AN INTENSELY STAR-FORMING GALAXY AT $z \sim 7$ WITH LOW DUST AND METAL CONTENT REVEALED BY DEEP ALMA AND HST OBSERVATIONS

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ABSTRACT

We report deep ALMA observations complemented with associated HST imaging for a luminous ($m_{\text{UV}} = 25$) galaxy, ‘Himiko’, at a redshift $z = 6.595$. The galaxy is remarkable for its high star formation rate, $100 M_\odot \text{yr}^{-1}$, securely estimated from our deep HST and Spitzer photometry, and the absence of any evidence for strong AGN activity or gravitational lensing magnification. Our ALMA observations probe an order of magnitude deeper than previous IRAM observations, yet fail to detect a $1.2 \mu m$ dust continuum, indicating a flux $< 52 \mu Jy$ comparable with or weaker than that of local dwarf irregulars with much lower star formation rates. We likewise provide a strong upper limit for the flux of [CII] $158 \mu m$, $L_{\text{[CII]}} < 5.4 \times 10^7 L_\odot$, a diagnostic of the hot interstellar gas often described as a valuable probe for early galaxies. In fact, our observations indicate Himiko lies off the local $L_{\text{[CII]}}$ - star formation rate scaling relation by a factor of more than 30. Both aspects of our ALMA observations suggest Himiko is an unique object with a very low dust content and perhaps nearly primordial interstellar gas. Our HST images provide unique insight into the morphology of this remarkable source, highlighting an extremely blue core of activity and two less extreme associated clumps. Himiko is undergoing a triple major merger event whose extensive ionized nebula of Lyman alpha emitting gas, discovered in our earlier work with Subaru, is powered by star formation and the dense circum-galactic gas. We are likely witnessing an early massive galaxy during a key period of its mass assembly close to the end of the reionization era.

Subject headings: galaxies: formation — galaxies: high-redshift — cosmology: observations

1. INTRODUCTION

Much progress has been achieved in recent years in charting the abundance and integrated properties of the earliest galaxies beyond a redshift of $z \approx 6$ selected via optical and near-infrared (NIR) photometry (e.g. Bouwens et al. 2010a, McLure et al. 2010, Castellano et al. 2010, Ouchi et al. 2010, Ellis et al. 2013, McLure et al. 2012, Schenker et al. 2012). The emerging picture indicates that the redshift $z < 10$ was a formative one in the assembly history of normal galaxies. Sources at $z \approx 7 - 8$ show moderately blue ultraviolet continua possibly consistent with young, metal-poor stellar populations with a star-formation rate (SFR) of $1 - 10 M_\odot \text{yr}^{-1}$ (e.g. Bouwens et al. 2010b, Finkelstein et al. 2010, Schaerer & de Barros 2010, Dunlop et al. 2012). Their small physical sizes ($\lesssim 0.7 \text{kpc}$; Oesch et al. 2010, Ono et al. 2013) and modest stellar masses ($10^9 - 10^{10} M_\odot$; Labbé et al. 2010) suggest they quickly merge into larger, more luminous systems. The abundance of sub-luminous, small galaxies at high redshift also indicates significant merging occurred at early times, given the faint-end slope of the UV luminosity function changes from a steep $\alpha \approx -1.9$ at $z = 7 - 8$ (Schenker et al. 2012, McLure et al. 2012) to $\alpha \approx -1.7$ at $z = 2 - 3$ (e.g. Reddy & Steidel 2009).

In practice it is hard to decipher the physical processes that govern the early assembly of galaxies from integrated properties alone. We therefore seek to complement statistical measures such as star formation rates and stellar masses by detailed evidence from well-studied individual examples. Likewise, our understanding of early cosmic history may be incomplete given so much is currently deduced from optical and near-infrared data alone (Robertson et al. 2013). Although optical and near-infrared selected sources at high redshift suggest they contain little or no dust (Bouwens et al. 2012, Dunlop et al. 2013), this may be a selection bias. Star formation obscured by dust cannot be quantified without identifying cold dust emission. Furthermore, the gas phase metallicity remains a key measurement for understanding early systems, most notably in locating the highly-prized pristine ‘first generation’ systems unpolluted by supernova enrichment. Neither optical nor near-
infrared facilities can currently address this important quest given the diagnostic metal lines used at lower redshift, such as [O\textsc{ii}]$\lambda\lambda3726,3729$Å and [O\textsc{iii}]$\lambda\lambda5007,4959$Å, cannot be measured beyond $z \approx 5$ until the launch of the James Web Space Telescope.

It is for this reason that state of the art sub-millimeter facilities such as the Atacama Large Millimeter Array (ALMA) offer enormous promise. First, they can quantify the possible bias in our current “optical” view of early galaxy formation by detecting the hidden cold dust in high redshift galaxies. Secondly, the CO/[C\textsc{ii}] 158μm features prominent in star forming regions in the local Universe offer a valuable tracer of metallicity at early times. Thus far, neither cold dust continuum nor these low-ionization tracers of metallicity have been observed beyond $z \sim 6$ (Vieira et al. 2013, Capak et al. 2011, Riechers et al. 2010, Coppin et al. 2010). Although a few QSOs have been observed at sub-mm wavelengths to $z \approx 6-7$ (Maiolino et al. 2002, Iono et al. 2006, Walter et al. 2009, Venemans et al. 2012, Willott et al. 2013, Wang et al. 2013), the presence of a powerful AGN undoubtedly complicates any understanding of the physical conditions in their host galaxies.

Detecting these important diagnostic signals of dust and metallicity from typical $z \approx 7$ galaxies is clearly a major observational challenge. Only upper limits on [C\textsc{ii}] and sub-mm continuum fluxes have been presented so far for the abundant population of Lyman break galaxies (LBGs) and Ly\textalpha emitters (LAEs) at $z \sim 7$. These limits have come from deep exposures with the Submillimetre Common-User Bolometer Array (SCUBA, Holland et al. 1999) facility on the James Clerk Maxwell Telescope and Plateau de Bure interferometric observations (e.g. Ouchi et al. 2009a, Walter et al. 2012, Kanekar et al. 2013). Very recently, one $z = 6.34$ source has been studied in this way following a comprehensive search for red objects in the Herschel HerMES blank field survey at $50-500μm$, Riechers et al. 2013. This source, HFLS3, has a very strong far-infrared continuum emission and prominent molecular/low-ionization lines. Its star formation rate, inferred from its far-infrared luminosity, is extremely high, 2900$M_\odot$ yr$^{-1}$. Clearly we need to understand the context of this remarkable object by observing other sources at a similar redshift.

