individual band and scaling to the measured peak brightness of J1c. This scaled, smoothed Sérsic model is then subtracted from each image centered on the position of J1c. Namely, we obtain magnitudes of $R_{702} = 20.6$ mag, $Z_{850} = 20.5$ mag, $J = 20.0$ mag, $H = 19.0$ mag, and $K = 18.2$ mag extracted from a $3''$ aperture centered on J1c in the $HST$ F702W WFPC2 and F850LP ACS images, and the ISAAC J-, H-, and K-band images, respectively. For the best-fit Sérsic models to J1c, integrated over 3'' apertures, we find $R_{702} = 21.5$ mag, $Z_{850} = 21.3$ mag, $J = 20.7$ mag, $H = 19.9$ mag, and $K = 19.2$ mag in these bands. We use the fit residuals in each band to constrain whether the light profile varies significantly with wavelength. Overall fit residuals are $\leq 15\%$–$20\%$ with random spatial distribution, consistent with a light profile of J1c that is not a strong function of wavelength (for illustration we use the $K$-band data in the right panel of Fig. 7). Our goal is to give an upper limit on the overall impact of J1c on the submillimeter source, which might lead to an oversubtraction and is conservative. However, doing the subtraction this way will lead to a region centered on J1c that is essentially at the background average in each image and appears as a hole in the source (Fig. 7). Thus, the detailed morphology of J1n and J1s over the region of J1c should not be overinterpreted (i.e., the hole in the light distribution is likely not real and is therefore not a sign of strong shear, for example). The S/N and rather coarse sampling in the SPIFFI data do not allow a similar correction for the spectra (except in the case of the Hα equivalent widths that are enumerated in Fig. 8).

By deriving the magnitudes in the F702W, F850LP, $J$, $H$, and $K$ bands based on the scaled Sérsic model, we fit the spectral...
energy distribution (SED) of J1c using the stellar population synthesis package of Bruzual & Charlot (2003) for solar metallicity and a Chabrier initial mass function (IMF). The SED is consistent with that of a \( z = 0.25 \) galaxy with an \( \geq 9 \) Gyr old stellar population of total mass \( \leq 5 \times 10^8 M_\odot \). We do not find any suitable model when placing J1c at \( z \sim 2.6 \), which supports the interloper hypothesis for J1c. For an isothermal sphere and assuming that the projected half-light radius is the half-mass radius of the galaxy, the stellar mass estimate corresponds to a velocity dispersion that is consistent with \( \sigma \leq 55 \) km s\(^{-1}\) adopted by Smail et al. (2005).

We use the data sets with J1c removed to investigate the stellar populations in J1s and J1n, assuming continuous star formation histories, solar metallicity, and a Chabrier IMF. Using only one star formation history and model is all that is justifiable given the considerable uncertainties in removing J1c and the overall faintness of J1n and J1s. For J1s, our fits are consistent with a \( 3 \times 10^8 \) Gyr old stellar population in J1s, \( A_V \sim 0.8 \) mag extinction, and a mass of \( \sim 8 \times 10^7 M_\odot \) (with the magnification factor \( \mathcal{M} \)). For J1n, we find a \( 1 \times 10^8 \) yr old stellar population, \( A_V \geq 6 \) mag, and a stellar mass of about \( 3 \times 10^7 M_\odot \). These age estimates are in approximate agreement with what would be estimated from the values of the rest-frame H\( \alpha \) equivalent widths. Figure 8 shows that the rest-frame equivalent widths of H\( \alpha \) are typically about 80 and 120 \( \AA \) for the most intense H\( \alpha \) emitting regions of J1s and J1n, respectively. Models of continuous star formation and solar metallicity imply ages of a few hundred Myr or less, with higher equivalent widths corresponding to younger ages (Leitherer et al. 1999). The H\( \alpha \) to H\( \beta \) line ratios imply significant extinction in both J1n and J1s, as discussed in \( \S \) 4.1.1 and shown in Table 2.

These mass estimates are likely only lower limits. To isolate the individual components, we extract the photometry from square apertures with 1.5" on each side (which is at least twice the seeing disk in any of the images). From a sample of 20 SMGs and optically faint radio galaxies with ACS imaging, Smail et al. (2004) find half-light diameters \( D_{1/2} \sim 1.5" \). For \( \mathcal{M} = 3-5 \) this implies that we are underestimating the stellar mass by a factor of \( \sim 2-6 \), depending on the exact morphology and light profile of J1n. Moreover, our population synthesis fits might be biased by the strong and clumpy extinction discussed in \( \S \) 4.2. As a consequence, we likely underestimate the overall age and extinction and hence the stellar mass. This also raises worries that a significant fraction of the total stellar population might be undetected due to strong extinction, if the most strongly dust-enshrouded areas are optically thick to the rest-frame K-band continuum (observed K-band). This concern of course generically applies to photometric studies of dusty high-redshift galaxies. Therefore, analyzing spectra appears to be more promising for estimating the physical properties of these dusty systems.

