THE STRONG GRAVITATIONALLY LENSED HERSHEYEL GALAXY HLOCK01: OPTICAL SPECTROSCOPY REVEALS A CLOSE GALAXY MERGER WITH EVIDENCE OF INFLOWING GAS

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ABSTRACT

The submillimeter galaxy (SMG) HERM E S J105751.1+573027 (hereafter HLock01) at \( z = 2.9574 \pm 0.0001 \) is one of the brightest gravitationally lensed sources discovered in the Herschel Multi-tiered Extragalactic Survey. Apart from the high flux densities in the far-infrared, it is also extremely bright in the rest-frame ultraviolet (UV), with a total apparent magnitude \( m_{\text{UV}} \approx 19.7 \text{ mag} \). We report here deep spectroscopic observations with the Gran Telescopio Canarias of the optically bright lensed images of HLock01. Our results suggest that HLock01 is a merger system composed of the Herschel-selected SMG and an optically bright Lyman break-like galaxy (LBG), separated by only 3.3 kpc in projection. While the SMG appears very massive \( (M_\ast \approx 5 \times 10^{11} M_\odot) \), with a highly extinguished stellar component \( (A_V \approx 4.3) \), the LBG is a young, lower-mass \( (M_\ast \approx 1 \times 10^{10} M_\odot) \), but still luminous \( (10 \times L_{\odot}) \) satellite galaxy. Detailed analysis of the high signal-to-noise (S/N) rest-frame UV spectrum of the LBG shows complex kinematics of the gas, exhibiting both blueshifted and redshifted absorption components. While the blueshifted component is associated with strong galactic outflows from the massive stars in the LBG, as is common in most star-forming galaxies, the redshifted component may be associated with gas inflow seen along a favorable sightline to the LBG. We also find evidence of an extended gas reservoir around HLock01 at an impact parameter of 110 kpc, through the detection of \( \mathrm{C}^\equiv \lambda \lambda 1334 \) absorption in the red wing of a bright Ly\( \alpha \) emitter at \( z \approx 3.327 \). The data presented here highlight the power of gravitational lensing in high S/N studies to probe deeply into the physics of high-z star forming galaxies.

Keywords: cosmology: observations — galaxies: evolution — galaxies: starburst — gravitational lensing: strong — galaxies: individual (HLock01)

1. INTRODUCTION

High-\( z \) submillimeter galaxies (SMGs) represent a population of the most massive and luminous galaxies in the early Universe. They are characterized by dust-enshrouded vigorous star formation, assembling their mass very rapidly over short time scales, the so-called starburst phase (see Blain...
eral studying the properties of the young stars, and to look make it almost impossible with current facilities to obtain ness of high-

Alaghband-Zadeh et al. 2012; Olivares et al. 2016; Casey man et al. 2004, 2005; Swinbank et al. 2004, 2005, 2006; using rest-frame optical nebular emission lines (e.g., Chap- investigate properties of the ionized gas in SMGs, mainly by

However, such studies are limited by the faintness of these galaxies, via spectral diagnostics in the rest-frame UV. Its centroid matches the position of the gas distribution traced by the molecular gas. It is thus important to provide detailed characterization of the physical properties of the early episodes of star formation in these galaxies, via spectral diagnostics in the rest-frame UV. However, such studies are limited by the faintness of these galaxies at short wavelengths, with the massive stars giving rise to the UV continuum being embedded in large quantities of dust. Considerable spectroscopic efforts have been successfully used to obtain accurate spectroscopic redshifts, probe for signs of active galactic nucleus (AGN) activity, and investigate properties of the ionized gas in SMGs, mainly by using rest-frame optical nebular emission lines (e.g., Chapman et al. 2004, 2005; Swinbank et al. 2004, 2005, 2006; Alaghband-Zadeh et al. 2012; Olivares et al. 2016; Casey et al. 2017; Danielson et al. 2017). However, the typical faintness of high-

One exception to this principle is the galaxy discussed in this paper, the strong gravitationally lensed SMG HERMES J105751.1+573027 (hereafter HLock01), which is unusually bright in both the optical (R \sim 19.7 mag) and in the far-IR (S_{250\mu m} \sim 400 mJy). HLock01 was identified with Herschel/ SPIRE in the Herschel Multi-tiered Extragalactic Survey (HerMES; Oliver et al. 2012), and investigated in a series of papers after significant follow-up effort (Conley et al. 2011; Gavazzi et al. 2011; Riechers et al. 2011; Scott et al. 2011; Bussmann et al. 2013; Wardlow et al. 2013). Here we give a summary of the main results from those papers. The discovery and its lensing nature was first presented by Conley et al. (2011), based on 880\mu m Submilimeter Array (SMA) interferometry and near-IR Kp adaptive optics (AO) observations using NIRCam on the Keck II telescope, in which the Herschel source was resolved into four components with a large separation of around 9\arcsec (see Figure 1). Using the Plateau de Bure Interferometer (PdBI), the Combined Array for Research in Millimeter-wave Astronomy (CARMA), and the Green Bank Telescope (GBT), Riechers et al. (2011) and Scott et al. (2011) established the redshift of HLock01 from several CO molecular emission lines as z_{CO} = 2.9574 \pm 0.0001. By studying the kinematics of the gas reservoir, Riechers et al. (2011) found a resolved velocity structure in the CO(J = 5 \rightarrow 4) emission, similar to what is observed in gas-rich mergers, but the low spatial resolution did not allow a definitive conclusion. The lens modeling was performed by Gavazzi et al. (2011) using NIRCam Kp and IRAM CO(J = 5 \rightarrow 4) imaging, as well as deep optical I-band imaging with the Subaru Telescope. They showed that the rest-frame UV and optical emission is magnified by a factor of \mu = 10.9 \pm 0.7 by a small group of galaxies at z_{photon} \sim 0.6. However, an offset of 2.4 kpc in the source plane was found between the stars that emit at visible/near-IR wavelengths and the gas distribution traced by the molecular gas.

Later on, Bussmann et al. (2013), and Wardlow et al. (2013) presented new imaging data for this system, using Hubble Space Telescope (HST) WFC3 F110W, new 880\mu m SMA with higher spatial resolution than the data presented in Conley et al. (2011), and Very Large Array (VLA) 1.4GHz data (at 1.1\arcsec resolution). The new images show the same spatial offsets of the bright lensed images seen between the short and long wavelengths (see Figure 1), noticed by Conley et al. (2011) and Gavazzi et al. (2011). A new lens model was determined by Bussmann et al. (2013) using the SMA 880\mu m data, showing a large dust distribution, magnified by 9.2 \pm 0.4 with an effective radius of 4 kpc in the source plane. Its centroid matches the position of the gas distribution traced by the molecular gas, which we attribute to the source of the luminous far-IR emission, but both are offset with respect to the stars that are seen in the visible/near-IR (UV/optical in the rest-frame). Finally, Rigopoulou et al. (2018) dis-
Figure 1. Left panel: $g$, $i$, and $K_s$ color image of HLock01 from GTC, Subaru, and WHT, respectively. Dashed lines show the positions of OSIRIS long-slit spectroscopic observations, all centered on the brightest lensed image A, and oriented so as to encompass the other bright lensed images B, C, and D. Right panel: near-IR high-resolution HST/WFC3 F110W image with labeled multiply lensed images at $z \simeq 2.95$ (blue) and foreground galaxies at $z \simeq 0.65$ (green). G4 is massive enough to split the lensed image B into two pieces on both sides (B1 and B2, see more details in Gavazzi et al. 2011). Orange contours show VLA data at 1.4 GHz and its beam is shown on the bottom right. A spatial offset of the bright lensed images is seen between the short (HST F110W, HLock01-B) and long wavelengths (VLA, HLock01-R). Each image is $16'' \times 16''$, centered on the brightest lensing galaxy, G1, and oriented such that north is up and east is to the left.

Discuss the applicability of the [O III]88/\[N II]122 line ratio as a metallicity indicator in high redshift submillimeter luminous galaxies and found that the gas metallicity of HLock01 is $0.6 < Z_{\text{gas}}/Z_\odot < 1.0$.

Due to the high dust content of HLock01, one could expect that its rest-frame UV and optical light are heavily obscured by dust, as in most SMGs. However, HLock01 is unusually bright in its rest-frame UV, and their colors are also consistent with those of $z \sim 3$ Lyman break galaxies (LBGs; Steidel et al. 1996) with $(G-R) = 0.5$ and $(U-G) = 1.4$. In this paper, we present a detailed analysis of the optically bright lensed images of HLock01, based on deep spectroscopic observations with the 10.4m Gran Telescopio Canarias (GTC). Throughout the paper we adopt the name “HLock01-B” for the optically bright LBG-like galaxy, and “HLock01-R” for the Herschel-selected SMG (where “B” and “R” stand for blue and red galaxies, respectively). Thanks to the large collecting area of the GTC, to the lensing magnification of HLock01-B, and to the small obscuration towards HLock01-B, we can perform a detailed analysis of its physical properties.

The paper is organized as follows. In Section 2, we describe our spectroscopic and imaging observations. Our analysis of the rest-frame UV spectrum of HLock01-B is presented in Section 3. The main properties of both components of HLock01, derived from SED fitting, are discussed in Section 4. Finally, in Sections 5 and 6, we discuss our results and summarize our main findings. A concordance cosmology with matter and dark energy density $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ are assumed throughout this work. All magnitudes are given in the AB system.

2. OBSERVATIONS

2.1. GTC/OSIRIS spectroscopic and imaging observations

Rest-frame UV spectroscopic observations were obtained with the Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy instrument (OSIRIS$^1$) on the 10.4m GTC. The data used in this paper were obtained in service mode over seven different nights, between 2015 April 26 and 2015 June 21 in dark and gray Moon conditions as part of the GTC program GTCMULTIPLE2A-15A (PI: R. Marques-Chaves). We used the R2500V and R2500R grisms, with dispersions of 0.80 and 1.04 Å px$^{-1}$, respectively. These two grisms provide a full spectral coverage of 4500 – 7700 Å, which corresponds to 1150 – 1950 Å in the rest-frame at $z \simeq 2.95$. The OSIRIS 1.2” wide slit was centered on the brightest lensed image of HLock01-B (image A), and oriented so as to encompass the other lensed images B, C, and D, at sky positions angles (PA) of $-39.4^\circ$, $-82.9^\circ$,

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1 http://www.gtc.iac.es/instruments/osiris/
and 44°, respectively (see Figure 1, left panel). Given this configuration, the corresponding instrumental resolution for the R2500V and R2500R grisms is \(\lambda \lambda \sim 180 \text{ km s}^{-1}\). In total, 15 exposures of 900 s were acquired with each grism, equally split between different PAs. A summary of the rest-frame UV spectroscopic observations of HLock01-B used in this work is shown in Table 1.