The present work is concerned with undertaking such a study for an extraordinarily luminous star-forming galaxy which will hopefully complement the study of HFLS3 by Riechers et al. 2013, Ouchi et al. 2009a. reported the discovery of the star-forming galaxy at $z = 6.595$, ‘Himiko’ 11, with a Spitzer/IRAC counterpart. This source was identified from an extensive 1 deg$^2$ optical survey for $z \approx 6.6$ galaxies in the UKIDSS/UDS field conducted with the Subaru telescope. This redshift was subsequently confirmed spectroscopically using Keck/DEIMOS. The unique features of this remarkable source are evident in comparison to the total sample of 207 galaxies at $z = 6.6$ found in the panoramic Subaru survey. Not only is Himiko by far the most luminous example ($M_{145} = 25$; $L(\text{Ly}\alpha) = 4 \times 10^{43}$ erg s$^{-1}$), but it is spatially extended in Ly\textalpha emission whose largest isophotal area is 5.22 arcsec$^2$, corresponding to a linear extent of over 17 kpc. The lower limit, $SFR > 34M_\odot$ yr$^{-1}$, is placed on the SFR of Himiko by the spectral energy distribution (SED) fitting analysis with the early photometric measurements and the stellar-synthesis and nebular-emission models (Ouchi et al. 2009a). Due to the large uncertainties of photometric measurements, Ouchi et al. 2009a cannot constrain $E(B-V)$, and provide only the lower limit of SFR with $E(B-V) \geq 0$.

The present paper is concerned with the analysis of uniquely deep ALMA and HST observations of this remarkable source. Given its intense luminosity and high star formation rate, the presumption is that it is being observed at a special time in its assembly history. We seek to use the cold dust continuum and [C\textsc{ii}] measures from ALMA to understand its dust content and gas phase metallicity. Likewise the matched resolution of HST will allow us to address its morphologic nature. By good fortune, one of the HST intermediate band filters closely matches the intense Lyman $\alpha$ emission observed for this source with Subaru. Ultimately, we then seek to understand the physical source of energy that powers the extensive Lyman $\alpha$ nebula.

A plan of the paper follows. We describe our ALMA and HST observations in §2 and present the detailed properties such as dust-continuum and metal-line emission, morphology, and stellar population in §3. We discuss the nature of this object in §4 and summarize our findings in §5. Throughout this paper, magnitudes are in the AB system. We adopt $(h,\Omega_m,\Omega_\Lambda,\sigma_8) = (0.7,0.3,0.7,1.0,0.8)$.

2. OBSERVATIONS AND MEASUREMENTS

2.1. ALMA

To understand whether obscured star-formation is an important issue as well as the metallicity of Himiko, a key source at high redshift, we carried out deep ALMA Band 6 observations in 2012 July 15, 18, 28, and 31 with 16 12m-antenna array under the the extended configuration of 36-400m baseline. The precipitable water vapor (PWV) ranged from 0.7 to 1.6 mm during the observations. We targeted Himiko’s [C\textsc{ii}] line of rest-frame 1900.54 GHz (157.74 μm) which is redshifted to 250.24 GHz (1.198mm) at a redshift of $z_{\text{Ly}\alpha} = 6.595$. Because a brighter dust continuum is expected at a higher frequency in the 1.2mm regime, we extended our upper sideband (USB) to the high-frequency side. Thus, we targeted the [C\textsc{ii}] line with the lowest spectral window (among 4 spectral windows) in the lower sideband (LSB) and set the central frequency of the 4 spectral windows are 250.24 and 252.11 GHz in LSB, and 265.90 and 268.04 GHz in USB. The two spectral windows and each sideband cover the frequency ranges contiguously. The total on-source integration time was 3.17 hours. We used 3c454.3 and J0423-013 for bandpass calibrators and J0217+017 for a phase calibrator. The absolute flux scale was established by observations of Neptune and Callisto. Our data were reduced with Common Astronomy Software Applications (CASA) package. We rebinned our data to a resolution of 166 MHz (200 km$^{-1}$). The FWHM beam size of the final image is $0''82 \times 0''.58$ with a position angle of 79°.5. The 1σ noise of continuum image is $\sigma_{\text{cont}} = 17.4 \mu$Jy beam$^{-1}$ over the the total bandwidth of 19.417 GHz whose 7.5 GHz is sampled. The 1σ noise of [C\textsc{ii}] line image is $\sigma_{\text{line}} = 83.3 \mu$Jy beam$^{-1}$ at 250.239 GHz over a channel

11 See Ouchi et al. (2009a) for the meaning of this name.
emission, UV continuum fluxes, and are free from contamination from Lyα. It fortuitously includes the spectroscopically-confirmed Lyα activity of 17 \( \mu \)Jy beam\(^{-1}\). We searched for a signal of \([\text{Cii}]\) for Himiko. We averaged fluxes over the two spectral windows of \(259.007-250.239\) GHz or 1.131-1.116mm in the range of frequency free from the \([\text{Cii}]\) line. Figure 1 presents the resulting ALMA continuum data at 259.01 GHz in frequency (or 1.167mm in wavelength) with a 1\( \sigma \) sensitivity of 17.4\( \mu \)Jy beam\(^{-1}\). There is a \(2\sigma\) flux peak in the beam size on the position of Himiko. However, there are a series of negative pixels nearby that correspond to the 2 – 3\( \sigma \) level per beam. We conclude therefore that Himiko remains undetected in the 1.2mm continuum with a 3\( \sigma \) upper limit is \(<\;52.1\mu Jy \;beam^{-1}\). We note that this sensitivity is two and one order(s) of magnitude better than those previously obtained by deep SCUBA/SHADES and IRAM/PdBI observations (Ouchi et al. 2009a; Walter et al. 2012). This clearly indicates Himiko has very weak millimeter emission. Table 1 summarizes the flux upper limits for the continuum and \([\text{Cii}]\) line derived from our ALMA data.

We averaged fluxes over the two spectral windows of LSB (249.30-253.05 GHz or 1.203-1.185mm) and USB (264.96-268.71 GHz or 1.131-1.116mm) in the range of frequency free from the \([\text{Cii}]\) line. Figure 1 presents the resulting ALMA continuum data at 259.01 GHz in frequency (or 1.167mm in wavelength) with a 1\( \sigma \) sensitivity of 17.4\( \mu \)Jy beam\(^{-1}\). There is a \(2\sigma\) flux peak in the beam size on the position of Himiko. However, there are a series of negative pixels nearby that correspond to the 2 – 3\( \sigma \) level per beam. We conclude therefore that Himiko remains undetected in the 1.2mm continuum with a 3\( \sigma \) upper limit is \(<\;52.1\mu Jy \;beam^{-1}\). We note that this sensitivity is two and one order(s) of magnitude better than those previously obtained by deep SCUBA/SHADES and IRAM/PdBI observations (Ouchi et al. 2009a; Walter et al. 2012). This clearly indicates Himiko has very weak millimeter emission. Table 1 summarizes the flux upper limits for the continuum and \([\text{Cii}]\) line derived from our ALMA data.

Further details of the ALMA observations and sensitivities are summarized in Table 1.

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2.2. HST

The primary goal of the associated HST observations of Himiko relate to the morphological nature of this remarkable source. We carried out deep HST/WFC3-IR broad-band (\(J_{125}\) and \(H_{160}\)\(12\)) thus maximizing the information content on its stellar content for SED fitting (\(33\)). The intermediate-band filter of \(F098M\) fortuitously includes the spectroscopically-confirmed Lyα line.