Below we adopt \( \geq 6 \times 10^{10} M_\odot \) as the stellar mass of J1n (correcting by a conservative factor of \( \sim 2 \) due to light not considered in the SED fit). We warn that given the relatively crude manner in which this estimate was made and the intrinsic difficulty in estimating the mass and star formation properties in heavily obscured galaxies from UV/blue optical SEDs, our estimates are comparably uncertain.

5. CHARACTERISTICS OF A HIGH-REDSHIFT STARBURST

5.1. Star Formation Intensity

Observations of low-redshift starburst galaxies suggest a fundamental upper threshold for the star formation rate (SFR) in galaxies (Lehnert & Heckman 1996b; Meurer et al. 1997). Such an upper limit may be indicative of self-regulation processes limiting the gas collapse (and subsequent star formation) through the negative feedback of superwinds (e.g., Lehnert & Heckman 1996b; see also \( \S \) 6) or perhaps dynamical processes and disk instabilities (e.g., Meurer et al. 1997). It is therefore interesting to investigate how SMM J14011+0252 J1 relates to the “maximal burst” galaxies observed at low redshift.

For low-redshift star-forming galaxies, Meurer et al. (1997) propose an upper bound of SFR\( \text{max} \sim 45 M_\odot \) yr\(^{-1}\) kpc\(^{-2}\) within one half-light radius \( r_{1/2} \). The exact value of the maximal star formation intensity depends on the choice of cosmology, the form of the chosen initial mass function, the relative role of extinction, the ability to measure half-light radii accurately at wavelengths where a substantial fraction of the bolometric luminosity originates, etc., and thus the numerical value of this threshold should not be interpreted too strictly. However, it does provide a useful guide on when star formation becomes “maximal”—whatever the cause (see also Lehnert & Heckman 1996a, 1996b; Tacconi et al. 2006). Do extreme starbursts in high-redshift galaxies have similar intensities? Below we address this question empirically, comparing the star formation intensity in SMM J14011+0252 with low-redshift starbursts (Lehnert & Heckman 1996b), using the same techniques. Such an estimate does not depend on the strength of the gravitational lensing, because surface brightness is conserved and \( \leq 10\% \) of the H\( \alpha \) emission is due to the wind component (\( \S \) 6), which is negligible.

We estimate the half-light area in H\( \alpha \), \( A_{H\alpha}^{1/2} \), by counting the pixels in J1n and J1s that are above the 50\% percentile of the flux distribution (following the method of Erb et al. 2003). In J1n and J1s we find \( A_{H\alpha}^{1/2} = 1.1 \) arcsec\(^2\) (68 kpc\(^2\)) and \( A_{H\alpha}^{1/2} = 0.875 \) arcsec\(^2\) (56 kpc\(^2\)), respectively. Using the measured H\( \alpha \)/H\( \beta \) decrements from these regions to correct the H\( \alpha \) emission line fluxes for extinction, we estimate intrinsic H\( \alpha \) fluxes of \( F_{H\alpha} = 1.1 \times 10^{-18} \) W m\(^{-2}\) in J1n and \( F_{H\alpha} = 0.37 \times 10^{-18} \) W m\(^{-2}\) in J1s. We follow Kennicutt (1998) with a \( 1-100 M_\odot \) Salpeter IMF to estimate star formation rates; i.e., we adopt SFR \( = 7.69 \times 10^{-35} L_{H\alpha} M_\odot \) yr\(^{-1}\), where the H\( \alpha \) luminosity \( L_{H\alpha} \) is given in watts. Our adopted IMF gives a total star formation rate similar to that if we had adopted a more appropriate IMF such as a Kroupa or Chabrier, namely, \( 450 M_\odot \) yr\(^{-1}\) in J1n and \( 150 M_\odot \) yr\(^{-1}\) in J1s. We thus find star formation rate densities of \( 7 M_\odot \) yr\(^{-1}\) kpc\(^{-2}\) in J1n and
Star formation rates based on $H\alpha$ luminosities tend to be lower by up to an order of magnitude compared to estimates based on infrared luminosities. This is because the most intense star-forming regions are likely to be optically thick to dust at the wavelength of $H\alpha$, so the total star formation rate will be underestimated. Using the FIR-estimated star formation rate of Paper I for a $1–100 M_\odot$ Salpeter IMF, 1920$M_\odot^{-1}$ yr$^{-1}$, and the measured half-light radius of the $H\alpha$ emission, we find $\Sigma_{\text{FIR,}H\alpha} = 28 M_\odot$ yr$^{-1}$ kpc$^{-2}$. Using the FWHM of the CO emission line region to estimate the diameter of the star-forming region ($1.6'' \times 0.5''$ and $2.5'' \times 0.5''$; D. Downes 2006, private communication), we find a similar star formation intensity of $\Sigma_{\text{FIR,CO}} = 48–30 M_\odot$ yr$^{-1}$ kpc$^{-2}$. Both estimates are within the range of the $80 \pm 20 M_\odot$ yr$^{-1}$ kpc$^{-2}$ that Tacconi et al. (2006) found for a sample of SMGs using high-resolution CO observations. [To mitigate against the considerable uncertainties in calibrating star formation intensities from surface brightnesses, we note that the FIR luminosity of J1 from Paper I, $L_{\text{FIR}} = 2.3 \times 10^{13} M_\odot^{-1}$ L$\odot$, and the CO radius of D. Downes (2006, private communication) correspond to a surface brightness of $S_{\text{FIR}} = (7.3–18) \times 10^{-10}$ L$\odot$ in J1, compared to a 90% percentile of the effective surface brightness, $S_{\text{eff},90} = 2 \times 10^{-11}$ L$\odot$ kpc$^{-2}$, given by Meurer et al. (1997).]