The data were processed with standard IRAF\(^2\) and PYTHON tasks. Each individual two-dimensional spectrum was bias-subtracted, and flat-field corrected. The wavelength calibration was done for every observing night using HgAr+Ne+Xe arc lamps. Finally, individual 2D spectra were background subtracted. The 1D spectra were then extracted and corrected for the instrumental response using observations of the standard stars Ross 640 and GD 153.

We also obtained spectra of the galaxies in the group responsible for the gravitational lensing of HLock01, with two additional long-slit spectra to encompass G1 – G4, and G3 – G5, respectively. For this, we used a lower spectral resolution grism, R1000R, which provides a wider spectral range (5100 – 10000 Å), which with a 1.2′′ wide slit gives a spectral resolution of \(\lambda \lambda \sim 400 \text{ km s}^{-1}\). The other lensing galaxies G2, and G6 are covered by the long-slit spectra discussed before to study the lensed images of HLock01-B. For the galaxies G1 and G2 we detect several absorption lines (e.g., K and H of Ca II \(\lambda \lambda 3934,3969, H_{\delta} \lambda \lambda 4102,\) and Mg b \(\lambda \lambda 5176\)) as well as a prominent Balmer break at redshift \(z_{G1} = 0.6464 \pm 0.0007\), and \(z_{G2} = 0.6492 \pm 0.0009\), respectively. The spectra of G3, G4, and G5 are too noisy for a reliable measurement of their redshifts, but we marginally detect a jump at 6500 – 6600 Å, compatible with a Balmer break at \(z \sim 0.65\). Thus, it appears that these galaxies belong to a group at \(z \sim 0.65\), slightly larger than the previously assumed redshift \(z_{\text{phot}} = 0.6 \pm 0.04;\) Oyaizu et al. 2008).

Additionally, broad-band imaging with the Sloan \(g′\) filter was obtained with OSIRIS on 2017 January 24, as part of the GTC program GTCMULTIPLE3A-16B (PI: I. Pérez-Fournon). The total exposure time was 2160 s, split into 18 individual exposures of 120 s each. Each frame was reduced individually following standard reduction procedures in IRAF. The registration and combination were done using SCAMP (Bertin 2006) and SWARP (Bertin 2010). The seeing of the final image is \(\sim 0.8′′\) (full width at half maximum, FWHM).

2.2. WHT/LIRIS near-IR imaging

Near-IR broad-band imaging was obtained on 2011 March 22 in the \(K_s\) filter (PI: I. Pérez-Fournon), using the Long-slit Intermediate Resolution Infrared Spectrograph instrument (LIRIS) mounted at the William Herschel Telescope (WHT). LIRIS has a field of view of 4.27′ × 4.27′ with a plate scale of 0.25′′ pixel\(^{-1}\). The total integration time was 60 minutes, split into 180 individual exposures of 20 s, adopting a random dither pattern in 15 different positions. The data reduction was carried out using the IAC’s IRAF LIRISDR\(^3\) task. The seeing of the final image was 0.63′′ FWHM. The astrometric and flux calibrations were performed using 2MASS stars in the field.

2.3. Ancillary data

Additional data used in this work consist of a combination of shallow and deep images. Archival \(U\) and \(R\) wide-field images and catalogs from MEGACAM on the Canada-France-Hawaii Telescope (CFHT), processed and stacked using the

\(\text{http://www.iac.es/galeria/jap/lirisdr/LIRISDATA_REDUCTION.html}\)

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Table 1. OSIRIS spectroscopic observations of HLock01-B.

<table>
<thead>
<tr>
<th>Lensed images</th>
<th>PA (°)</th>
<th>Grism</th>
<th>Date</th>
<th>Time (sec)</th>
<th>Seeing (arcsec)</th>
<th>Moon</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/B</td>
<td>-39.5</td>
<td>R2500V</td>
<td>2015 May 09</td>
<td>5 × 900</td>
<td>0.7 dark</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-39.5</td>
<td>R2500R</td>
<td>2015 May 09</td>
<td>5 × 900</td>
<td>0.8 dark</td>
<td></td>
</tr>
<tr>
<td>A/C</td>
<td>-82.2</td>
<td>R2500V</td>
<td>2015 Apr 26</td>
<td>3 × 900</td>
<td>0.8 gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-82.2</td>
<td>R2500R</td>
<td>2015 Apr 26</td>
<td>3 × 900</td>
<td>0.9 gray</td>
<td></td>
</tr>
<tr>
<td>A/D</td>
<td>44.0</td>
<td>R2500V</td>
<td>2015 Jun 11</td>
<td>2 × 900</td>
<td>0.8 dark</td>
<td></td>
</tr>
<tr>
<td></td>
<td>44.0</td>
<td>R2500R</td>
<td>2015 Jun 11</td>
<td>2 × 900</td>
<td>0.8 dark</td>
<td></td>
</tr>
</tbody>
</table>

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\(^2\) http://iraf.noao.edu/

\(^3\) http://www.iac.es/galeria/jap/lirisdr/LIRISDATA_REDUCTION.html
3. REST-FRAME UV SPECTRUM OF HLOCK01-B

As in other star-forming galaxies, the rest-frame UV spectrum of HLock01-B is characterized by the integrated light from the hot young stellar population with superimposed resonant strong absorption lines produced by the interstellar medium (ISM) and stellar winds. These spectral features can provide detailed information on dynamical, physical, and chemical properties of the atomic and ionized gas in the galaxy, as well as insights on the properties of the young OB stars responsible for the bright continuum (e.g., Pettini et al. 2000, 2002; Shapley et al. 2003; Jones et al. 2012; Steidel et al. 2016; Rigby et al. 2017b,a). Large-scale outflows of interstellar gas, resulting from the kinetic energy deposited by the star formation activity, are a common feature in these galaxies (e.g., Shapley et al. 2003; Steidel et al. 2010).

Despite the differences in the S/N of the spectra of the different lensed images, there are no differences in the profiles of the absorption features and no evidence for velocity offsets between them, as expected. Spectra of the lensed images B and D show redder UV slopes ($\beta$), likely due to differential extinction from the proximity of their light path to the foreground galaxies. Thus, we will focus our rest-frame UV analysis on the spectrum of the lensed image A, which has higher S/N ($\sim 20 - 40$, depending on the wavelength range) and is less affected by absorption in the interstellar medium of the foreground galaxies.

The rest-frame UV spectrum of the lensed image A of HLock01-B, shown in Figure 2, is remarkably similar to the $z \approx 3$ LBG composite spectrum (Shapley et al. 2003). It shows a damped Ly$\alpha$ absorption line, and a series of strong absorption lines associated either with stellar winds from massive stars (e.g., C IV $\lambda\lambda1548,1550$), and ISM lines of several species. However, there are significant differences between the expected wavelengths and velocities ($\Delta v \approx 500$ km s$^{-1}$) of the ISM in the $z \simeq 3$ template (in orange in Figure 2) and in our spectrum (discussed in Section 3.2).

The OSIRIS spectrum also shows several narrow absorption lines produced by intervening systems at lower redshifts along the line of sight to HLock01-B. We identify at least two intervening metal systems at $z = 1.4583 \pm 0.0008$, and $z = 2.1889 \pm 0.0007$. Some of these absorption lines may contaminate the profiles of lines of HLock01-B, and hence they are taken into account in our analysis (in Section 3.2).

In addition, three strong Ly$\alpha$ lines at $z = 2.72$, 3.15, and 3.27 were serendipitously detected in two of our GTC long-slit spectra (see Appendix A). In particular, the Ly$\alpha$ line at $z = 3.27$ is associated with an Ly$\alpha$ emitting galaxy at 14$\arcsec$ SW from the lensing galaxy G1, and shows an unusual absorption line in its red emission wing consistent with C II $\lambda\lambda1334$ at the redshift of HLock01-R ($z_{CO} = 2.9574$; Riechers et al. 2011; Scott et al. 2011). We discuss this absorption feature in Section 5.3.

3.1. Systemic redshift of HLock01-B

Stellar photospheric features are formed in the photospheres of hot stars, and although much weaker than the ISM lines, they can provide a measurement of the systemic redshift of the galaxy. Within the wavelength range covered by our data, we identified several photospheric absorption features (marked with dotted lines in Figure 2), but some of them are blends from multiple transitions. Using the cleanest among these, listed in Table 2, we derive the mean redshift of the stars to be $z_{stars} = 2.9546 \pm 0.0004$.

The nebular C III] $\lambda\lambda1906,1908$ emission is weakly detected ($3\sigma$) at $z_{CIII] = 2.954 \pm 0.002$, in agreement with $z_{stars}$, but the doublet is not resolved in our spectrum, and the existing data are too noisy for a reliable measurement of this feature. Therefore, throughout the paper we adopt the redshift of stellar photospheric lines as the systemic redshift of HLock01-B, $z_{sys} = 2.9546 \pm 0.0004$.

The difference of $\Delta v = 210$ kms$^{-1}$ between the systemic redshift of HLock01-B $z_{sys} = 2.9546$, and the redshift of HLock01-R from the molecular gas lines $z_{CO} = 2.9574$ (Riechers et al. 2011; Scott et al. 2011) cannot be explained by errors in redshift measurements. The velocity offset derived here and the complex dynamical structure of the molecular gas reservoir discussed in Riechers et al. (2011) suggest that HLock01-B is a separate galaxy, different from the Herschel SMG (HLock01-R), but both forming a close merger. Nevertheless, similar velocity offsets, interpreted as rotational velocities in some cases, have been found in a few massive galaxies at high-z (e.g., Law et al. 2012; Jiménez-Andrade et al. 2017; Toft et al. 2017). A more detailed discussion is presented in Section 5.1.