\(12\) \(J_{125}\) and \(H_{160}\) are referred to as \(F125W\) and \(F160W\), respectively, and medium-band (\(F098M\)) observations for Himiko. The two broad-band filters of \(J_{125}\) and \(H_{160}\) measure the rest-frame UV continuum fluxes, and are free from contamination from Lyα emission.

![Figure 1](image1.png)

**FIG. 1.**— ALMA continuum data for Himiko at 259 GHz (1.16mm). The gray scale indicates the intensity at each position where darker regions imply higher intensities. The black contours denote −3, −2, and −1\( \sigma \) levels, while yellow contours show +1, +2, and +3\( \sigma \) significance levels, where the \(1\sigma\) flux corresponds to 17.4\( \mu \)Jy beam\(^{-1}\). The white cross indicates the position of Himiko. The ellipse in the lower corner denotes the beam size.

![Figure 2](image2.png)

**FIG. 2.**— As Figure 1 but for \([\text{Cii}]\) velocity channel maps of Himiko whose 1\( \sigma \) intensity is 83.3\( \mu \)Jy beam\(^{-1}\). The six panels present maps of 200 km s\(^{-1}\) width at central velocities of −600, −400, −200, 0, +200, and +400 km s\(^{-1}\) from the top left to the bottom right. 0 km s\(^{-1}\) corresponds to \([\text{Cii}]\) emission at the redshift \(z_{\text{Ly}α} = 6.595\), i.e. 250.24 GHz (1.198mm).
of Himiko at 9233Å (Ouchi et al. 2009a) with a system throughput of 40%, close to the peak throughput of this filter (∼45%). Thus, the F098M image is ideal for for mapping the distribution of Lyα emitting gas.

Our observations were conducted in 2010 September 9, 12, 15-16, 18, and 26 with an ORIENT of 275 degrees. Some observations were partially lost because HST went into ‘safe mode’ on 2010 September 9, 22:30 during the execution of one visit. The total integration times for usable imaging data are 15670.5, 13245.5, 18064.6 seconds for F098M, J125, and H160, respectively. The various WFC3 images were reduced with WFC3 and MULTIDRIZZLE packages on PyRAF. To optimize our analyses, in the multidrizzle processing we chose a final pixfrac= 0.5 and pixel scale of 0.′′05132. We degraded images of F098M and J125 to match the PSFs of these images with the one of H160 that has the largest size among the HST images. We ensured the final WFC3 images have a matched PSF size of 0′′.19 FWHM.

Figure 3 presents a color composite HST UV-contiuum image of Himiko, together with a large ionized Lyα cloud identified by the Subaru observations (Ouchi et al. 2009a). This image reveals that the system comprises 3 bright clumps of starlight surrounded by a vast Lyα nebula ≥ 17 kpc across. We denote the three clumps as A, B, and C. Figure 4 shows the HST, Subaru, and Spitzer images separately. The F098M image in Figure 4 detects only marginal extended Lyα emission, because of the shallower surface brightness limit of the 2.4m HST compared to the 8m Subaru telescope. Nevertheless, we have found a possible bright extended component at position D in Figure 4. We perform 0′′.4-diameter aperture photometry for the clumps A-C and location D as well as 2′′-diameter aperture photometry which we adopt as the total magnitude of the system. Tables 2 and 3 summarize the photometric properties. It should be noted that Himiko is not only identified as an LAE, but also would be regarded as a LBG or ‘dropout’ galaxy.

Using the optical photometry of Ouchi et al. (2009a) (see also Table 3), we find no blue continuum fluxes for the filters from B through i′ to the relevant detection limits of 28−29 mag. The very red color of i′ − z′ > 2.1 meets typical dropout selection criteria (e.g. Bouwens et al. 2011). Because the z′-band photometry includes the Lyα emission line and a Lyα-continuum break, we can also estimate the continuum-break color using our HST photometry of J125 and H160 and the optical i-band photometry.

Assuming the continuum spectrum is flat ($\nu F(\nu) = $const.), we obtain a continuum break color i′ − J125 > 3.0 or i′ − H160 > 3.0, further supporting that Himiko as a LBG. Importantly, these classifications apply also to the clumps A-C ruling out that some could be foreground sources.

The UV continuum magnitudes of clumps A-C range from 26.4 to 27.0 magnitudes in J125 and H160. Each clump has a UV luminosity corresponding to the characteristic luminosity $L^*$ of a z ~ 7 galaxy, m=26.8 mag (Ouchi et al. 2009a, Bouwens et al. 2011). Moreover, the variation in luminosity across the components is small; there is no single dominant point source in this system, confirming earlier deductions that the system does not contain an active nucleus.

The F098M image shows that Lyα emission is not uniformly distributed across the 3 clumps. Clump A shows intense Lyα emission with a rest-frame equivalent width ($EW_0$) of $68^{+13}_{-11}$Å placing it in the category of a Lyman alpha Emitter (LAE), whereas clumps B and C are have emission more typical of Lyman break galaxies (LBGs) with a rest-frame Lyα equivalent width ($EW_0$) less than
20 Å given the measurement uncertainties.

In summary, the HST and Subaru data indicates Himiko is a triple \( L^* \) galaxy system comprising one LAE and two LBGs surrounded by an extensive 17 kpc diffuse \( {\rm Ly}_\alpha \) halo. Importantly, from the above morphological studies, the possibility that Himiko is gravitational lensed by a foreground concentration can be readily eliminated. Already, Ouchi et al. (2009a) made a strong case against lensing given the Keck spectroscopy revealed a velocity gradient of 60 km s\(^{-1}\) across the system. We can further reject this supposition given there are clear asymmetries in the outermost images (one has strong \( {\rm Ly}_\alpha \) emission and the other does not).

2.3. Spitzer

Although Spitzer cannot match the resolution of the above morphological data, we use the very deep Spitzer/IRAC SEDS data reaching 26 mag at the 3\( \sigma \) level (Ashby et al. 2013) to investigate the counterpart of the overall Himiko system at 3.6\( \mu \)m and 4.5\( \mu \)m bands. To improve the relative astrometric accuracy, we have re-aligned the SEDS images to the HST images, referring bright stellar objects commonly detected in the Spitzer and HST images. The relative astrometric errors are estimated to be \( \approx 0.1' \). We obtain total magnitudes of Spitzer/IRAC images from a 3\( '' \)-diameter aperture and use an aperture correction given in Yan et al. (2005). The total magnitudes are 23.69 \pm 0.09 mag and 24.28 \pm 0.19 mag at 3.6\( \mu \)m and 4.5\( \mu \)m bands, respectively. Because the Spitzer/IRAC 5.8\( \mu \)m and 8.0\( \mu \)m and Spitzer/MIPS 24\( \mu \)m band images are not available in the SEDS data set, we use the relatively shallow Spitzer/SpUDS data. Table 3 summarizes these total magnitudes and fluxes.

3. RESULTS

Ouchi et al. (2009a) found that Himiko has a high SFR (\( > 34 M_{\odot}yr^{-1} \)) and derived a moderately high stellar mass (\( 0.5 - 5.0 \times 10^{10}M_{\odot} \)) from the Subaru photometry and shallow Spitzer/SpUDS data. Here, we attempt to improve upon these estimates and, for the first time, secure information on dust content and interstellar medium (ISM) metallicity.