In spite of the large uncertainties of each method, none of the estimates for J1 exceed the star formation intensities in low-redshift “maximal burst” galaxies.

The most fundamental physical motivation for postulating a stringent upper bound to the star formation rate in a self-gravitating system comes from causality. This limit is given by consuming all of the gas (modulo a star formation efficiency per unit gas mass) within one dynamical time, either a crossing or free-fall timescale (see, e.g., Lehner & Heckman 1996b), Tacconi et al. (2006) find that none of the SMGs, including SMM J14011+0252, violate causality arguments. Specifically, within the context of such a hypothesis, Tacconi et al. find that SMGs form stars with efficiencies similar to those seen in local galaxies and star-forming regions, 0.1–0.3, and within a few dynamical timescales. Our results here suggest that SMM J14011+0252 does not violate the stringent causality limits, either.

5.2. No “New Mode” of Star Formation

At low redshift, only ultraluminous infrared galaxies (ULIRGs) reach similarly large infrared luminosities as SMGs, $L \gtrsim 10^{12}$ L$\odot$, whose properties are typically attributed to the effects of massive gas collapse during major mergers (Sanders & Mirabel 1996). Motivated by the extended nature of star formation in SMM J14011+0252, Goldader et al. (2002) hypothesize that there might be an intrinsically more efficient mechanism of star formation at high redshift, with no equivalent in the local universe, which does not require a major merger to trigger extreme star formation.

Our data do not confirm this hypothesis; in fact, they rather point toward SMM J14011+0252 being a merger (§ 4.2). As discussed above, our data do not indicate a higher intensity of star formation than at low redshift, and the half-light radii of $H\alpha$ emis-

Fig. 9.—Integrated $K$-band spectrum of J1n, showing the detected emission lines: [O i] $\lambda$6300, [N ii] $\lambda\lambda$6548, 6583, $H\alpha$, [N ii] $\lambda$6583, and the [S ii] $\lambda\lambda$6717, 6730 doublet. Gaussian line fits are shown in blue; for all lines we assumed the FWHM and redshift measured for $H\alpha$. The inset shows a zoom onto the $H\alpha$ and [N ii] lines. Note the blue wings of $H\alpha$ and [N ii] lines.