3.2. Kinematics of the ISM
Figure 2. Combined GTC/OSIRIS rest-frame UV spectrum of the lensed image A of HL00k1-B. Vertical dotted lines identify the best defined photospheric absorption lines used to derive the systemic redshift of HL00k1-B ($z_{sys} = 2.9546 \pm 0.0004$). Strong absorption lines associated with interstellar gas and stellar winds are marked with vertical dashed lines. The C III $\lambda\lambda 1906, 1908$ nebular emission doublet and fine-structure emission lines of Si II are marked with dash-dotted lines. For comparison, we show in orange the $z \sim 3$ LBG subset composite with the damped Ly$\alpha$ profile from Shapley et al. (2003) at the systemic redshift of HL00k1-B (downshifted for clarity). The wavelength windows of four metallicity indices (e.g., F1370, etc.), used to derive the metallicity of young stars in HL00k1-B, are also marked. Short vertical blue and green lines mark the positions of absorption lines of intervening systems at $z \approx 1.458$ and $z \approx 2.189$, respectively. The sky emission is also plotted in red, showing the locations of strong sky emission lines.
Within our spectral range, we identify 11 strong absorption features, including low-ionization lines (Si II λ1260, O I λ1302, Si II λ1304, C II λ1334, Si II λ1526, Fe II λ1608, and Al II λ1670), and high-ionization lines associated with a hot gas phase (Si IV λ1393, 1402, and C IV λ1548, 1550). In low-ionization lines, the interstellar component usually dominates over the stellar contribution, and thus they are useful for studying the kinematics of the ISM (Shapley et al. 2003; Steidel et al. 2010). High-ionization lines are associated with strong winds from young stars, and predominantly trace gas at higher temperatures ($T \geq 10^4$ K).

For the kinematic analysis of the ISM, we firstly normalized the GTC/OSIRIS spectrum of HLock01-B using the pseudo-continuum windows that are free of absorption and emission features identified by Rix et al. (2004).

Figure 3 shows the normalized profiles of the strongest absorption lines seen in our spectrum. We note that all ISM lines present an unusual velocity profile with the maximum optical depth located at $v \simeq +370$ km s$^{-1}$ relative to the stars of HLock01-B, or $v = (170 \pm 10)$ km s$^{-1}$ relative to the Herschel SMG at $z_{\text{CO}} = 2.9574$. This can be understood as gas apparently moving towards the young stars, since all the interstellar lines are seen against the UV stellar continuum. This absorption is strong in the low-ionization lines (the first three columns in Figure 3), likely with saturated profiles $^6$, but it is also present, although notably weaker in high-ionization ones, like C IV and Si IV (the last two columns in Figure 3). The spectrum of HLock01-B also shows a secondary, but broader absorption component centered at a mean $v = (-220 \pm 60)$ km s$^{-1}$ relatively to its systemic redshift, which is a characteristic of large-scale out-

Table 2. Stellar photospheric lines in HLock01-B.

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda_{\text{obs}}$ (Å)</th>
<th>$\lambda_{\text{c}}$ (Å)</th>
<th>$z_{\text{sys}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si III</td>
<td>1294.54</td>
<td>5119.71</td>
<td>2.9548 ± 0.0003</td>
</tr>
<tr>
<td>C II</td>
<td>1323.93</td>
<td>5235.54$^a$</td>
<td>2.9543 ± 0.0006$^a$</td>
</tr>
<tr>
<td>N III</td>
<td>1324.35</td>
<td>5235.54$^a$</td>
<td>2.9543 ± 0.0006$^a$</td>
</tr>
<tr>
<td>O IV</td>
<td>1343.35</td>
<td>5312.72</td>
<td>2.9546 ± 0.0010</td>
</tr>
<tr>
<td>Si III</td>
<td>1417.24</td>
<td>5604.64</td>
<td>2.9546 ± 0.0010</td>
</tr>
<tr>
<td>S V</td>
<td>1501.76</td>
<td>5939.25</td>
<td>2.9548 ± 0.0003</td>
</tr>
<tr>
<td>N IV</td>
<td>1718.55</td>
<td>6796.37</td>
<td>2.9548 ± 0.0004</td>
</tr>
</tbody>
</table>

Notes.

$^a$ Vacuum wavelengths.

$^b$ Values measured from the centroid for the individual photospheric line.

$^c$ Value refers to the blended C II and N III photospheric line.

$^6$ We test if some of these lines are saturated, by considering the linear part of the curve of growth. In this case, the ratios of the rest-frame equivalent widths (EW$_0$) of different transitions of a given ion can be related through their oscillator strengths. For example, for the Si II lines in the unsaturated case we would expect EW$_0$ (1260)/EW$_0$ (1526) $\approx$ 5, EW$_0$ (1260)/EW$_0$ (1304) $\approx$ 10, and EW$_0$ (1304)/EW$_0$ (1526) $\approx$ 0.5. Our spectrum shows ratios of $\approx 1.0, 2.5,$ and 0.4, respectively, suggesting that at least Si II λ1260 may be saturated.
flows of material in HLock01-B. This blueshifted component is stronger in high-ionization lines than in the low-ionization ones (it is detected in C II λλ1334, Si II λλ1260, and Si II λλ1526, but is not clear in O I λλ1302, Fe II λλ1608 or Al II λλ1670), suggesting that the outflowing gas is mostly ionized, or the neutral gas has a lower covering factor than the ionized gas.

The absorption profiles resulting from these two components extend over a velocity range \( \Delta v \approx 1700 \text{ km s}^{-1} \), from \( \sim -1000 \) to \( +700 \text{ km s}^{-1} \), much larger than in other high-\( z \) lensed LBGs (Pettini et al. 2000, 2002; Cabanac et al. 2008; Quider et al. 2009, 2010; Dessauges-Zavadsky et al. 2010). The C IV doublet is even broader than the ISM lines, with \( \Delta v \gtrsim 3000 \text{ km s}^{-1} \), indicative of a strong contribution from winds due to radiation pressure of the most massive, and luminous stars of HLock01-B. The velocity profile of the C IV doublet shows a strong P-Cygni profile, with the red-emission wing being attenuated by the two narrow, redshifted (\( v \approx +370 \text{ km s}^{-1} \)) interstellar absorption components of C IV.

**Figure 4.** Example of the double-Gaussian fit of the low- (C II λλ1334) and high-ionization lines (Si IV λλ1393). Lower and upper axes are the velocity (in \( \text{km s}^{-1} \)) relative to the stars of the LBG (HLock01-B) and to the molecular gas of the SMG (HLock01-R), respectively. The y axis is the normalized flux. The redshifted (red color) and blueshifted (blue color) components represent outflowing and inflowing gas along the line of sight of HLock01-B, respectively. The sum of the two components is also shown in gray. Black dashed and green dot-dashed vertical lines mark the zero velocity position with respect to \( z_{\text{sys}} = 2.9546 \) (HLock01-B) and \( z_{\text{C0}} = 2.9574 \) (HLock01-R), respectively.

In order to understand the blueshifted and redshifted ISM absorption components, we simultaneously fit two Gaussians to the low- and high-ionization lines. Figure 4 shows an example of our fit to the low-ionization C II λλ1334, and high-ionization Si IV λλ1393 lines, and Table 3 summarizes the results for all strong absorption components, except the ones that are affected by the proximity of other lines (O I λλ1302, Si II λλ1304, and Fe II λλ1608). In C IV λλ1548,1550 we only fit the redshifted component, as the blueshifted one is affected by strong winds.

The fitted blueshifted component (blue dashed lines in Figure 4) has its peak located at \( z_{\text{blue}} = 2.9519 \pm 0.0009 \) (or \( v_{\text{blue}} \approx -220 \text{ km s}^{-1} \) relative to the systemic redshift of HLock01-B), and shows a broad profile (FWHM \( \approx 900 \text{ km s}^{-1} \), after accounting for the instrumental broadening) extended over a velocity range from \( -1000 \) to \( +600 \text{ km s}^{-1} \). Despite the fact that a potentially large contribution from stellar winds may be present in the high-ionization lines, for the low-ionization ones, this effect is negligible. Thus, the broadness of the blueshifted component in the low-ionization line C II (as well as in others like Si II λλ1260, Si II λλ1526, see Figure 3) suggests highly turbulent kinematics of the outflowing gas. As a comparison, the velocity profile of the low-ionization interstellar lines in the \( z \sim 3 \) LBGs composite spectrum of Shapley et al. (2003) shows an average FWHM \( = (560 \pm 150) \text{ km s}^{-1} \). Despite the broadness of the outflowing low-ionization lines in HLock01-B, they show smaller rest-frame equivalent widths (by a factor of two) than in typical LBGs.

The fitted redshifted component (red dashed line in Figure 4) has its peak located at \( z_{\text{red}} = 2.9596 \pm 0.0003 \), and shows a narrow profile (FWHM \( = 310 \) and \( 104 \text{ km s}^{-1} \), for C II and Si IV, respectively). If dynamically related to HLock01, its positive velocity relatively to both HLock01-B (\( v \approx +370 \text{ km s}^{-1} \)) and HLock01-R (\( v \approx +170 \text{ km s}^{-1} \)) is indicative of gas moving towards the system. This narrower component is seen in all absorption lines, but appears almost unresolved in the high-ionization ones, suggesting that these lines are dominated by the interstellar component. Moreover, the differences in the FWHM between the redshifted component in low- and high-ionization lines (see Table 3) also suggest that cold and warm gas may have different kinematics and origins. A more clear picture of the origin of this redshifted component of the ISM may come from deeper and higher spectral resolution observations. In particular, fully resolved ISM components of HLock01-B with unsaturated profiles may be used to derive chemical abundances, using the apparent optical depth method, as has been done in other studies of strongly lensed star-forming galaxies (e.g., Pettini et al. 2002; Quider et al. 2009; Dessauges-Zavadsky et al. 2010).

### 3.3. Stellar metallicity and age of HLock01-B

Leitherer et al. (2001), Rix et al. (2004), and later on Sommariva et al. (2012), showed that several blends of stellar UV photospheric absorption lines can be used to trace the metallicity of young stars, by measuring equivalent widths of these blends in specific wavelength windows. These metallicity indicators have been successfully applied in several works (e.g., Quider et al. 2009, 2010; Patricio et al. 2016), using high S/N spectra due to the faintness of these absorption lines. They are defined as the F1370, F1425, F1460, F1501, and F1978 indices, and their wavelength windows are shown in Figure 2 (except for the latter one which is not covered by our data).

We measured the equivalent widths of the features in each
of these spectral windows using our normalized spectrum. We then applied the calibrations of Sommariva et al. (2012) to obtain the corresponding metallicity. Table 4 summarizes our measurements. All indices agree in a sub-solar metallicity, and we use the mean value to derive the metallicity of the UV stars in HLock01-B as $Z_{\text{stars}} = (0.4 \pm 0.1)Z_{\odot}$.

Table 4. Metallicity estimates following Sommariva et al. (2012).