3.1. Far Infrared SED

We investigate obscured star-formation and dust properties of Himiko from its far-infrared (FIR) SED using the newly available ALMA 1.2mm continuum data. The SED from the optical to millimeter wavelengths is shown in Figure 5 together with that of various local starburst templates. The figure demonstrates that Himiko’s millimeter flux is significantly weaker than that of dusty
starbursts in the local universe such as Arp220 and M82, as well as the spiral galaxy NGC6946; it is more comparable to those of dwarf galaxies of much lower mass. Similarly, Himiko’s rest-frame optical flux derived from Ouchi et al. (2009). The open diamond with an arrow shows the upper limit from our deep HST photometry. Cross and plus symbols denote HST/WFC3 F098m and Suprime-Cam NB921 photometry that includes Lyα emission and Gunn-Peterson trough in their bandpasses. Open circles and arrows are data points and the upper limits taken from Ouchi et al. (2009). The open diamond with an arrow shows the upper limit from the IRAM observations (Walter et al. 2012). Red, magenta, green, and blue lines represent the SEDs of local galaxies, Arp220, M82, M51, and NGC6946 (Silva et al. 1998), respectively, redshifted to z = 6.595. SEDs of local dwarf irregular galaxies similarly redshifted are presented with cyan lines (Dale et al. 2009). All local galaxy SEDs are normalized in the rest-frame UV, where Himiko’s SED is determined reliably.

We can estimate a far-infrared luminosity of Himiko from our 1.2mm continuum limit. Assuming an optically thin graybody of modified blackbody radiation with a dust emissivity power-law spectral index of $\beta_d = 1.5$ and a dust temperature of $T_d = 40K$ (Eales et al. 1989; Klaas et al. 1997), we obtain a $3\sigma$ upper limit of $L_{\text{FIR}} < 8.0 \times 10^{10}L_\odot$ integrated over 8–1000µm. We also estimate $3\sigma$ upper limits of $< 7.4 \times 10^{10}$ and $< 6.1 \times 10^{10}L_\odot$ at 40 – 500µm and 42.5 – 122.5µm, respectively. Note that these upper limits depend upon the assumed dust temperature and $\beta_d$. For $T_d = 25K$ and $T_d = 60K$, the $3\sigma$ upper limit luminosities in 8–1000µm are $< 2.7 \times 10^{10}$ and $< 3.0 \times 10^{11}L_\odot$, respectively. Similarly, for $\beta_d = 0$ and $\beta_d = 2$, the $3\sigma$ upper limit luminosities in 8–1000µm are $< 3.5 \times 10^{10}$ and $< 1.2 \times 10^{11}L_\odot$, respectively.

The foregoing upper luminosity limits do depend somewhat on dust temperature and spectral index. Based on the Herschel measurements, Lee et al. (2012) find that the average dust temperature is $\sim 30 K$ under $\beta_d = 1.5$ for a relatively high redshift ($z \sim 4$) LBGs with a luminosity of $L > 2L^*$ comparable to Himiko. In the local universe, the median dust temperatures are 33 K, 30 K, and 36 K, for E/S0, Sb-Sbc, and infrared bright galaxies, respectively. (Sauvage & Thuan 1994; Young et al. 1989). Recent numerical simulations have claimed that LAEs may have a relatively high dust temperature, due to the proximity of dust to star-forming regions. However, even in this case the maximum temperature reaches only $T_d \sim 40 K$ (Yajima et al. 2012a). On the other hand Himiko’s dust must be heated to some lower limit by the cosmic microwave background (CMB) whose blackbody temperature scales as $T_{\text{CMB}}(1+z)$, where $T_{\text{CMB}} = 2.73 K$. Assuming local thermal equilibrium between ISM of Himiko and CMB at $z = 6.595$ (da Cunha et al. 2013), this yields a lower limit of $T_d \approx 21K$. Thus, it is appropriate to consider a range of $T_d \sim 20 – 40 K$ with $\beta_d \approx 1.5$. Because the larger assumed dust temperature $T_d = 40 K$ with $\beta_d = 1.5$ provides a weaker upper limit, we adopt a conservative $3\sigma$ upper limit of $L_{\text{FIR}} < 8.0 \times 10^{10}L_\odot$ (8 – 1000µm). Tables 1 and 3 present the $3\sigma$ upper limit of luminosity.

### 3.2. ISM metallicity from [Cii] Emission

We now turn to estimating the metallicity of the ISM of Himiko using with [Cii] emission as a valuable tracer in star-forming regions. Despite our significant integration, no line is seen. Figure 5 and Table 3 presents the upper limit to the [Cii] luminosity in the context of the correla-
tion with the star formation rate (SFR) (de Looze et al. 2011). In the case of Himiko, the SFR was obtained by SED fitting of the rest-frame UV to optical data including a correction for dust extinction (Section 3.3). Himiko clearly departs significantly from the scaling relation; the deficit amounts to a factor $\simeq 30$. Given the SFRs of de Looze et al. (2011) for local galaxies are derived in a similar manner to that for Himiko, including contributions from dust-free and dusty starbursts with GALEX’s UV and Spitzer’s infrared fluxes, respectively, it seems difficult to believe this deficiency arises from some form of bias arising from comparing different populations.

Graci´a-Carpio et al. (2011) and Diaz-Santos et al. (2013) present $L_{[CII]}/L_{\text{FIR}}$ ratios for local starbursts that depend on $L_{\text{FIR}}$ and the FIR and mid-IR surface brightnesses. As a result, Diaz-Santos et al. (2013) argue that $L_{[CII]}$ may not represent a particularly reliable indicator of SFR. However, FIR and mid-IR luminosities only trace dusty starbursts and typically exclude dust-free measures such as the UV luminosity. Because galaxies with fainter FIR/mid-IR luminosities have a larger ratio of $L_{[CII]}/L_{\text{FIR}}$ in the datasets probed by Graci´a-Carpio et al. (2011) and Diaz-Santos et al. (2013), more dust-free star-formation is expected in such systems. In this sense, the analysis of de Looze et al. (2011) is perhaps more relevant as a prediction of what to expect for Himiko. Nonetheless, given the importance of using $L_{[CII]}$ as a possible tracer and the discussion that follows below, independent studies of $L_{[CII]}$ as a function of UV luminosity and $L_{\text{FIR}}$ would be desirable.

Figure 6 also shows that HFLS3 at $z = 6.3$ (Riechers et al. 2013) follows the local scaling relation. However, it should be noted that the SFR of HFLS3 is derived from the far-infrared luminosity and thus any contribution from dust-free star-formation would be missing. In this sense, the SFR is possibly a lower limit, in which case HFLS3 may also depart somewhat from the local relation.

The absence of [CII] emission in Himiko is perhaps the most surprising result from our ALMA campaign. The emission line is often assumed to be the most robust far-IR tracer of star formation in high redshift galaxies, such that it may replace optical lines such as Ly$\alpha$ in securing spectroscopic redshifts in the reionization era. Our failure to detect this line in one of the most spectacular $z \simeq 7$ galaxies has significant implications which we discuss in Section 4.