6. A STARBURST-DRIVEN SUPERWIND AT $z = 2.6$

6.1. Properties of the Superwind

Actively star-forming galaxies with intensities exceeding $0.1 M_\odot$ yr$^{-1}$ kpc$^{-2}$ are known to drive “superwinds,” irrespective of redshift (Heckman 2003). SMM J14011+0252 J1 easily surpasses this limit (§ 5) and can therefore be expected to drive such a wind. Blue asymmetries in emission line profiles, e.g., $H\alpha$ and [N ii] $\lambda$6583 line profiles, are common in starburst galaxies in the local universe with substantial evidence for driving vigorous outflows (Lehnert & Heckman 1996a) and are also the most common evidence for winds at high redshift. Velocity offsets of a few hundred kilometers per second in UV absorption lines tracing the interstellar medium (ISM) relative to the systemic redshift are also frequently used as evidence for winds (Shapley et al. 2003; Swinbank et al. 2005). In J1, rest-frame UV absorption lines are blueshifted relative to $H\alpha$ by $\sim 500$ km s$^{-1}$ (Ivison et al. 2000; Tezca et al. 2004), and we also observe blue wings of $H\alpha$ and [N ii] $\lambda$6583 emission lines in J1n (see Fig. 9, inset). Gaussian fits to the residuals have relative offsets of $\sim 330$ km s$^{-1}$ between line wing and core for the $H\alpha$ lines and $\sim 350$ km s$^{-1}$ for [N ii] in J1n. About 10% of the $H\alpha$ flux is in the wing and $\sim 25$% of [N ii] $\lambda$6583. J1s does not have a pronounced blue wing.

The wavelength coverage and quality of our J1 data sets are outstanding for a strongly star-forming galaxy at $z \sim 2.6$, allowing for a more detailed analysis to firmly establish that starbursts and outflows in high-redshift galaxies are causally linked by the same basic mechanism as at low redshift. Starburst-driven winds at low redshift are caused by thermalized ejecta of supernovae and stellar winds producing an overpressurized, expanding bubble of hot, X-ray emitting gas, which sweeps up, entrains, accelerates, and ionizes the ambient interstellar medium (Heckman et al. 1990). This results in high gas pressures and shocklike optical emission line ratios. Positive correlations between ionization state and line widths have been observed at low redshift (e.g., Lehner & Heckman 1996a; Rupke et al. 2005), implying that the relative importance of shock heating increases as the gas is accelerated to outflow velocities of a few hundred kilometers per second, where the emission line luminosity rapidly increases with increasing shock speed (Dopita & Sutherland 1995).
For J1 we can investigate each of these properties explicitly. The [N II] 6583/Hα line ratios are $\sim 0.7$ in the integrated emission of J1, which is generally higher than observed in H II regions (photoionization by massive stars), and can be easily caused by shocks. The [N II]/Hα line ratio in the wings of J1 is 0.83, indicating a higher shock contribution in the outflowing gas. We also find a good correlation between the [N II] 6583/Hα ratio and [N II] 6583 line width in J1 (Fig. 10, left), but not in J1s. We also find no correlation with Hα line widths (Fig. 10, right), similar to nearby “supernovae” galaxies (Lehnert & Heckman 1996a).

With the electron densities derived in § 4.1.1 we estimate the pressure of the electron gas using the conversion given in Lehnert & Heckman (1996a) and considering that much of the [S II] and [O II] lines fluxes are produced in partially ionized zones of the nebulae (Shull & McKee 1979): $P \approx 4 \times 10^{-12} n_e$ or $2 \times 10^{-9}$ dyn cm$^{-2}$ for the electron densities $\sim 400$ cm$^{-3}$ derived in § 4.1.1. This is in excellent agreement with the pressures in the nuclei of nearby starburst galaxies with evidence for driving supernovae (Lehnert & Heckman 1996a) and is factors of $\sim 10^3 - 10^4$ higher than the pressure of the local ISM in the Milky Way, providing the necessary prerequisite for an expanding or outflowing gas bubble.

However, compared to low-redshift starburst galaxies, the wind in J1 seems to have a relatively high surface brightness. Maximum Hα surface brightnesses in the low-redshift sample of Lehnert & Heckman (1996a) are $\lesssim 800$ $L_\odot$ pc$^{-2}$ and for our cosmology would correspond to an observed flux $f_{\text{obs}} \approx 2.3 \times 10^{-21}$ $h_7^{\frac{1}{2}}$ W m$^{-2}$ pixel$^{-1}$ at the redshift of J1, about an order of magnitude lower than the total Hα flux in the wing of J1 ($\sim 10\%$ of the total Hα flux, or $\sim 1.1 \times 10^{19}$ W m$^{-2}$ pixel$^{-1}$). This might be due to a higher gas fraction in J1, leading to a larger covering factor of gas clouds that are being shocked. Tacconi et al. (2006) estimate a gas fraction of $f_{\text{gas}} \sim 0.4$ in SMMGs, supporting such speculation.

Since the wind causes a correlation between the [N II] 6583/Hα ratio and the [N II] line width, we also investigate its impact on the overall velocity field (Fig. 5), again using correlations between the spatially resolved emission line properties to localize and compare the signatures of mechanical heating and kinematic parameters. The top and bottom panels of Figure 11 show the correlations between line properties for the Hα and [N II] 6583 lines in J1n, respectively. The data are given separately for spatial pixels with high and low [N II]/Hα ratios. Open squares indicate spatial pixels where [N II]/Hα $< 0.55$, whereas filled circles indicate pixels with [N II]/Hα $> 0.55$. Crosses indicate typical uncertainties.