<table>
<thead>
<tr>
<th>Index</th>
<th>Range (Å)</th>
<th>EW (Å)</th>
<th>$Z/Z_{\odot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1370</td>
<td>1360 – 1380</td>
<td>1.4 ± 0.2</td>
<td>0.35</td>
</tr>
<tr>
<td>F1425</td>
<td>1415 – 1435</td>
<td>0.9 ± 0.1</td>
<td>0.28</td>
</tr>
<tr>
<td>F1460</td>
<td>1450 – 1470</td>
<td>1.0 ± 0.1</td>
<td>0.39</td>
</tr>
<tr>
<td>F1501</td>
<td>1496 – 1506</td>
<td>0.6 ± 0.1</td>
<td>0.59</td>
</tr>
</tbody>
</table>

The strength of any P-Cygni features formed in the expanding winds of the most massive stars is also sensitive to the metallicity, along with the age and the initial mass function (IMF) of the stellar population. In order to study the P-Cygni stellar wind features in HLock01-B we use model spectra computed with the spectral synthesis code STARBURST99 (Leitherer et al. 1999, 2001) and perform $\chi^2$ minimization to our normalized data. In generating the STARBURST99 spectra, we assumed both continuous and instantaneous star-formation scenarios. We adopt a Salpeter slope for the IMF between 1 and 100 $M_{\odot}$, and ages ranging from 1 to 100 Myr. STARBURST99 models were generated using libraries of empirical UV spectra from Large and Small Magallenic Cloud stars (LMC/SMC, which correspond to a metallicity $Z_{\text{MC}} \approx 0.4Z_{\odot}$) and Galactic stars ($\approx 1Z_{\odot}$).

Figure 5 shows two high-ionization lines associated with stellar winds used in this fit: $N\,\lambda\lambda 1238,1242$ (left panels); and $C\,\lambda\lambda 1548,1550$ (middle panels). STARBURST99 models are plotted for continuous (upper panels) and instantaneous (lower panels) star-formation scenarios. We excluded in the fit the region encompassing the interstellar absorption in C IV, between 1543 and 1553 Å, which is not associated with the stellar P-Cygni profile.

The $\chi^2$ ($N_{\text{dof}} = 38$) as a function of the age of the stellar population for all models is shown in the right panel of Figure 5. The model using LMC/SMG stars (0.4$Z_{\odot}$) with a ~6 Myr old burst matches the data better ($\chi^2/N_{\text{dof}} = 39/38$), reproducing quite well both the line profiles of $N\,\lambda\lambda 1238,1242$ and $C\,\lambda\lambda 1548,1550$, in particular the regions of the blueshifted absorption wing component of the C IV P-Cygni profile and its red-emission wing (regions of 1536 to 1542 and 1554 to 1563 Å, respectively). Bursts over significantly longer periods ($\lesssim 25$ Myr) can also recover the stellar blueshifted absorption of C IV, but fail to reproduce the red emission wing of HLock01-B (see lower panels of Figure 5 for an example of a 15 Myr old burst). However, our results should be treated with care, given the assumptions made on the slope and upper end cut-off of the IMF. Moreover, the P-Cygni profile of $N\,\lambda\lambda 1238,1242$
could also be affected by the red wing of the damped Ly$\alpha$ absorption line (see Section 3.4).

All methods used in this work to derive the metallicity of the young stars in HLock01-B point to a $Z_{\text{stars}} \simeq 0.4Z_{\odot}$ value. Our metallicity measurements are slightly different from the measurement of gas metallicity in HLock01-R ($0.6 < Z_{\text{gas}}/Z_{\odot} < 1.0$) by Rigopoulou et al. (2018), using the [O III]88/[N II]122 line ratio as a metallicity indicator. This provides additional evidence that the bright Herschel-SMG (HLock01-R) and the bright LBG-like galaxy (HLock01-B) are likely different galaxies with distinct enrichment histories.

3.4. The damped Ly$\alpha$ profile

The Ly$\alpha$ line in the spectrum of HLock01-B shows a strong damped Ly$\alpha$ profile, with the minimum lying in the range from $\simeq 4809$ to $4815$ Å (or $v \simeq +100$ to $+500$ km s$^{-1}$ relative to $z_{\text{sys}}$, see Figure 6). We used the software PYASTRONOMY\(^7\) to generate theoretical Voigt profiles and perform $\chi^2$ minimization to the Ly$\alpha$ profile. However, we noted differences in the absorption profile in the blue and red damping wings, with the absorption being more pronounced in the latter. The blue wing is more noisy and less constrained than the red one, likely due to additional absorption from the intergalactic medium in the line of sight towards HLock01-B. The red wing is well fitted with a neutral hydrogen column density $N(\text{H i}) = (5.83 \pm 1.24) \times 10^{20}$ cm$^{-2}$ centered at $\simeq 4813$ Å or $v \simeq +370$ km s$^{-1}$ with respect to $z_{\text{sys}}$. Therefore, we interpret that most of the damped absorption is due to the redshifted component of the ISM seen in the spectrum of HLock01-B, which consists primarily of neutral gas, and presents a large optical depth. Our derived column density of H i is in the range of typical values measured in other lensed galaxies (e.g., Pettini et al. 2000; Cabanac et al. 2008; Dessauges-Zavadsky et al. 2010).

\(^7\) https://github.com/aczesla/PyAstronomy
3.5. Weak emission lines

As discussed in Section 3.1, the nebular C III] \( \lambda \lambda 1906,1908 \) emission is barely detected in our OSIRIS spectrum, and the doublet is not resolved. Despite the low significance of the detection (3\( \sigma \)) we fit a Gaussian to the unresolved C III] doublet. We derive \( z_{\text{CIII}} = 2.954 \pm 0.002 \) and \( \text{EW}_{\text{CIII}} = (1.0 \pm 0.3) \) Å. Other semiforbidden transitions often detected in the spectra of star-forming galaxies are the O III] \( \lambda \lambda 1661,1666 \) lines, but these are not detected in our spectrum, despite the high continuum S/N in this spectral region (around 25). The absence of these nebular lines in HLock01-B may be due to their faintness or to contamination with the overlapping blueshifted component of the Al II \( \lambda \lambda 1670 \) interstellar line.

In addition to C III], we also detect emission features from the excited fine-structure transitions Si II* \( \lambda \lambda 1264, 1309, \) and 1533. Their profiles appear slightly asymmetric (see Figure 2), with the centroids redshifted with respect to \( z_{\text{sys}} \) by a mean of \( \simeq +120 \pm 50 \) km s\(^{-1}\). This velocity offset may be due to the neighboring red component of resonance absorption features (Si II \( \lambda \lambda 1260, \) O I + Si II \( \lambda \lambda 1303, \) and Si II \( \lambda \lambda 1526 \)), which attenuate the blue edges of the fine-structure emission profiles. We measure rest-frame equivalent widths of 0.32 ± 0.06, 0.22 ± 0.09, and 0.26 ± 0.14 Å for Si II* \( \lambda \lambda 1264, 1309, \) and 1533, respectively.

4. PHYSICAL PROPERTIES FROM THE SPECTRAL ENERGY DISTRIBUTION

Conley et al. (2011) analyzed the SED of HLock01, considering only a single lensed background source. They simultaneously fitted the emission in the optical/near-IR with longer wavelength data (far-IR and submm), but the fit did not explain the IRAC fluxes and overestimated the \( K_s \) and MIPS 70\( \mu \)m flux densities by a factor of 2 or more. We now know that HLock01 is composed of two different, spatially and spectrally offset sources, and thus the energy balance method (between dust-absorbed stellar continuum and the reprocessed dust emission in the far-IR), which was previously invoked, cannot be applied to the integrated photometry by considering a single source.

From a revised photometric analysis of both background sources, presented in Appendix B, we show that their SEDs are well defined at short (HLock01-B) and long wavelengths (HLock01-R), where these two components dominate, respectively. HLock01-B is very bright in the rest-frame UV and optical, but faint (or undetected) in the current VLA and SMA data. On the other hand, HLock01-R shows a very red and obscured counterpart in the rest-frame UV and optical, but is very bright in the submm. However, to deblend the emission from the two components in the IRAC bands is challenging, given the limitation of the low spatial resolution. The centroids of the bright lensed images A and C seen in the IRAC 3.6 and 4.5 \( \mu \)m bands are slightly offset (\( \simeq 0.7'' \)) with respect to the bright counterparts in the optical and submm, suggesting a contribution of both to the total flux density in IRAC bands. However, the small rest-frame UV spectral slope of HLock01-B, \( \beta = -1.9 \pm 0.1 \) (measured from the observed \( R \) and \( I \) bands, and assuming a simple power law \( F_\lambda = \lambda^{\beta}, \) and the low Balmer/4000 Å break color (F110W− \( K_s = 0.15 \) mag), suggest that the contribution of the LBG in the mid-IR is modest compared with the emission from the SMG. Also, typical LBGs are faint in the mid-IR (\( S_{24\mu m} \simeq 20−30 \mu \)Jy; Magdis et al. 2010b; Reddy et al. 2012), even those showing a redder UV \( \beta \) slope (Reddy et al. 2006; Coppin et al. 2007; Siana et al. 2008, 2009; Reddy et al. 2010; Magdis et al. 2017), which are on average more massive and show larger infrared luminosities.

Additionally, in strong gravitational lensing the finite extent of one or multiple background sources can lead to significant differential magnification, and their intrinsic properties, derived from photometric or spectroscopic diagnostics, can be incorrect if this effect is not taken into account (e.g., Hezaveh et al. 2012; Serjeant 2012). Of particular importance in treating differential magnification are the cases with multiple background sources with significantly different SEDs and positions in the source plane (e.g., the \( \epsilon \sim 2.9 \) gravitational lensed system analyzed in MacKenzie et al. 2014).

To check this effect in HLock01, we use the high S/N and high spatial resolution HST/F110W imaging data to update the lens model already described in Gavazzi et al. (2011). The procedure is detailed in Appendix C. Figure 7 shows the mean positions and ellipses characterizing the galaxy shapes.
in the source plane for all wavebands. Stellar emission in the optical/near-IR (LBG) is coincident and slightly offset by 0′′.42 ± 0′′.07 in the source plane from the mutually coincident VLA, CO, and dust emission (SMG). We find magnification factors of $\mu = 8.5 \pm 0.5$ for $HST$ F110W, $\mu = 8.3 \pm 0.3$ for GTC g-band, $\mu = 8.2 \pm 0.6$ for VLA, $\mu = 9.2 \pm 0.8$ for PdBI CO ($J = 5 \rightarrow 4$), and $\mu = 9.2 \pm 0.5$ for the SMA dust continuum. The differential magnification appears to be small, since the bulk of the source emission of the LBG and SMG stands relatively far from the caustics without crossing them (see Figure 7), and thus changes of magnification as a function of source plane position vary very little. We thus assume, for simplicity, lensing magnifications of $\mu_{HST} = 8.5 \pm 0.5$ and $\mu_{SMA} = 9.2 \pm 0.5$ to be the same in the spectral range in which the LBG and the SMG are well detected, respectively.