### 3.3. Improved Physical Properties from the Near-Infrared SED

Although some constraints on the integrated properties of Himiko were derived in our earlier work (Ouchi et al. 2009a), no $E(B-V)$ estimate and only the lower limit of SFR with $E(B-V) \geq 0$ were obtained, due to the large uncertainties of photometric measurements. We now refine these estimates based on our significantly deeper HST and Spitzer data. Our near-IR SED is taken using total magnitudes from the HST images (§2.3), the Spitzer/IRAC SED images (§2.5) and JHK DR8 data from the UKIDSS/UDS survey. We tabulate these total magnitudes in Table 3 including ground-based optical data previously given in Ouchi et al. (2009a).

We present the SED of Himiko in Figure 7 and undertake $\chi^2$ fitting of a range of stellar synthesis models in the same manner as Ono et al. (2010b) using the stellar synthesis models of Bruzual & Charlot (2003) with dust attenuation formulae given by Calzetti et al. (2000). We adopt Salpeter initial mass function (IMF; Salpeter 1955) with lower and upper mass cutoffs of 0.1 and 100 $M_\odot$, respectively. Applying models of constant and exponentially-decaying star-formation histories with metallicities ranging from $Z = 0.02$ – 1.0 $Z_\odot$, we search for the best-fit model in a parameter space of $E(B-V) = 0$ and age $= 1$ – 810 Myr (where the latter upper limit corresponds to the cosmic age at $z = 6.595$). Nebular continuum and line emission, estimated from the ionizing photons from young stars, are optionally included following the metallicity-dependent prescriptions presented in Schaerer & de Barros (2009; Ono et al. 2010b).

For a constant star-formation rate history with no nebular emission and a fixed metallicity of $Z = 0.2 Z_\odot$, we find our best-fit model has a stellar mass of $M_* = 3.6_{-0.6}^{+0.4} \times 10^{10} M_\odot$, a stellar age of $3.6_{-0.4}^{+0.4} \times 10^8$ yr, a SFR of $9.2_{-2.2}^{+2.2} M_\odot$ yr$^{-1}$, and extinction of $E(B-V) = 0.15$ with a reduced $\chi^2$ of 3.1. This is a significant improvement over our much weaker earlier constraints which did not have the benefit of the HST/WFC3 or Spitzer/SEDS data (Ouchi et al. 2009a). The new infrared data provide a critical role in determining the Balmer break thereby resolving the degeneracy between extinction and age. On the other hand, the fit itself is not very satisfactory. The reduced $\chi^2$ is large and there is a significant discrepancy at 3.6$\mu$m. Since the 3.6$\mu$m and 4.5$\mu$m bands sample the strong nebular lines of H$\beta$+[OIII] and H$\alpha$, respectively, at $z = 6.595$, this encourages us to include nebular emission in our fitting procedure. In fact, in Figure 4 we note the IRAC 4.5$\mu$m emission shows a positional offset with respect to that at 3.6$\mu$m suggesting the possibility of contamination by nebular emission.

Adding nebular emission to the stellar SED models given above, the best fit has a more satisfactory reduced $\chi^2 = 1.6$, and we derive a reduced stellar mass of $M_* =$

### Table 4

**Stellar Population of Himiko**

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_*$</th>
<th>$E(B-V)_*$</th>
<th>Age</th>
<th>SFR</th>
<th>sSFR</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
</tr>
<tr>
<td>stellar+nebular</td>
<td>$1.5_{-0.2}^{+0.2} \times 10^{10}$</td>
<td>0.15*</td>
<td>182$^{+22}_{-20}$</td>
<td>100 $\pm$ 2</td>
<td>6.7 $\pm$ 0.9 $\times 10^{-9}$</td>
<td>1.55</td>
</tr>
<tr>
<td>pure stellar</td>
<td>$3.0_{-0.4}^{+0.4} \times 10^{10}$</td>
<td>0.15*</td>
<td>363$^{+144}_{-75}$</td>
<td>98 $\pm$ 2</td>
<td>3.3 $\pm$ 0.5 $\times 10^{-9}$</td>
<td>3.13</td>
</tr>
</tbody>
</table>


The uncertainty of color excess is smaller than our model-parameter grid of $E(B-V) = 0.01$.
1.5$^{+0.2}_{-0.2}$×10$^{10}$M$_\odot$, a younger stellar age of 1.8$^{+0.2}_{-0.2}$×10$^{8}$yr, but similar values for the SFR of 100$^{+1.2}_{-1.2}$M$_\odot$yr$^{-1}$ and extinction of E(B−V) = 0.15. Table 4 summarizes the results of our SED fitting with the pure stellar and stellar+nebular models. In the stellar+nebular models, we assume that all ionizing photons lead to nebular emission lines corresponding to an escape fraction fesc=0. If we allow fesc to be a free parameter, following Ono et al. (2012) we find no change from the model above (i.e. fesc=0) and formally establish that fesc < 0.2. Labbé et al. (2010) and Finkelstein et al. (2010) have suggested from their pure stellar models that HST z = 7 − 8 dropout galaxies have modest stellar masses (10$^8$−10$^9$M$_\odot$) and are quite young (30 − 300Myr), in contrast with Himiko’s stellar mass (M_* ≃ 3.0 × 10$^{10}$M$_\odot$) and age (360Myr) estimated with our pure stellar models. Of course, Himiko is more massive and energetic than typical LBGs seen in the small area of Hubble Ultra Deep Field. Its most notable feature is its high specific star-formation rate, sSFR ≃ 3.3 × 10$^{-9}$−10$^{-8}$ yr$^{-1}$, for the pure stellar and stellar+nebular cases, respectively. Even though the stellar masses are very different, Himiko, SMGs and LBGs at z = 3 share comparable sSFRs $\sim$10$^{-9}$−10$^{-8}$ yr$^{-1}$ (see Figure 12 of Ono et al. 2010a).

3.4. UV Spectral Slopes on the Spatially Resolved Images

![Fig. 7.— The optical to near-infrared SED of Himiko newly obtained by our deep HST and Spitzer observations, together with photometry from ground-based observations. The red lines represent the best-fit SEDs of stellar synthesis models with (left) and without (right) nebular lines (see Ono et al. 2010 for detailed model descriptions). The filled squares denote HST and Spitzer/SEDS fluxes of Himiko defined by the total magnitudes. The open squares show z-band fluxes that are not used for the SED fitting, due to the Lyα line contamination. The large error bars at ≤ 0.8μm and > 5μm are those obtained by Subaru and Spitzer/SpUDS observations given by Ouchi et al. (2009a). The red crosses represent the broadband fluxes expected from the best-fit SED models. For various assumptions the fits indicate that Himiko has a SFR of 100M$_\odot$ yr$^{-1}$, stellar mass of 2 × 10$^{10}$M$_\odot$, and a selective extinction of E(B−V) = 0.15 (see text for details).](image1)