### 6.2. Self-Regulated Star Formation?

As discussed above, there are several arguments about what might be regulating star formation within galaxies (see also Tacconi et al. 2006; Lehnert & Heckman 1996b), including negative feedback from the superwind, if the overpressurized bubble can plausibly provide pressure support. Can this hypothesis explain the variation of velocity dispersions in J1 and limit the rate of star formation? If we adopt a disk geometry, this scenario implies that gas collapse can be balanced if the momentum flux injection, $P_{\text{mid}}$, is comparable to the midplane pressure, $P_{\text{mid}}$. In hydrostatic equilibrium, $P_{\text{mid}}$ is

$$P_{\text{mid}} = \frac{1}{2} \pi G \Sigma_{\text{tot}} \Sigma_{\text{gas}} = 4.6 \times 10^{-10} \Sigma_{\text{tot}} \Sigma_{\text{gas},8} \text{ dyn cm}^{-2},$$

where $\Sigma_{\text{tot},9}$ and $\Sigma_{\text{gas},8}$ are the surface mass densities of all of the matter and just the gas in units of $10^9 M_\odot$ kpc$^{-2}$ and $10^8 M_\odot$ kpc$^{-2}$, respectively. We use the size of molecular emission (FWHM = 2.2″ $\times$ 0.5″; Downes & Solomon 2003), the molecular gas mass estimated in Paper I (and references therein), and our dynamical mass estimate, $M_{\text{dyn},11} \sim 10^{11} M_\odot$ (see § 8), to estimate a total midplane pressure, $P_{\text{mid}} \approx 10^{-9}$-$10^{-8}$ M dyn cm$^{-2}$. The pressure provided by the wind can be derived from the total momentum flux of the outflow. Following Heckman et al. (1990) and Lehnert & Heckman (1996a) we parameterize the momentum injection by the wind as $P_{\text{wind}} \approx 3 \times 10^{34} L_{\text{IR},11}$ dyn, where $L_{\text{IR},11}$ is the infrared luminosity in units of $10^{11} L_\odot$. With the infrared luminosity estimated in Paper I, $2.6 \times 10^{11} L_\odot$, this implies a momentum
flux injection rate of $8 \times 10^{36} \text{M}^{-1} \text{dyn}$, similar to the most powerful local starbursts (Heckman et al. 1990). With the above size estimate, we find $P_{\text{wind}} \approx 15 \times 10^{-9} \text{dyn cm}^{-2}$. This implies $P_{\text{wind}} \approx 0.3P_{\text{mid}}$ and $0.5P_{\text{mag}}$ for $M = 5$ and $3$, respectively. Although this is somewhat smaller than unity if taken at face value, given the large uncertainties this is clearly consistent with the notion that star formation may be self-regulated through its own feedback in the most powerful starbursts, in particular at high redshift.

7. THE BLUE COMPONENT J2—INTRINSIC PROPERTIES AND A PROBE FOR THE DYNAMICAL MASS OF J1

Our data sets also include component J2 of SMM J14011+0252, which is about 1.3" to the northwest from J1c. J2 is considerably bluer than J1 at observed optical wavelengths (e.g., Ivison et al. 2000). Smail et al. (2005) pointed out that its rest-frame UV colors are similar to those of $z \sim 3$ Lyman break galaxies, although its redshift is relatively low for such a comparison. Our population synthesis fits (see § 4.4) indicate a $\geq 3 \times 10^9 \text{yr}$ old stellar population with $4.5 \times 10^9 \text{M}_\odot$ stellar mass and $A_V = 0.5$ mag. This implies an older and more massive stellar population than that favored by Motohara et al. (2005), although it is nonetheless a consistent result because Motohara et al. only compared their photometry with an instantaneous burst and a $10^9 \text{yr}$ old continuous star formation episode.

As noted by previous authors (e.g., Ivison et al. 2001; Tecza et al. 2004), the spectrum of J2 is blueshifted by $-160 \pm 18$ km s$^{-1}$ with respect to J1. In addition to detecting H$\alpha$, we also identify [N II] $\lambda$6583 line emission in the K band and the [O III] $\lambda\lambda$4959, 5007 doublet in the H band. H$\beta$ was not detected in J2, probably because of a nearby strong night-sky line (see Table 2 for the emission line properties).