Figure 7. Source plane reconstruction of HLock01. The posterior mean effective ellipses of the reconstructed components of HLock01-B (LBG) from $HST$ F110W and GTC g-band are represented by blue colored ellipses. Pink, yellow and red colored ellipses represent the effective radius of the reconstructed components of CO, VLA and dust emission associated with HLock01-R (SMG), respectively. A relative offset of 0′′.42 ± 0′′.07 is seen between $HST$ F110W and VLA, which corresponds to 3.3 ± 0.6 kpc.

We firstly used the SED-fitting code FAST (Fitting and Assessment of Synthetic Templates; Kriek et al. 2009) to derive the stellar population properties of HLock01-B. Optical $U$, $g$, $R$, and $I$, and near-IR F110W and $K_s$ flux measurements were used in this fit (see Appendix B). We excluded fluxes from IRAC from this fit, given the uncertainties of the contribution of HLock01-B in these bands. However, the 2.2 $\mu m$ $K_s$ band corresponds to rest-frame emission at 5600 Å, above the Balmer/4000 Å break, which is sensitive to the age of the stellar population. We assume stellar population synthesis models of Bruzual & Charlot (2003), the Chabrier (2003) IMF, and an exponentially declining star-formation history ($\propto e^{-t/\tau}$). We adopt a grid for the age of the stellar population, ranging from 20 Myr to the maximum age of the Universe at $z \approx 2.95$, and star-formation histories with $\tau$ between 0.3 and 10 Gyr, both in steps of 0.1 dex. The attenuation curve of Calzetti et al. (2000) was adopted, and the allowed $A_v$ range was 0−3 mag in steps of 0.05 mag. We also fixed the metallicity to $Z/Z_{\odot} = 0.4$, the value measured in Section 3.3 for the young O and B stars. The best-fit model ($\chi^2/N_{\text{dof}} = 1.6/3$) gives an intrinsic (i.e., corrected for the lensing magnification $\mu_{HST} = 8.5 \pm 0.5$ and assumed to be the same in the spectral range in which the LBG is well detected) stellar mass log($M_*/M_{\odot}$) = 10.1 ±0.3, and an attenuation of the stellar light of $A_v = 0.84 \pm 0.25$, with age log(age$_{M}/$yr$^{-1}$) = 7.3 ±0.6. Errors refer to 68% confidence intervals derived using 500 Monte Carlo simulations. After correction for the lensing magnification, the star-formation rate of the best fit model is SFR = 710 ± 180 M$_{\odot}$/yr$^{-1}$.

We further performed a multi-band SED fit of HLock01-R using the high-$z$ extension of MAGPHYS (Multi-wavelength Analysis of Galaxy Physical Properties; da Cunha et al. 2008, 2015) to explore its SFR, and stellar and dust mass ($M_d$). MAGPHYS uses the Bruzual & Charlot (2003) stellar populations with a Chabrier (2003) IMF and assumes the attenuation model of Charlot & Fall (2000). We used the flux measurements from 1.1 $\mu$m to radio. In the Spitzer/IRAC bands, we used the difference between the total fluxes (measured in Appendix B) and the expected flux of HLock01-B from the best-fit SED, as indicated in Table B1. The best-fit model (reduced $\chi^2 = 3.1$) gives a lensing corrected ($\mu_{SMA} = 9.2 \pm 0.5$) stellar mass log($M_*/M_{\odot}$) = 11.7 ±0.2, a mass weighted age log(age$_{M}$/yr$^{-1}$) = 8.6 ± 0.1, and a large attenuation $A_v = 4.26 \pm 0.35$ mag. We find a dust mass log($M_d/M_{\odot}$) = 8.8 ± 0.1, with a dust temperature $T_d = (53.6 \pm 0.2)$ K. The uncertainties are derived from the 16th and 84th percentiles. The best-fit SED also yields an intrinsic total infrared luminosity $L_{IR} = (1.5 \pm 0.1) \times 10^{11} L_{\odot}$, which is defined as the luminosity from 8 − 1000 $\mu$m in the rest frame. Using a Kennicutt relation (Kennicutt 1998) with a Chabrier IMF (Chabrier 2003), the total infrared luminosity implies a star-formation rate of $\approx 1500$ M$_{\odot}$/yr$^{-1}$. All values were corrected for the lensing magnification derived from the SMA 880 $\mu$m data ($\mu_{SMA} = 9.2 \pm 0.5$), which for simplicity, we assume to be the same from the observed near-IR to submm bands for HLock01-R.

We followed Delvecchio et al. (2017) and Miettinen et al. (2017) to look for a possible AGN contribution in HLock01-R. We use the three-component fitting code SED3FIT (Berta et al. 2013), which accounts simultaneously for stellar, dust, and AGN emission. However, the stellar and dust components of SED3FIT use the model libraries of da Cunha et al. (2008), rather than the ones used in the new high-$z$ extension of MAGPHYS (da Cunha et al. 2015), which are expected to be better suited for high-$z$ SMGs. We found a poor fit to our
5. DISCUSSION

5.1. Close merger or a large rotational disk?

Our high S/N GTC/OSIRIS spectrum of the optically bright lensed images of HLock01 (HLock01-B) shows several well-defined UV photospheric absorption lines, for which we secured the systemic redshift $z_{\text{sys}} = 2.9546 \pm 0.0004$. This value differs by $-210$ km s$^{-1}$ from the redshift of HLock01-R measured from the molecular gas lines $z_{\text{CO}} = 2.9574 \pm 0.0001$ (Riechers et al. 2011; Scott et al. 2011). A spatial offset of 3.3 kpc (in projection) has also been found in the source plane between the bulk of the stars that emit at rest-frame UV/optical wavelengths (HLock01-B), and the molecular gas and dust distribution associated with the luminous far-IR emitting source HLock01-R.

Although similar or even larger rotational velocities have been found in massive disk SMGs at high-$z$ (e.g., Carilli et al. 2010; Daddi et al. 2010; Jiménez-Andrade et al. 2017; Jones et al. 2017), a scenario with HLock01-B being a dust-free region, that is part of a large rotational disk of HLock01-R, is unlikely. Such asymmetry in the dust distribution, with the lack of dust attenuation in HLock01-B, would be difficult to explain. Additionally, despite the large errors, the differences in the metallicity measured in the stars of HLock01-B and in the gas of the Herschel SMG HLock01-R (Rigopoulou et al. 2018) suggest they are different galaxies with different enrichment histories.

Therefore, bringing together our GTC spectroscopic results and the complex velocity structure seen in the molecular gas reservoir in HLock01-R (Riechers et al. 2011), we argue that HLock01 comprises two close but different sources forming a pair of merging galaxies (HLock01-B and HLock01-R) separated by 3.3 kpc in projection. The merger scenario is also sustained by the broadness of the blueshifted ISM absorption lines seen in the spectrum of HLock01-B, suggesting highly turbulent gas likely produced by the close merger. While HLock01-R appears to be an evolved massive galaxy with a very large obscured star-formation rate,
HLock01-B is a young lower-mass satellite galaxy with photometric properties similar to those of LBGs, yet undergoing a young burst ($\gtrsim 6$ Myr) of star formation, likely triggered by the gravitational interaction with the nearby massive SMG.

It is worth mentioning that without the gravitational lensing effect our results could easily be mistaken. Firstly, without the magnification in the apparent flux of HLock01-B, the systemic redshift, measured from faint stellar photospheric lines, would be difficult to obtain. In the absence of strong UV nebular emission lines, as is the case of HLock01-B, a significant continuum S/N is required to detect faint photospheric absorption lines. Secondly, the projected 3.3 kpc spatial offset seen between the two different objects in the source plane would correspond to only 0.4″ without the lensing distortion, which is challenging to observe due to the limitation on the spatial resolution and sensitivity of current instruments.

It is thus no surprise that most high-$z$ close mergers ($\lesssim 10$ kpc projected separation) have been discovered through the gravitational lensing effect (e.g., Ivison et al. 2010a; MacKenzie et al. 2014; Messias et al. 2014; Rawle et al. 2014; Wuys et al. 2014; Spilker et al. 2015; Marrone et al. 2018), with a few exceptions of unlensed, well separated, SMG-SMG, SMG-QSO or SMG-LBG bright interacting pairs resolved with interferometric observations (e.g., Ivison et al. 2002, 2008; Smail et al. 2003; Salomé et al. 2012; Oteo et al. 2016; Lu et al. 2017; Riechers et al. 2017).

5.2. Outflow/Inflowing gas

Turning to the rest-frame UV spectral features, the internal kinematics of HLock01-B are very complex and different from what is observed in typical LBGs, showing two distinct components of the ISM. The blueshifted component of the ISM is centered at $v_{\text{ISM}} \approx -220$ km s$^{-1}$ relative to the stars, which we associate with galaxy-scale outflows of material via stellar and supernova-driven winds, as seen in many other high-$z$ star-forming galaxies (e.g., Shapley et al. 2003; Steidel et al. 2010). This component is stronger (i.e., larger equivalent widths) in high ionization lines, like Si IV and C IV, similar to what is found in other young, low-metallicity galaxies (e.g., Erb et al. 2010; James et al. 2014). It is also detected in some low-ionization lines, but with a much broader profile ($\text{FWHM} \approx 900$ km s$^{-1}$) than in typical LBGs ($\approx 560$ km s$^{-1}$; Shapley et al. 2003; Steidel et al. 2010), extending over a large velocity range from approximately $-1000$ to $+600$ km s$^{-1}$. We interpret that the broadness of the blueshifted absorption lines in HLock01-B is the result of a combination of strong winds of massive stars in the LBG and a complex velocity structure due to the close gravitational interaction with the massive SMG.

On the other hand, the redshifted component seen in all strong absorption lines (see Figures 3 and 4) is highly unusual and not seen in the many high-$z$ galaxies studied (e.g., Shapley et al. 2003; Steidel et al. 2010). This component can be understood as gas apparently moving towards the young stars of HLock01-B, because the absorbing gas must lie in front of the LBG. We relate this component with the large column density of foreground neutral gas ($N(\text{H}I) = (5.83 \pm 1.24) \times 10^{20}$ cm$^{-2}$) giving rise to the damped Ly$\alpha$ absorption seen in the spectrum of HLock01-B (see Section 3.4). The detection of this absorption in both low- and high-ionization ISM lines also suggests that the gas has a broad range of temperatures, from cold, mostly neutral (e.g., O I) to warmer and ionized gas (e.g., Si IV, and C IV).