![Fig. 8.— The UV to FIR luminosity ratio, log(L_{FIR}/L_{1600}), as a function of the UV-continuum slope, β. The filled square presents the upper limit of log(L_{FIR}/L_{1600}) and the measurement of β for the total luminosities of Himiko. Solid line denotes the relation for local starburts given by Meurer et al. (1999). The new HST data gives us the first reliable measurement of the UV continuum slope for each of the morphological components identified in Figure 4. The UV spectral slope provides a valuable indicator of the combination of dust extinction, metallicity, the upper IMF and stellar age. We estimated the UV slope, β, from the J125 and H160 photometry that samples the continua at the rest-frame wavelengths of ∼ 1600 and ∼ 2100Å neither of which is contaminated by either Lyα emission nor the Lyα-continuum break. We calculate β via

$$β = -\frac{J_{125} − H_{160}}{2.5 \log (λ_1/λ_2)} = 2.\tag{1}$$

where λ_1 and λ_2 are the central wavelengths of the J125 and H160 filters, respectively. The estimates for each component are summarized in Table 2. We obtain β = −2.00 ± 0.57 for the entire system of Himiko, comparable to the average UV slope of ≃ L* LBGs, β = −2.00 ± 0.22 (Bouwens et al. 2012, see also Dunlop et al. 2013). Figure 8 shows the UV to FIR luminosity ratio, log(L_{FIR}/L_{1600}), and the UV-continuum slope, β, for the entire system of Himiko, and compares these estimates with the relation of local starburts (Meurer et al. 1999). Figure 8 indicates that Himiko has log(L_{FIR}/L_{1600})-β values comparable with or smaller than those of local dust-poor starbursts. Since the Small Magellanic Cloud (SMC) extinction has a smaller log(L_{FIR}/L_{1600}) value at a given β (see Figure 10 of Reddy et al. 2010) due to SMC’s steeper extinction curve in Aλ/Av=1/λ than that for local starbursts, it may be more appropriate for Himiko. Our result also suggests that Himiko is not associated with additional FIR sources which are invisible in the rest-frame UV. These implications are consistent with the conclusions of UV-FIR luminosity ratio discussed in Figure 5.](image2)
from the relation given in Ono et al. (2010a) under the formation rate relations of UV and Lyα (2012) claim that selection and photometric biases lead and C, respectively. Blue, cyan, green, and red solid lines represent measures for the entire system, Clumps A, B, and C, respectively. Thin lines are the same, but for constant star-formation models. The associated dotted lines show the effect of ignoring nebular emission. The arrow indicates the effect of applying an extinction with $E(B-V)_s = 0.1$ (see the text for details).

More interestingly, the UV slopes of the individual substructures provide valuable information on the nature of Himiko. Clumps B and C have $\beta = -2.04 \pm 0.47$ and $\beta = -2.22 \pm 0.28$, respectively, comparable to the average UV slope of $\approx L^{*}$ LBGs. However, Clump A presents a very blue UV slope, $\beta = -2.84 \pm 0.32$. Because this component is detected at the $\approx 20\sigma$ level in both $J_{125}$ and $H_{160}$, the UV slope is quite reliable. Bouwens et al. (2012) claim that selection and photometric biases lead to an error of only $\Delta \beta \approx 0.1$ for the brightest of their sources with $\approx 20\sigma$ photometry (see also Dunlop et al. 2013). Even including such a possible bias, Clump A remains significantly bluer than the average $\approx L^{*}$ LBGs at the $\approx 2\sigma$ level.

As presented in Section 2.2 Clump A also shows Lyα emission. Together with the blue UV slope, this suggests a very young and/or metal poor component. However, the Lyα equivalent width is only $EW_{\alpha} = 68^{+14}_{-13}\alpha$. To understand the significance of this, in Figure 9 we compare $\beta$ and $EW_{\alpha}$ for the entire Himiko system and the various clumps with the stellar and nebular models of Raiter et al. (2010), where Salpeter IMF is assumed. In Figure 9 the arrow size in $\beta$ for the stellar extinction of $E(B-V)_s = 0.1$ is calculated with the combination of the empirical relation, $A_{1600} = 4.43 + 1.99\beta$ (Meurer et al. 1999), and Calzetti extinction, $A_{1600} = k_{1600}E(B-V)_s$, where $k_{1600}$ is 10 (Ouchi et al. 2004a). Similarly, the arrow size in $EW_{\alpha}$ for $E(B-V)_s = 0.1$ is estimated from the relation given in Ono et al. (2010a) under the assumption of $f_p$ flat continuum and the standard star-formation rate relations of UV and Lyα luminosities in the case B recombination. Figure 9 shows that the data points of Himiko fall on the tracks of star-formation photoionization models (Raiter et al. 2010) within the measurement errors and the dust-extinction correction uncertainties, and indicates that Lyα emission of Himiko can be explained by the photoionization by massive stars.

4. DISCUSSION

We now bring together our key results, both from the earlier Subaru program (Ouchi et al. 2009a) and the present HST and ALMA campaigns, in order to understand the significance of our upper limits on the [C II] and dust emission and thereby the nature of Himiko.

4.1. The Low Dust and Metal Content of Himiko

We have shown (Figure 5) that Himiko’s submm emission is comparable with or weaker than that of local dwarf irregulars with far lower star-formation rates, indicating intensive star-formation in a dust-poor gaseous environment. In fact, assuming the local starburst $SFR - L(FIR)$ relation of Kennicutt (1998) with the Himiko’s FIR upper limit luminosity of $< 8 \times 10^{10}L_{\odot}$, we obtain $SFR(FIR) < 14M_{\odot}yr^{-1}$ that is far smaller than not only our best optical-NIR estimate SFR of $\approx 100M_{\odot}yr^{-1}$, but also the UV-luminosity SFR of $SFR(UV) = 30 \pm 2M_{\odot}yr^{-1}$ with no dust extinction correction. This is also true under the assumption of the $SFR - L(FIR)$ relation (Buat & Xu 1996) valid for local dust poorer disk systems of Sb and later galaxies, which provide $SFR(FIR) < 25M_{\odot}yr^{-1}$. In this way, Himiko does not follow the $SFR - L(FIR)$ relation of typical local galaxies, indicating a dust-poor gaseous environment. This seems similar to observations which find extended Lyα emission in dust poor low-z galaxies (Hayes et al. 2013) and a high-z QSO (Willott et al. 2013). Based on numerical simulations, Daval et al. (2010) find that $z \sim 6 - 7$ LAEs are dust poor with a dust-to-gas mass ratio smaller than Milky Way by a factor of 20. Daval et al. (2010) predict a 1.4mm continuum flux of $\approx 50\mu Jy$ for sources with $L(Ly\alpha) = 2 - 3 \times 10^{43}$ erg s$^{-1}$ at $z = 6.6$, a result comparable with our ALMA observations. Deeper ALMA observations could further test the model of Daval et al. (2010) and place important constraints on the dust-to-gas mass ratio.