These results differ from those of Motohara et al. (2005), who identified H$\beta$ but not [O III]. The discrepancy is easily explained by the lower resolution of their data ($R = 210$) and unfortunate spectral positions of the emission lines (H$\beta$ is near a strong night-sky line, [O III] $\lambda$5007, lying within a set of a strong telluric absorption features). We measure a 3$\sigma$ limit on the H$\beta$ flux, $F_{\text{H}\beta} \lesssim 9 \times 10^{-21}$ W m$^{-2}$, compatible with relatively low extinction as indicated by the blue, “LBG-like” colors of J2 (see, e.g., Smail et al. 2005), $E(B-V) \sim 0.23$, and an extinction corrected (lensed) H$\alpha$ luminosity $L_{\text{lensed}} = 2.3 \times 10^{38}$ W, which corresponds to a star formation rate of $\sim 18 \text{M}_\odot$ yr$^{-1}$. For a magnification $M \geq 3$, the star formation rate is $\geq 6 \text{M}_\odot$ yr$^{-1}$, lower than the typical rates in UV-selected, star-forming BX galaxies at similar redshift (e.g., Erb et al. 2003) and 2 orders of magnitude less than the highest estimates of the star formation rates in J1.

H$\alpha$ emission in J2 extends over $\sim 1.25\" \times 0.75\"$ and is offset from the continuum peak by $-0.4\"$ to the northeast. Extracting both line and continuum information from the same data cube and the reasonable S/N of both the line and continuum emission imply that this offset is significant. We do not measure a significant velocity gradient in the H$\alpha$ line emitting gas, but we measure an intrinsic FWHM = $66 \pm 8$ km s$^{-1}$, for a reasonable set of assumptions about the mass distribution, which corresponds to a dynamical mass of $M_{\text{dyn,J2}} \sim 10^9 \text{M}_\odot$.

We calculate the [O III] abundance of J2 from $R_{23}$ to compare with the J1 abundance discussed in Paper I and to investigate whether the two components have similar or distinct evolutionary histories. As seen in Figure 12, oxygen abundances are significantly different in J1 and J2, using the 3$\sigma$ upper limit on H$\beta$ to determine the abundance in J2. The [N II]/H$\alpha$ ratio of $\sim 0.23 \pm 0.07$ in J2 indicates that the upper branch is appropriate for estimating the metallicities.

The position of J2 in the emission line diagnostic diagrams of Osterbrock (1989) is also interesting. The [S II] line doublet is not detected in J2. The upper limit on the H$\beta$ flux only provides a lower limit for the [O III]/H$\beta$ ratio. The emission line diagnostic ratios and excitation diagrams indicate comparably high ionization for J2, placing it near the limit of the AGN portion of the diagram. The distinct position of J2 indicates higher ionization or temperature compared to J1 and is likely a direct consequence of the lower metallicity of J2 (and perhaps a concomitant lower dust content). The orbit of J2 can also be used to estimate an approximate dynamical mass of J1, which is particularly valuable, as the complex velocity field in J1 makes it difficult to robustly estimate a dynamical mass estimate from the intrinsic kinematics. Following Paper I we add $6.5 \times 10^{10} \text{M}_\odot$ in gas to the $\geq 6 \times 10^{10} \text{M}_\odot$ of stellar mass we found in § 4.4. J1 appears to dominate the overall baryon budget by about an order of magnitude, which is consistent with the narrow line widths in J2 compared to J1n and is certainly suggested by our astrometry, which places the peak of the CO emission within the emission of J1n.

We place the barycenter on J1n and use a simple virial estimate for the mass, $M_{\text{vir}} = \Delta V^2 R G^{-1} = 2 \times 10^{10} \Delta V_{100}^2 R_{\text{vir}} \text{M}_\odot$, where $G$ is the gravitational constant, $\Delta V_{100}^2$ is the relative velocity between J1 and J2 in units of 100 km s$^{-1}$, and $R_{\text{vir}}$ is the distance between J1 and J2 in kiloparsecs. Since true inclination, eccentricity, form of the potential, etc., are all unconstrained and the physical separation is unknown, the true mass is likely factors of a few larger (both radius and velocity, for example, are seen in projection).