The origin and nature of the redshifted component seen in all strong absorption lines in the spectrum of HLock01-B is unclear, and with the available data we cannot arrive at a definite conclusion. Interpreting the redshifted component also depends strongly on the spatial location of the SMG and LBG along our line of sight. The relatively low dust attenuation in HLock01-B ($A_V = 0.8^{+0.1}_{-0.3}$) may suggest that the SMG is located in the background, otherwise the stellar continuum of the LBG would be highly attenuated by the foreground dust content of HLock01-R (see Figure 7). Therefore, it is unlikely that the redshifted component is associated with outflows from HLock01-R or rotating gas in its disk seen from the background HLock01-B.

In this sense, the redshifted component could be associated with a dwarf galaxy or a damped Ly$\alpha$ system falling towards HLock01. Gas ejected by a previous episode of star formation or AGN activity in HLock01 would not easily escape its intense gravitational pull. If cooled enough, these reservoirs of gas would provide additional fuel to prolong the star-formation activity (e.g., Davé et al. 2011; Hopkins et al. 2014; Narayanan et al. 2015; Wang et al. 2015; Emonts et al. 2016). Assuming that the gas is dynamically linked and collapsing towards HLock01, it is more likely that the gas is falling into the massive SMG with $v \approx +170$ km s$^{-1}$, instead of falling to HLock01-B with $v \approx +370$ km s$^{-1}$, which seems too high for a $10^{10} \text{M}_\odot$ galaxy.

Evidence of accretion of cool, metal-enriched gas has been found in only a few spectra of star-forming galaxies at moderately low-$z$ (e.g., Sato et al. 2009; Coil et al. 2011; Rubin et al. 2012; Martin et al. 2012), and is more elusive at high-$z$ (e.g., Bouché et al. 2013; Wiseman et al. 2017) due to the faintness of individual high-$z$ galaxies. Some authors suggest that the low detection rate of infalling gas is due to the geometry and alignment of the streams, which can only be detected in absorption if favorably aligned with our line of sight (Kimm et al. 2011; Martin et al. 2012). Nevertheless, accretion of cold gas, either in the form of cold flows, mergers or recycled gas from stellar feedback, plays an important role in star-formation histories and galaxy growth.

5.3. Extended gas reservoir?

We reported an unusual absorption line at $\approx 5281$ Å in the red-wing of a bright Ly$\alpha$ emission at $z \approx 3.327$, associated with an object 14″ SW of HLock01 (see Appendix
This absorption is consistent with C II λλ1334 at $z = 2.9574 \pm 0.0008$, very close by $\Delta v = (8 \pm 76) \text{ km s}^{-1}$ to the redshift of HLock01-R measured from the molecular gas ($\lambda_{CO} = 2.9574 \pm 0.0001$). The limited spectral coverage of the Ly$\alpha$ emission line and the faintness of the continuum associated with the $z \approx 3.327$ galaxy does not let us unambiguously confirm if the absorption line is C II at the redshift of HLock01-R, or a different absorption line system at a lower redshift. If related with HLock01-R, it may suggest a substantial gas reservoir in the halo at an impact parameter of 110 kpc. It is worth noting that Fu et al. (2016) used QSO absorption line spectroscopy in three high-$z$ SMG-QSO close pairs, with the QSO at a larger redshift than the SMG, to probe the circumgalactic medium (CGM) at similar impact parameters. However, they did not find evidence of optically thick H I gas or strong neutral absorbers in the CGM. Our results suggest that at least massive SMGs, such as HLock01-R, may have prominent cool gas reservoirs in their halos, that could fuel a prolonged star formation phase.

5.4. Physical Properties

The intrinsic physical properties (corrected for lensing magnification) derived from multiband SED fitting reveal that HLock01-R is a far-IR luminous SMG (as already discussed in earlier papers, e.g., Conley et al. 2011; Wardlow et al. 2013), with an ongoing SFR $\gtrsim 1500 M_{\odot} \text{yr}^{-1}$, but yet heavily obscured at short wavelengths. Our new analysis reveals a large, highly obscured stellar mass, similar to the most massive and extreme SMGs during the peak of star formation (e.g., Hainline et al. 2011; Ma et al. 2015; Schinnerer et al. 2016; Miettinen et al. 2017; Nayyeri et al. 2017). However, as already discussed in Conley et al. (2011) and Wardlow et al. (2013), HLock01-R has a moderately low $q_{IR} = 1.8 \pm 0.4$ (which is the logarithmic ratio of $L_{IR}$ and the rest-frame 1.4GHz flux density), compared with the mean value for HerMES sources ($q_{IR} = 2.40 \pm 0.12$; Ivison et al. 2010b). This may indicate a hidden, radio emitting AGN, but from our SED analysis in Section 4, we have shown that if HLock01-R harbors an AGN, its contribution to the total $L_{IR}$ and SFR is modest ($\lesssim 1\%$), as also noted by Rigopoulou et al. (2018), and even assuming a maximum of 20% of an AGN contribution to the IRAC fluxes, the stellar mass of HLock01-R will be lower only by 0.1 dex, which is within our measurement errors. Moreover, Hayward & Smith (2015) have also shown that the physical properties derived using MAGPHYS are robust even when the AGN contributes 25% of the total UV to IR luminosity. Our deep GTC/OSIRIS rest-frame UV spectroscopy does not show any line or continuum emission at the positions of the lensed images of HLock01-R, as some of them are included in the regions covered by our long-slit spectra (see Figure 1, left panel). However, follow-up observations are required to constrain the presence of an AGN in HLock01-R. Nevertheless, even assuming a small AGN contribution, our results show that HLock01-R has already formed the majority of its stellar content, with a gas mass fraction of $f_{gas} = M_{gas}/M_* = 0.07 \pm 0.02$ (for $M_{gas} = 3.3 \times 10^{10} M_{\odot}$, as measured in Riechers et al. 2011), a specific star formation rate $sSFR = M_{star} / M_* = 2.76_{-0.85}^{+2.22} \text{ Gyr}^{-1}$, and a depletion time scale ($\tau_{d} = M_{gas}/sSFR$) of only 22 Myr (assuming no gas input). Moreover, it is plausible that additional gas input from the ongoing merger and inflows of material from a substantial gas reservoir in the halo will extend the starburst phase of HLock01-R for a prolonged time, becoming an even more massive elliptical galaxy in the local Universe.

On the other hand, HLock01-B appears to be a young, lower-stellar mass galaxy with very different properties than HLock01-R. In the optical, it is one of the brightest gravitationally lensed high-$z$ star-forming galaxies known so far (e.g., Yee et al. 1996; Allam et al. 2007; Belokurov et al. 2007; Smail et al. 2007; Lin et al. 2009; Wuyts et al. 2010; Bayliss et al. 2011; Dahlé et al. 2016; Marques-Chaves et al. 2017), with an apparent total magnitude of $R = 19.73 \pm 0.01$. Even after accounting for the magnification produced by the lensing group of galaxies ($\mu_{HST} = 8.5 \pm 0.5$), it is still very luminous in the rest-frame UV with an absolute magnitude $M_{UV} = -23.4$, two and a half magnitudes more luminous than typical LBGs ($L_{UV}$) at a similar redshift (Reddy & Steidel 2009). The stellar mass and SFR derived in Section 4 yield a specific star formation rate of 55 Gyr$^{-1}$ well above the main sequence at that redshift (e.g., Mannucci et al. 2009; Magdis et al. 2010a; Álvarez-Márquez et al. 2016). The nature and properties of this kind of UV ultra-luminous galaxies (i.e., $M_{UV} \lesssim -23$) are still poorly understood, given the lack of examples reported in the literature (e.g., Allam et al. 2007; Bian et al. 2012; Le Fèvre et al. 2013; Ono et al. 2017; Marques-Chaves et al. 2017). This is due in part to the fact that this kind of galaxy is extremely rare, and finding them requires wider-field surveys with deep, multi-band observations. The high UV luminosities also place these sources in the transition between luminous galaxies and faint AGNs, needing either extensive multi-wavelength imaging (e.g., X-ray, mid-IR, and radio) or spectroscopic follow-up. However, we stress that the unusual kinematics of the ISM and its high UV luminosity and SFR are not representative of the $z \sim 3$ LBG population. Our results suggest that the gravitational interaction with the massive SMG may have triggered the larger UV luminosity and SFR. The interaction may also be the origin of the large obscured SFR and far-IR luminosity in the SMG. Despite this, HLock01-B shares many of its properties with the population of $z \sim 3$ LBGs. Its UV colors, $(G - R) \approx 0.5$, and $(U - G) \approx 1.4$, are consistent with the standard color selection criteria of $z \sim 3$ LBGs (Steidel et al. 1996, 2003). However, HLock01-B presents $(R - K) = 0.29 \pm 0.07$, bluer than typical $z \sim 3$ LBGs ($R - K \approx 1.0$; Shapley et al. 2001) and Ly$\alpha$ emitting galaxies ($R - K \approx 0.4$; Ono et al. 2010).

Table 5 summarizes the main physical properties of both
components of HLock01.

<table>
<thead>
<tr>
<th>Table 5. De-magnified Physical Properties of HLock01.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
</tr>
<tr>
<td>z</td>
</tr>
<tr>
<td>$M_*$</td>
</tr>
<tr>
<td>Age</td>
</tr>
<tr>
<td>Av</td>
</tr>
<tr>
<td>SFR</td>
</tr>
<tr>
<td>sSFR</td>
</tr>
<tr>
<td>Z</td>
</tr>
</tbody>
</table>

6. SUMMARY AND CONCLUSIONS

We have presented a detailed study of HLock01, one of the first gravitational lensed sources discovered in the HerMES survey. Unlike other SMGs, HLock01 is apparently very bright in all observed spectral bands, even in the optical. It is magnified by a factor of around 9 by a galaxy group-scale dark matter halo at $z = 0.645$ and comprises four images in the observed plane. We have used OSIRIS on the GTC to secure a high S/N ($\gtrsim 30$) rest-frame UV spectrum of the optically bright lensed images of HLock01, with an intermediate-resolution ($\simeq 180$ km s$^{-1}$), covering the wavelength interval 1150 – 1950 Å in the rest-frame. From the analysis of these data together with other existing observations of HLock01, we arrive at the following main results.

1. We measured the systemic redshift of the optically bright lensed images of HLock01 (HLock01-B) $z_{\text{sys}} = 2.9546 \pm 0.0004$ using weak stellar photospheric lines. This value is offset by $-210$ km s$^{-1}$ from the redshift measured previously from the molecular gas lines $z_{\text{CO}} = 2.9574 \pm 0.0001$ associated with the luminous far-IR source of HLock01 (HLock01-R). Our results show that the dust-obscured, far-IR emitting source HLock01-R, and the optically bright source HLock01-B, are most likely different galaxies undergoing a close merger or an interacting pair separated by only 3.3 kpc in projection.