Similarly, our strong upper limit on the [CII] 158μm line (Figure 6) places it significantly below the scaling relation of $L_{[CII]}$ and SFR obeyed by lower redshift galaxies. This discovery indicates the following four possibilities: Himiko has a) a hard ionizing spectrum from an AGN, b) a very high density of photo-dissociation regions (PDRs), c) a low metallicity, and d) a large column density of dust. In the case of a), a hard ionizing spectrum of AGN can produce little [CII] luminosity relative to FIR luminosity, due to the intense ionization field (Stacey et al. 2010). As we discuss in (ii) of Section 4.2, there are no signatures of AGN: no detections of X-ray and high-ionization lines as well as extended sources plus non-AGN like Lyα profile+surface brightness. We can rule out the possibility of a). In the case of b), a very high density of PDRs gives more rapid collisional de-excitations for the forbidden line of [CII], and quench a [CII] emission line. In the case of c), the PDRs in Himiko are composed of metal poor gas that may be quite typical of normal galaxies observed at early epochs.
The ratio of [CII] luminosity to FIR luminosity as a function of FIR luminosity. The thick bar with the arrow presents the FIR upper limit for Himiko at the arbitrary position in the vertical axis, and the gray shaded region denotes the excluded range. The ratios for star-forming (SF) and AGN-dominated galaxies at $z = 1 - 2$ are shown with magenta and blue hexagons, respectively, while those of the intermediate SF+AGN population at $z = 1 - 2$ are represented with cyan hexagons (Stacey et al. 2010). Similarly, SF and AGN dominated galaxies at $z > 2$ are indicated by magenta pentagons and blue hexagons, respectively (Marsden et al. 2003; Maiolino et al. 2004, 2009; Iono et al. 2006; Pett et al. 2004; Ilison et al. 2010; Venemans et al. 2012). The black open diamond represents HFLS3 at $z = 6.3$ (Riechers et al. 2013). Black open and filled circles denote local normal galaxies (Malhotra et al. 2001) and ULIRGs (Maiolino et al. 2003 and references therein), respectively, together with well-known local galaxies of the LMC, M82, and Arp220.

De Looze (2012) has argued that offsets from the [CII]-SFR relation can be explained in terms of metal abundance and this would imply a gas-phase metallicity of $\lesssim 0.03Z_\odot$. Indeed, for our young stellar age of 160 – 410 Myr, standard ionization-photon bounded HII regions with a local chemical abundance would yield [CII] emission somewhat above the local scaling relation, due to the expected large PDRs. Moreover, the recent numerical simulations predict that a [CII] flux drops as metallicity decreases (Vallini et al. 2013). Vallini et al. (2013) claim that Himiko’s gas-phase metallicity is subsolar with their models and the previous IRAM [CII] upper limit. Comparing these numerical models with our strong ALMA upper limit of [CII] would place further constraints on metallicity of Himiko. In the case of d), the depth of C$^+$ zones in PDRs is determined by dust extinction. Since the C$^+$ zones extend over the dust extinction up to $A_v \lesssim 4$ (Malhotra et al. 2001), heavy dust extinction in ISM does not allow to make a large C$^+$ zones emitting [CII]. However, from no detection of 1.2 mm dust continuum discussed above, the heavy dust extinction narrowing the PDRs is unlikely. As dust extinction and gas phase metallicity generally correlate closely (Storchi-Bergmann et al. 1994; see also Finlator et al. 2006), the weak dust emission also suggests a very low metallicity gas. Thus, the case of c) is probably true, which contribute the weak [CII] emission. The case of b) could also help weakening the [CII] emission. To summarize, faint [CII] and weak dust emission can be explained in a self-consistent manner with a very low metallicity gas and little dust in a near-prrimordial system.

It is informative to compare the above conclusion with the only other well-studied galaxy at this redshift, HFLS3 at $z = 6.34$ (Riechers et al. 2013), recognizing that both it and Himiko were selected on the basis of their extreme properties. Figure 10 presents the ratio of [CII] to the FIR luminosity as a function of FIR luminosity. Although Himiko is significantly offset from the trend shown by AGN and local starbursts, this is not the case for HFLS3. Although Riechers et al. (2013) claim that HFLS3 is free from AGN activities on the basis of the level of excitation for CO and H$_2$O, its small [CII] to L$_{\text{FIR}}$ ratio of $L_{\text{[CII]}}/L_{\text{FIR}} = 5 \times 10^{-4}$ suggests otherwise (Stacey et al. 2011; Sargsyan et al. 2012). On the other hand, the recent study of Diaz-Santos et al. (2013) finds that a luminous infrared galaxy (LIRG) with compact star-forming regions show a smaller $L_{\text{[CII]}}/L_{\text{FIR}}$ value, and that a $L_{\text{[CII]}}/L_{\text{FIR}}$ value of pure star-forming LIRG drops by an order of magnitude, from $10^{-2}$ to $10^{-3}$. Thus, there is another possibility that HFLS3 could be a pure star-forming source more compact than those of local pure star-forming LIRGs.

4.2. Nature of Himiko

In considering the origin of Himiko’s extreme star formation rate and extensive Lyα halo, it is convenient to return to the various explanations originally proposed by Ouchi et al. (2009a) on the basis of the Subaru, UKIDSS, and shallow Spitzer data available at the time, taking into account the progress achieved with our new deep ALMA, HST, and Spitzer data.

(i) A Gravitationally-Lensed Source: Ouchi et al. (2009a) discounted this possibility on the basis of the resolved kinematics of the extended Lyα halo. In Section 2.2, we have strengthened the objections to this hypothesis since our HST data reveal three $L^*$ sources whose morphological asymmetries are not consistent with gravitational lensing. Moreover, we can find no potential foreground lens in the vicinity of Himiko (Ouchi et al. 2009a). Such a lens would have to be one of the three clumps revealed in the HST images, each of which has a 0.9μm-continuum break and blue UV continuum consistent with being physically associated at $z \approx 6.6$. Our deep IRAC data also show no potential lensing sources near Himiko, suggesting that there are no lensing objects with very red color, such as dusty starbursts at intermediate redshifts, invisible in the optical and NIR bands. Thus, we conclude that Himiko is not a gravitational lensed system.

(ii) Halo gas ionized by a hidden AGN: Our HST images do not reveal any obvious point source that could represent an active nucleus (Figure 2). Moreover, as noted by Ouchi et al. (2009a), Himiko is undetected at X-ray wavelengths of 0.5 – 2 keV down to $6 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, and the Keck optical spectrum does not reveal any high ionization features such as Nv. Recently, very deep VLT/X-Shooter NIR spectroscopy has found no high ionization lines including CIV/L1549.
as would be expected for a hard ionizing AGN source (Zabl et al. 2013 submitted to MNRAS). Finally, radiative transfer simulations by Baek & Ferrara (2013) show that the Lyα line profile and surface brightness of Himiko is inconsistent with heating from either a Compton-thick or Compton-thin AGN. Thus, we conclude the Lyα halo is unlikely to be heated by an active galactic nucleus.