8. SURFACE MASS DENSITIES AND THE FUTURE EVOLUTION OF SMM J14011+0252 AND OTHER SMGs

In addition to the high dynamical masses of SMGs (Genzel et al. 2003; Greve et al. 2005), mass densities (Tacconi et al. 2006), their luminosity-weighted ages, high star formation rates, and possibly strong clustering indicate that they will likely evolve into massive early-type galaxies in cluster environments at low redshift (Smail et al. 2004 and references therein). Interestingly, the
characteristics of local galaxies also seem highly dependent on their mass surface densities (and perhaps less so on their overall mass), as suggested by a recent analysis of Kauffmann et al. (2006). They studied nearly 400,000 low-redshift galaxies drawn from the Sloan Digital Sky Survey (SDSS) and find significant differences between the structural parameters of early- and late-type galaxies that do not strongly depend on the total mass of the galaxy. Namely, they find that concentration parameters $C > 2.5$ and stellar mass surface densities $\mu_*> 3 \times 10^8 M_\odot$ kpc$^{-2}$ correspond to the regime of galaxy spheroids and bulges, independent of the total stellar mass of these systems. Above this threshold of mass surface density, they find that star formation is increasingly suppressed (the specific star formation rate is low) and must have ceased many Gyr ago. As a consequence, Kauffmann et al. (2006) hypothesize that with increasing compactness and surface density of the galaxy, stars were formed in short, vigorous episodes at high redshift, with extended periods of inactivity (Kauffmann et al. [2006] parameterize this in terms of a consumption timescale, $t_{\text{consum}} \propto \mu_*^{-1}$). Substantial growth at later epochs was then only possible through mergers of galaxies with low gas fractions. To identify SMM J14011+0252 and other SMGs as "spheroids in formation," it is therefore not sufficient to address their large masses or even their dynamical mass densities given their high gas fractions and unknown dark matter distributions. They must also have high stellar mass densities, short gas consumption timescales, and strong feedback suppressing further star formation. Do SMGs have all these properties?

Our analysis of the stellar mass surface density in SMM J14011+0252 J1 is that it is at the transition value of $3 \times 10^8 M_\odot$ kpc$^{-2}$, and the dynamical estimate of the mass surface density in SMM J14011+0252 J2 is $3 \times 10^9 M_\odot$ kpc$^{-2}$, well above the transition. The stellar masses ($M_*= 3 \times 10^{10} M_\odot$) and average half-light radius ($\sim 5$ kpc) of a large sample of SMGs (e.g., Smail et al. 2004) suggest an average stellar mass surface density of $\langle \mu_\text{SMG} \rangle = 4 \times 10^8 M_\odot$ kpc$^{-2}$. Similar estimates can be made from dynamical mass estimates and sizes from CO interferometric observations ($\sim 10^9 M_\odot$ kpc$^{-2}$ for stars, gas, and possible contributions from dark matter; Tacconi et al. 2006; Greve et al. 2005). It appears that SMM J14011+0252 and SMGs in general have sufficiently high surface mass densities to be above the critical point in the study of Kauffmann et al. (2006).

Population synthesis fits of the stellar population of SMM J14011+0252 yield ages of up to a few hundred Myr, similar to the ages of typical radio-detected SMGs with spectroscopic redshifts (about a few hundred Myr; Smail et al. 2004). Based on the infrared luminosity and the gas mass, we estimate a gas consumption timescale of about 30–40 Myr for SMM J14011+0252. From a large sample of SMGs with CO detections, Greve et al. (2005) set a limit on the gas consumption timescale of $\sim 40$ Myr, consistent with that for SMM J14011+0252. Thus, individual SMGs appear to be forming most of their stars in intense bursts of moderate duration (a few hundred Myr). In addition, their star formation appears to be highly "bursty" independent of the duration of the star formation. The duty cycles of SMGs have been estimated through a variety of methods to about $\sim 0.1$ (Chapman et al. 2005; Bouche et al. 2005; Genzel et al. 2003; Tecza et al. 2004; Blain et al. 2004). Again, SMGs seem to form their stars in intense bursts of modest durations with long periods of relative inactivity. To explain the fractions of local galaxies with strong 4000 Å breaks, Kauffmann et al. (2006) infer gas consumption timescales of $\sim 100$ Myr, similar to estimates of SMGs.

As discussed in § 6, SMM J14011+0252 is driving a vigorous superwind. While the importance of starburst-driven winds to galaxy evolution is generally agreed upon, they are not thought to be powerful enough or to accelerate material to the escape velocities of the most massive galaxies (Heckman et al. 2000). However, SMM J14011+0252 is driving a wind, which at the very least will lower the overall star formation efficiency of SMM J14011+0252 (see discussion in §§ 5.1 and 6.2). If this is indeed a general characteristic of SMGs, then the role of winds in their ultimate evolution could be substantial.