2. We find a stellar metallicity for the stars in HLock01-B $Z_{\text{stars}} \simeq 0.4Z_\odot$ based on two independent methods: blends of stellar photospheric lines; and P-Cygni profiles from the most luminous O and B stars. This value differs slightly from that measured for the gas in HLock01-R ($0.6 < Z_{\text{gas}}/Z_\odot < 1.0$), based on far-IR fine-structure line ratios. A young ($\gtrsim 6$ Myr) starburst model with a Salpeter IMF, stellar masses from 1 to 100 M$_\odot$, and an LMC/SMC metallicity explains well the properties of the high-ionization lines in HLock01-B.

3. The interstellar absorption lines in the spectrum of HLock01-B exhibit two distinct components. One is blueshifted by $-220$ km s$^{-1}$ relative to the stars of HLock01-B, which we associate with galaxy-scale outflows via stellar and supernovae driven winds. However, it also shows a broader profile (FWHM $\simeq 900$ km s$^{-1}$) than in most star-forming galaxies at $z = 2 – 3$, indicating highly turbulent kinematics of the outflowing gas likely due to the close merger. This component is stronger in high ionization lines, suggesting that the gas is mostly ionized or the neutral gas has a lower covering factor than the ionized gas.

Another absorption component is seen in the spectrum of HLock01-B, but is redshifted relative to either HLock01-B and HLock01-R by $+370$ and $+170$ km s$^{-1}$, respectively, which can be understood as gas moving towards both galaxies. We relate this component with the strong damped Ly$\alpha$ line seen in HLock01-B, with a column density of $N$(H I) = $5.83 \pm 1.24 \times 10^{20}$ cm$^{-2}$. Although with the available data we cannot arrive at a definitive conclusion on its nature and origin, we interpret this absorption feature as gas falling towards HLock01-R, which is more massive, with v $\simeq 170$ km s$^{-1}$, but viewed in absorption along a favorable line of sight towards HLock01-B. This component is detected in both low- and high-ionization interstellar lines, but with slightly different absorption line profiles, suggesting that the gas has a broad range of temperatures, and possibly different origin.

4. We detected an unusual absorption line in the red wing of the bright Ly$\alpha$ emission at $z \simeq 3.327$ at 14$''$ SW from the lensing galaxy G1, that we tentatively associate with C II $\lambda\lambda 1334$ at the redshift of HLock01-R. If this absorption is related with HLock01-R and not with an absorbing system at a different redshift, it indicates a substantial gas reservoir in the halo of HLock01 at a projected distance of 110 kpc. Additionally, we report a broad absorption line QSO at a projected distance of 2.5 Mpc from HLock01, with a redshift very close to HLock01-R ($\Delta v \simeq 300$ km s$^{-1}$).

5. Our revised SED fitting with two different galaxies, one very bright in the optical and the other in the far-IR, implies that both are physically very distinct. HLock01-B appears to be a young, lower-mass satellite galaxy of HLock01-R, undergoing an intense episode of star formation activity likely triggered by the interaction. HLock01-R shows an already evolved stellar population, and its high stellar mass in combination with the low gas fraction suggests that the SMG has already assembled most of its stellar mass. However, additional gas input from the satellite galaxy HLock01-B and from the reservoir of gas around HLock01-R may extend the starburst phase of the SMG, eventually forming one of the most massive galaxies in the local Universe.
We would like to thank the anonymous referee for their suggestion which significantly improved the clarity of this paper. We also thank Alice Shapley for allowing us to use their rest-frame UV composite spectrum of LBGs and Helmut Dannerbauer for useful discussions. Based on observations made with the Gran Telescopio Canarias (GTC) and with the William Herschel Telescope (WHT), both installed in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, on the island of La Palma. We thank the GTC and WHT staff for their help with the observations. R.M.C. acknowledges Fundación La Caixa for the financial support received in the form of a PhD contract. R.M.C., I.P.F., P.M.N., and C.J.A. acknowledge support from the Spanish Ministerio de Economía y Competitividad (MINECO) under grant number ESP2015-65597-C4-4-R. Y.S. has been partially supported by the 973 program (No. 2015CB857003) and the National Natural Science Foundation of China (NSFC) under grant numbers 11603032 and 11333008. J.L.W. gratefully acknowledges an STFC Ernest Rutherford Fellowship and additional support from the Spanish Ministerio de Economía y Competitividad (MINECO) under grant number ESP2015-65597-C4-4-R. Y.S. has been partially supported by the 973 program (No. 2015CB857003) and the National Natural Science Foundation of China (NSFC) under grant numbers 11603032 and 11333008. J.L.W. gratefully acknowledges an STFC Ernest Rutherford Fellowship and additional support from STFC (ST/P000541/1).

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**Facilities:** GTC (OSIRIS), HST (WFC3), WHT (LIRIS), Spitzer (IRAC), Herschel (SPIRE), SMA, VLA.

**APPENDIX**

**A. ENVIROMENT OF HLOCK01**

We serendipitously detected in two of our 1.2′′-wide GTC long-slit spectra (PA = −39°.5 and 44°) three strong, asymmetric lines that we interpret as Lyα emission at $z = 2.721 ± 0.001$, $z = 3.145 ± 0.001$, and $z = 3.327 ± 0.001$, at 2.37′, 4.35′, and 14′′ from the lensing galaxy G1, respectively. Figure A1 shows the profiles of the Lyα emission, as well as the coordinates and magnitudes of the associated objects seen in CFHT R-band data. In particular, the Lyα emission at $z = 3.327$ shows a broad profile (FWHM $\approx 1000$ km s$^{-1}$, after accounting for the instrumental broadening), and has an observed flux of $F_{\text{Ly}\alpha} = (1.38 \pm 0.2) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. A more detailed analysis of this object will be presented in Marques-Chaves et al. (in prep.), based on recent observations with GTC. We noticed that the red-wing of the Lyα emission shows an unusual and unresolved (FWHM < 180 km s$^{-1}$) absorption line at 5281.2 ± 0.9 Å (see Figure A1, bottom right corner), which is not related to this galaxy. This could be an absorption system at any lower redshift, but surprisingly it is consistent with C II λλ1334 absorption at $z = 2.9574 \pm 0.0008$, very close ($\Delta v = -8 \pm 76$ km s$^{-1}$) to the redshift of HLock01-R measured from the molecular gas ($\z_{\text{CO}} = 2.9574 \pm 0.0001$; Riechers et al. 2011; Scott et al. 2011). If this absorption is physically related with HLock01, it may suggest a substantial gas reservoir in its halo, at an impact parameter $b = 110$ kpc.

We also report on a $z = 2.961$ quasar, SDSS J105715.48+573324.3, at 5.5′ NW from HLock01 (see Figure A1 at the top right corner). This object was cataloged as a broad absorption line quasar (BAL QSO) by Trump et al. (2006) from the third edition of the Sloan Digital Sky Survey (SDSS: York et al. 2000) Quasar Catalog (Schneider et al. 2005). The redshift of this BAL QSO is very close to the one of HLock01-R ($\Delta v \approx 300$ km s$^{-1}$) and is located at a projected distance of 2.5 Mpc.

**B. BROAD-BAND PHOTOMETRY**

In addition to the photometry presented in Conley et al. (2011) and Wardlow et al. (2013), we also performed photometry on the new imaging data. These measurements are summarized in Table B1.
We use aperture photometry in the $U$ band from the corresponding CFHT/MEGACAM catalog, which contains detections of all four lensed images, since the light contamination from the red, lensing galaxies is negligible in $U$-band. For GTC $g$-band, we applied aperture photometry on the lensed images A, C, and D. We exclude photometry of the lensed image B, as it is strongly blended with the lens galaxy G4, but we use the lens model to correct for the omitted light from image B (a roughly 15% correction).

Despite the short exposure time of the $HST$ F110W data, faint emission is seen close to the radio and submm lensed images A and C (see Figure B2). $K$-band imaging from WHT/LIRIS and NIRCam/Keck-II (the latter discussed in Gavazzi et al. 2011; Calanog et al. 2014) also reveal faint emission at these positions. The red colors from the optical to 2.2$\mu$m imaging seen in Figure B2 (left panel) and Table B1 suggest that this faint emission corresponds to the obscured rest-frame UV and optical light of the Herschel SMG. Associating this faint emission to HLock01-R, we measure the flux in a small aperture (0.77$''$ diameter) at the position of the faint near-IR source detected close to the radio and submm lensed image C. For HLock01-B, we use larger
apertures (2″ − 3″) on the lensed images A, C, and D, and then subtract the contribution of HLock01-R, which in any case is less than 5%. The lens model was used again to add the light from the lensed image B.

Near-IR WHT/Ks photometry of the individual components (SMG and LBG of HLock01) was obtained after modeling the light distribution of each component in the lensed images A and C, using the two dimensional fitting program GALFIT (Peng et al. 2002, 2010). We use Sersic profiles centered at the centroids of the HST/F110W emission, allowing only one pixel freedom (≃ 0.254″). A nearby star was chosen as a point-spread function (PSF) model. Note that we only perform the fit in the lensed images A and C, the only ones that show detections of the faint, obscured counterparts of the SMG and LBG of HLock01. The lens model of Gavazzi et al. (2011) was used again to add the light from the lensed images B and C. Figure B2 shows our GALFIT model, as well as the resulting residuals after subtracting the Ks GALFIT model.

This field has been observed by the SWIRE survey (Lonsdale et al. 2003) in the cryogenic phase of Spitzer and to deeper levels in the two first bands of IRAC (3.6 and 4.5 μm) by the SERVS survey (Mauduit et al. 2012) in the post-cryogenic phase.

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Table B1. Photometry of HLock01.