(iii) Clouds of HII regions in a single virialized galaxy: Ouchi et al. (2009a) discussed the possibility that Himiko could be a single virialized system. Since the new HST data reveals three distinct UV luminous clumps each comparable to the characteristic luminosity $L^*$, we consider that Himiko is unlikely to be a single virialized system. Although there are many reports of disk galaxies with prominent clumps at $z \approx 2-3$ (e.g. Genzel et al. 2011), the absence of stellar disk (Figure 4) distinguishes Himiko from a single galaxy with clumpy structures such found at the lower redshifts.

(iv) Cold gas accretion onto a massive dark halo producing a central starburst:

Some theoretical studies have suggested that cold gas can efficiently penetrate into the central regions of a dark halo if that halo is more massive than the shock-heating scale of $\sim 4-7 \times 10^{11} M_\odot$ at $z > 4$ (Dekel et al. 2009; Ocvirk et al. 2008). Given Himiko’s stellar mass $(1.5-3 \times 10^{10} M_\odot)$, Section 3.3) and little or no evolution in the ratio of stellar mass, $M_*$, to halo mass inferred for $0 < z < 1$ ($M_* / M_{\text{DH}} \lesssim 0.05$, Leauthaud et al. 2012), we expect a halo mass of $M_{\text{DH}} \gtrsim 3-6 \times 10^{11} M_\odot$. Abundance matching considerations support this estimate. Ouchi et al. (2009a) calculated there should be at least one halo of mass $10^{12} M_\odot$ in the survey volume of $8 \times 10^5$ comoving Mpc$^3$ where Himiko was found (see also Behroozi et al. 2012).

Although Himiko’s halo mass does likely lie in the range where cold accretion could be possible, we note that some recent simulations have cast doubt on the efficiency of this mode of assembly (Nelson et al. 2013; Vogelsberger et al. 2013).

(v) Outflowing gas excited by shocks or UV radiation from starbursts and/or mergers:

The extensive Lyα nebula may be powered by star formation itself, but the gas could also be shock heated by strong outflows driven by multiple supernova explosions in an intensive starburst (Mori et al. 2004). Figure 9 shows the relation between the UV slope $\beta$ which characterizes the stellar population and the Lyα equivalent width $EW_{\alpha}$. This shows that the photoionization models of Raiter et al. (2010) whereby Lyα photons are scattered by the ISM and circum-galactic medium (CGM) can explain the properties of Himiko, notwithstanding the uncertainties in $\beta$. The success of this model depends, of course, on the escape fraction of ionizing photons which should be moderately low ($<50\%$) so that scattering is effective. However, the conclusion is robust even if we adopt a moderate dust extinction of $E(B-V)_* = 0.15$ (Section 3.3).

Thus, within the uncertainties, the amount of star formation observed is sufficient to power the extended Lyα nebula; outflow and shocks are not required. This simple photoionization scenario is consistent with the negligible hidden star-formation suggested by the weak dust and carbon emission from our ALMA observations. As discussed in Ouchi et al. (2009a), the FWHM of the Lyα line is only $v_{\text{FWHM}} = 251 \pm 21$ km s$^{-1}$, further indicating that powerful outflows are not present.

(vi) Merging bright galaxies:

Although not a separate hypothesis from (v) above, we can ask what triggers the intense star formation that likely powers the extended nebula. In Figure 4, we have identified three $L^*$ clumps which are highly suggestive of a rare triple merger. As Ouchi et al. (2009a) reported, Himiko presents a small velocity offset of Lyα emission across the nebula ($\Delta v = 60$ km s$^{-1}$) with a narrow line width ($v_{\text{FWHM}} = 251$ km s$^{-1}$; See Figure 7 of Ouchi et al. 2009a for the Lyα line velocities that are measured on the slit position shown with the red box in Figure 1 of Ouchi et al. 2009a). Thus, the merger would have to be largely confined to the direction perpendicular to the line of sight.

Although a triple major merger is a rare event, our data suggest that the explanation is the most plausible. Recent numerical simulations predict that some extended Lyα sources originate in mergers (Yajima et al. 2012b). One interesting feature of Himiko is that the brightest Lyα clump is very red ($9.1 \pm 0.3$), further indicating the blue Lyα clump A and Clump B. Given the discussion in (v) above, this indicates that Lyα photons are mainly produced by Clump A, a very young and metal poor component.

5. SUMMARY

We have taken deep ALMA and HST/WFC3-IR data and supplementary Spitzer SEDS photometry for the remarkably luminous star-forming galaxy, Himiko, at $z=6.595$ which has an extended Lyα nebula. at $z \approx 7$. Following the original discovery (Ouchi et al. 2009a), these new data provide valuable insight into its physical properties and thereby offer an unique perspective on how the earliest massive galaxies formed. We summarize our conclusions as follows:

1. The 1.2mm dust continuum flux from this star-forming galaxy is very weak, < 52$\mu$Jy, and comparable with or weaker than that observed for local dwarf irregulars with much lower star formation rates.

2. We find a surprisingly stringent upper limit to the flux of the [Cii] 158$\mu$m line, $L_{\text{[CII]}} < 5.4 \times 10^2 L_\odot$, placing it a factor $\sim$30 below expectations based on the scaling relation established between $L_{\text{[CII]}}$ and star formation rate for lower redshift galaxies. This indicates a very metal poor system and may imply the [C II] line will be a poor diagnostic of early $z > 7$ galaxies.

3. Our deeper HST+Spitzer photometry allows us to considerably refine the stellar population properties of Himiko. Using models with and without nebular lines, we infer a stellar mass of $1.5-3 \times 10^{10} M_\odot$ and a star formation rate of $\sim 100 \pm 2 M_\odot$ yr$^{-1}$, comparable with the properties of luminous LBGs at $z \approx 3$.

4. Our HST image has revealed three $L^*$ galaxy clumps which, together our earlier kinematic constraints, suggests a rare triple merger. One clump reveals intense Lyα emission and an extremely blue color continuum of $\beta = -2.84 \pm 0.32$ suggestive of metal-poor star-formation and an age of less than 200 Myr.

5. From these properties, we conclude we are witnessing
intense star formation induced by this triple merger and that the associated photoionizing radiation is sufficient to power the extensive Lya nebula.

Although a rare object, Himiko has offered the first coherent view of how the most massive galaxies started forming at a time close to the end of cosmic reionization at $z \sim 7$.

We are grateful to Pratika Dayal, Andrea Ferrara, Rob Kennicutt, Kyoungsoo Lee, Masao Mori, Dominik Richarders, Dimitra Rigopoulou, Daniel Schaerer, Masayuki Umemura, Fabian Walter, and Chris Willott for their useful comments and discussions. We thank the ALMA observatory and HST support staff for their invaluable help that made these pioneering observations possible. The HST reduction was supported by a NASA STScI grant GO 12205. This work was supported by World Premier International Research Initiative (WPI Initiative), MEXT, Japan, and KAKENHI (23244025) Grant-in-Aid for Scientific Research (A) through Japan Society for the Promotion of Science (JSPS). This paper makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.00115.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. This work is based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program #12265. Support for program #12265 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech.

Facilities: ALMA (Band6) HST (WFC3-IR) Spitzer (IRAC)

REFERENCES

Star-Forming Galaxy Unveiled with ALMA and HST