Hence, the "submillimeter bright phase" of galaxies is characterized by high surface mass densities, above the interesting dividing point of the characteristics of local galaxies as found by Kauffmann et al. (2006). Their star formation appears to be episodic (duty cycle of $\approx 0.1$) and of relatively short duration (a few hundred Myr; e.g., Smail et al. 2004), and they have evidence for feedback, which we have suggested may regulate the intensity of their star formation. This adds further evidence that SMGs do indeed have all the characteristics necessary to become local massive early-type galaxies.

9. SUMMARY

We presented an integral-field study of the rest-frame optical emission line gas in the $z \sim 2.6$ SMM J14011+0252 J1/J2 complex, allowing unprecedented insight into the nature of a high-redshift starburst and its outflow. Identifying J1c as a $z \sim 0.25$ interloper through Sérsic profile and SED fitting, we removed the seeing-matched J1c contamination from the images and find that J1n and J1s appear as individual components in all wavebands, at a projected distance of a few kiloparsecs. The positions of these two components are in excellent agreement with the distribution of H$\alpha$ emission in our SPIFFI H$\alpha$ map and also with the H$\alpha$ velocity field, which is reminiscent of two nearby corotating disks that are marginally resolved spatially. Including J2, SMM J14011+0252 thus appears as a triple system. From the J2 orbital motion, we estimate a dynamical mass of $M_{\text{dyn,J1}} \sim 1.0 \times 10^{11} M_\odot$ for the J1n/J1s complex.

The dust-enshrouded J1n is the most massive component, as indicated by its stellar mass, about a few $10^{10} M_\odot$ [compared to $\sim (1-2) \times 10^9 M_\odot$ for J1s and J2], and the bright CO line emission, which coincides with J1n within the astrometric uncertainties. The starburst in J1n is "maximal" with a similar intensity ($\lesssim 50 M_\odot$ yr$^{-1}$ kpc$^{-2}$) comparable to the apparent limit at low redshift. The H$\alpha$ half-light radius is similar to the H$\alpha$ half-light radii in low-redshift ULIRGs. Overall, star formation in J1n is intense, but its properties do not greatly differ from those of low-redshift ULIRGs, highlighting the similarity between SMGs and ULIRGs at optical wavelengths, i.e., in the extended gas. Given these similarities and the complex large-scale kinematics, J1 does not appear to be a good candidate for an alternative, highly efficient "high-redshift mode" of star formation but appears to be governed by similar rules as low-redshift galaxies with intense star formation, although it may be "scaled up" (Tacconi et al. 2006).

The intense starburst in J1 drives a superwind, as evident from blue emission line asymmetries, offsets between rest-frame UV interstellar absorption lines relative to H$\alpha$, and enhanced [N II] $\lambda 6583$/H$\alpha$ line ratios in J1n. The [N II]/H$\alpha$ ratios correlate with [N II] line width, indicating an increasing contribution of mechanical heating as the gas is accelerated in the wind, similar to low-redshift starburst-driven winds. Measured densities (from the [O III] $\lambda 3726, 3729$ and [S II] $\lambda 6717, 6731$ doublets) indicate pressures of $\sim 2 \times 10^{-9}$ dyn cm$^{-2}$, similar to pressures estimated in the expanding bubbles of overpressurized hot gas in local starburst galaxies. These results are a direct indication that the basic physics of starburst-driven winds are rather similar at low and high redshift and supports the approach of studying local starburst galaxies to
better understand the basic mechanisms of high-redshift galaxy formation. The strong wind may explain why Hα equivalent width and reddening in SMM J14011+0252 are positively correlated, which is likely a sign of patchy extinction.

The bluer component of the SMM J14011+0252 system, J2, is very different from J1, with mass $\sim 10^7 \, M_\odot$ estimated from the narrow emission lines and SED fitting. Its gas-phase oxygen abundance, measured from $R_{23}$, is $12 + \log [O/H] = 8.5$, about 0.4 dex lower than in J1 (Paper I). This signals that the two galaxies have had independent evolutionary histories and that J2 is likely going to be accreted by the more massive J1n.

The “submillimeter bright phase” of galaxies, which SMM J14011+0252 is now in, is characterized by high surface mass densities; their star formation appears to be episodic and of relatively short durations, and they have evidence for feedback. These are just the characteristics needed to form early-type spheroid-dominated galaxies in the local universe (Kauffmann et al. 2006). We find that only J1n has the necessary stellar mass surface density $\mu_*$ $> 3 \times 10^7 \, M_\odot \, kpc^{-2}$, while the blue components appear less concentrated. With their current star formation timescales, however, it appears unlikely that they will substantially change the final characteristics of the most massive component J1n.

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Detailed Portrait of $z = 2.6$ Submillimeter Galaxy

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