<table>
<thead>
<tr>
<th>Telescope/Detector</th>
<th>λ (μm)</th>
<th>HLock01-B(^a) (LBG)</th>
<th>HLock01-R(^a) (SMG)</th>
<th>Units</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHT/MEGACAM (U)</td>
<td>0.38</td>
<td>8.2 ± 0.6</td>
<td>—</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>GTC/OSIRIS (g)</td>
<td>0.48</td>
<td>29.7 ± 0.8</td>
<td>—</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>INT/WFC (R)</td>
<td>0.63</td>
<td>46.5 ± 0.6</td>
<td>—</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>Subaru/SuprimeCam (I)</td>
<td>0.76</td>
<td>47.9 ± 0.04</td>
<td>—</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td><em>HST</em> /F110W</td>
<td>1.16</td>
<td>53.5 ± 2.5</td>
<td>2.3 ± 0.6</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>WHT/LIRIS (Ks)</td>
<td>2.20</td>
<td>60.8 ± 4.7</td>
<td>16.3 ± 3.8</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>Spitzer/IRAC (11)</td>
<td>3.6</td>
<td>74 ± 9</td>
<td>82 ± 9(^d)</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>Spitzer/IRAC (12)</td>
<td>4.5</td>
<td>75 ± 11(^c)</td>
<td>113 ± 11(^d)</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>Spitzer/IRAC (13)</td>
<td>5.8</td>
<td>76 ± 20(^c)</td>
<td>219 ± 20(^d)</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>Spitzer/IRAC (14)</td>
<td>8.0</td>
<td>63 ± 20(^c)</td>
<td>341 ± 20(^d)</td>
<td>μJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>Spitzer/MIPS</td>
<td>24</td>
<td>—</td>
<td>1.24 ± 0.02</td>
<td>mJy</td>
<td>Wardlow et al. (2013)</td>
</tr>
<tr>
<td>Spitzer/MIPS</td>
<td>72</td>
<td>—</td>
<td>16.1 ± 0.3</td>
<td>mJy</td>
<td>Wardlow et al. (2013)</td>
</tr>
<tr>
<td>Spitzer/MIPS</td>
<td>160</td>
<td>—</td>
<td>244.4 ± 1.4</td>
<td>mJy</td>
<td>Wardlow et al. (2013)</td>
</tr>
<tr>
<td>Herschel/SPIRE</td>
<td>250</td>
<td>—</td>
<td>403 ± 7</td>
<td>mJy</td>
<td>Wardlow et al. (2013)</td>
</tr>
<tr>
<td>Herschel/SPIRE</td>
<td>350</td>
<td>—</td>
<td>377 ± 10</td>
<td>mJy</td>
<td>Wardlow et al. (2013)</td>
</tr>
<tr>
<td>Herschel/SPIRE</td>
<td>510</td>
<td>—</td>
<td>249 ± 7</td>
<td>mJy</td>
<td>Wardlow et al. (2013)</td>
</tr>
<tr>
<td>SMA</td>
<td>880</td>
<td>—</td>
<td>52.8 ± 0.5</td>
<td>mJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>CSO/Z-Spec</td>
<td>1000 – 1100</td>
<td>—</td>
<td>27.5 ± 0.6</td>
<td>mJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>CSO/Z-Spec</td>
<td>1100 – 1200</td>
<td>—</td>
<td>20.4 ± 0.5</td>
<td>mJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>CSO/Z-Spec</td>
<td>1200 – 1300</td>
<td>—</td>
<td>16.2 ± 0.5</td>
<td>mJy</td>
<td>Conley et al. (2011)</td>
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<tr>
<td>CSO/Z-Spec</td>
<td>1300 – 1400</td>
<td>—</td>
<td>12.0 ± 0.5</td>
<td>mJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>CSO/Z-Spec</td>
<td>1400 – 1500</td>
<td>—</td>
<td>9.9 ± 0.6</td>
<td>mJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>CARMA</td>
<td>3400</td>
<td>—</td>
<td>0.61 ± 0.19</td>
<td>mJy</td>
<td>Conley et al. (2011)</td>
</tr>
<tr>
<td>VLA</td>
<td>214000</td>
<td>—</td>
<td>0.97 ± 0.05</td>
<td>mJy</td>
<td>Wardlow et al. (2013)</td>
</tr>
</tbody>
</table>

Notes.

\(^a\) Total flux densities of the four lensed components, uncorrected for lensing magnification.
\(^b\) Obtained by modeling the light profiles using GALFIT.
\(^c\) Expected Spitzer/IRAC fluxes of HLock01-B, extrapolated from the best fit SED using flux measurements from 0.38 to 2.20 μm (see Section 4).
\(^d\) Refers to the difference between the total flux densities measured in Appendix B (156, 188, 295, and 404 μJy for the Spitzer/IRAC bands I1, I2, I3, and I4, respectively) and the expected flux densities of HLock01-B from the best-fit SED.

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8 This can be explained through the lensed images A and C being less affected by foreground contamination and their lensing magnifications are higher than the ones of images B and D (see Gavazzi et al. 2011).
In the *Spitzer* Enhanced Imaging Products (SEIP) catalog\(^9\) of this area (based on the SWIRE data) the individual lensed images A and C are the only ones resolved and detected. However their fluxes appear relatively large and inconsistent ($f_A/f_C \lesssim 1$) with the expected values from the individual magnifications provided by the lens model of Gavazzi et al. (2011) ($f_A/f_C \simeq 1.7$). Given the limited spatial resolution of IRAC ($\simeq 2''$), the cataloged fluxes of the lensed images A and C are likely contaminated by foreground light, mainly due to the G1, G4, and G6 lensing galaxies. To perform better photometry on HLock01, we use GALFIT to model the light distribution of both foreground and background components in the SERVS images. We use Sérsic profiles centered at the positions of the detected *HST*/F110W counterparts, and a nearby star was chosen as a PSF model. We then measure the flux density of our best-fit model of the lensed images A and C, and use the lens model to add the expected light from the other lensed images to obtain the total observed flux. Modeling the light distribution using GALFIT to separate the fluxes from the SMG and the LBG does not help and will introduce significant uncertainties in their measurements, since the spatial separation of the SMG and the LBG in the lensed images A and C is substantially lower ($\simeq 0.9''$) than the intrinsic PSF in IRAC data ($\simeq 2''$ FWHM). Finally, in the 8.0 $\mu$m IRAC band the foreground light contamination appears to be much lower than in the other IRAC bands, thus we use the 3.8'' aperture photometry for the lensed images A and C provided in the SEIP catalog, with the appropriate aperture corrections. Again we use the lens model to add the expected light of the lensed images B and D.

C. LENS MODELING

We use the $\simeq 0.2''$ FWHM *HST*/F110W image data to update the lens model already described in Gavazzi et al. (2011). The procedure is identical and uses the dedicated code SL\_FIT (for more details see also: Gavazzi et al. 2007, 2008, 2011, 2012). We fit model parameters of simple analytical lensing potentials and model background galaxies as simple elliptical Sérsic profiles. The lensing potential is primarily constrained by the *HST* data, with the highest resolution and S/N. The mass distribution is then held fixed in order to fit for the parameters defining the light distribution in the other channels. We assume the deflector to be made of an isothermal elliptical mass distribution centered on the galaxy G1 and we also include the perturbing galaxies G2, G3 and G4 as point masses centered on the substructure light emission. We allow for the presence of a core radius that softens the inner mass distribution in each case. Unlike in Gavazzi et al. (2011) we do not place masses at G5 and G6, since they have a negligible impact on the mass model and their masses are essentially unconstrained. G1, being by far the most massive galaxy in the vicinity, is assumed to be at the center of the group-scale total mass distribution. The collective effect of a few possible perturbing galaxies 10-20'' South of G1 may induce some external shear, which will contribute to the quadrupole of the mass distribution, but having too few constraints spanning too small a radial range around G1, we assume that the ellipticity of the mass distribution centered on G1 will absorb the total quadrupole. Higher order effects (like $m = 1$ or $m = 3$ multipoles) would
also be hard to constrain with the current data.

The lensed features exhibiting a cross-like (or barely fold-like) configuration requires a source relatively close to the optical axis, and thus, relatively far for a widely opened main astroid caustic. We do not expect much magnification nor huge spatial variations of the magnification over the extent of the source. This contrasts with a cusp configuration (see e.g. the cluster MS 0451.6-0305 in MacKenzie et al. 2014).

Figure C3. Lens inversion results in several bands. Top to bottom: HST F110W; GTC g band; 880 μm SMA; PdBI CO (J = 5 → 4); and VLA 1.4GHz observations. From left to right: input image (foreground deflectors are preliminarily subtracted off for HST); reconstructed image plane model; residual of input − reconstructed image; and finally the source−plane reconstruction. All the images are centered on the lensing galaxy G1 (α = +10:57:50.959, δ = +57:30:25.66, J2000) and oriented such that north is up and east is to the left. At long wavelengths, the limited spatial resolution induces large fluctuations in the shown reconstructed maximum a posteriori sources (right panels), which can get very elongated (see Figure 7 for a comparison of more realistic posterior mean sources).
Modeling the HST F110W data first, we assume the background source is made of one single elliptical exponential profile for which we adjust source plane position, ellipticity, orientation, effective radius, and flux. Before fitting the lensed light emission, we performed a fit to the foreground light emission (i.e., G1 to G5) in order to subtract it off. The result is shown in the top row panels of Figure C3. The formal uncertainty on the recovered Einstein radius (i.e. lens amplitude) is unrealistically small (~0.2% relative), given the high signal-to-noise ratio of the widely extended lensed images. However, large-scale structure mass fluctuations along the line of sight, as well as unaccounted for substructures in the lensing mass distribution, should place a lower limit of order 1-2% on the accuracy to which the Einstein radius can be measured. By artificially increasing the pixel rms errors in the F110W imaging data by a factor of 10, we are able to mimic this additional source of noise. As a result, we achieve a one percent accuracy on the recovered Einstein radius as 4.08 ± 0.05, consistent with the previous model of Gavazzi et al. (2011). The core radius is found to be 1′′1 ± 0′′1, and the mass distribution is very elongated, with an axis ratio b/a = 0.38 ± 0.03. The mass of perturbing galaxies is poorly constrained: $M_{G2} = (6.0^{+4.4}_{-3.0}) \times 10^{10} M_\odot$, $M_{G3} \leq 4.4 \times 10^{10} M_\odot$, except the case of G4 which induces a splitting of one of the multiple images (B1-B2), yielding $M_{G4} = (9.1^{+6.0}_{-4.0}) \times 10^{10} M_\odot$. We find a total magnification $\mu = 8.5 \pm 0.5$ in the HST F110W band. The formal errors on magnification do not account for the mass-sheet degeneracy (related to a strong assumption about the mass density slope), which is responsible for the differences with the magnification we reported in Gavazzi et al. (2011). Channel-to-channel differential magnifications are, on the other hand, more robust and do not depend on the assumed mass distribution. From the best-fit mass model inferred from HST F110W data, we extract for the position, ellipticity, size, and flux of an exponential disk in the GTC, VLA, PdBI CO ($J = 5 \rightarrow 4$), and SMA continuum data. The output of the modeling in all the channels is shown in Figure C3. From top to bottom, each row represents the results of HST F110W, GTC g band, 880 μm SMA, PdBI CO ($J = 5 \rightarrow 4$), and VLA 1.4GHz observations. The overall aspect does not change much with respect to the model of Gavazzi et al. (2011). The geometry of the source at long wavelengths is poorly determined and the elongated shape of the best-fit sources in the lower panels is not significant.

REFERENCES
