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EXTINCTION AND NEBULAR LINE PROPERTIES OF A HERSCHEL-SELECTED LENSED DUSTY STARBURST AT Z = 1.027

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ABSTRACT

We present Hubble Space Telescope (HST) WFC3 imaging and grism spectroscopy observations of the Herschel-selected gravitationally-lensed starburst galaxy HATLASJ1429-0028. The lensing system consists of an edge-on foreground disk galaxy at z = 0.218 with a nearly complete Einstein ring of the infrared luminous galaxy at z = 1.027. The WFC3 spectroscopy with G102 and G141 grisms, covering the wavelength range of 0.8 to 1.7 μm, resulted in detections of [NII], Hβ, [SII], and [OIII] for the background galaxy from which we measure line fluxes and ratios. The Balmer line ratio Hα/Hβ of 7.5 ± 4.4, when corrected for [NII], results in an extinction for the starburst galaxy of E(B − V) = 0.8 ± 0.5. The Hα based star-formation rate, when corrected for extinction, is 60 ± 50 M⊙ yr−1, lower than the instantaneous star-formation rate of 390 ± 80 M⊙ yr−1 from the total IR luminosity. We also compare the nebular line ratios of HATLASJ1429-0028 with other star-forming and sub-mm bright galaxies. The nebular line ratios are consistent with an intrinsic ultra-luminous infrared galaxy with no evidence for excitation by an active galactic nucleus (AGN). We estimate the metallicity, 12 + log(O/H) of HATLASJ1429-0028 to be 8.49 ± 0.16. Such a low value is below the average relations for stellar mass vs. metallicity of galaxies at z ∼ 1 for a galaxy with stellar mass of ~ 2 × 10^{11} M⊙. The combination of high stellar mass, lack of AGN indicators, low metallicity, and the high star-formation rate of HATLASJ1429-0028 suggest that this galaxy is currently undergoing a rapid formation.

Subject headings: cosmology: observations — submillimeter: galaxies — infrared: galaxies — galaxies: evolution

1. INTRODUCTION

Dusty star-bursting galaxies, especially those that are identified at far-IR/sub-mm wavelengths, have infrared luminosities LIR ∼ 10^{12} − 10^{13} L⊙, implying star-formation rates (SFRs) in excess of 200 M⊙ yr−1 (see review by [Casey, Narayanan, & Cooray 2014]). As a primary contributor to the cosmic far-IR background, a significant fraction of cosmic star formation and metal production could have occurred in these star-bursting galaxies. Due to deep and wide surveys with the Herschel Space Observatory [Pilbratt et al. 2010], we now have large samples of dusty, star-burst galaxies at z > 1. Despite large number statistics our knowledge on the physical processes within such galaxies is still limited.

Traditional studies at optical and IR wavelengths involving nebular lines to probe the interstellar medium (ISM) of these dusty starbursts are challenging due to high dust extinction. One way to overcome this limitation is to make use of the flux magnification provided by gravitational lensing. Sub-mm surveys provide an efficient way to select lensed high-redshift galaxies due to the negative K-correction of the thermal dust spectral energy distribution (SED) and the steep faint-end slope of the sub-mm source counts [Blain 1996]. The two large area surveys, Herschel-ATLAS [Eales et al. 2010] and HerMES [Oliver et al. 2012], have resulted in sufficiently large samples of lensed galaxies [Negrello et al. 2010; Wardlow et al. 2013; Bussmann et al. 2013] from which we can find interesting targets for detailed follow-up observations.

Here we present results on the rest-frame optical spectroscopy of a lensed starburst galaxy to study its nebular line emission and line ratios. We make use of the Hubble Space Telescope Wide Field Camera 3 (HST/WFC3) grisms for these observations. To detect both Hα and Hβ over the wavelength covered by WFC3 grisms we require lensed galaxies to be at z < 1.6. One feasible target for WFC3 grism observations from currently known lensed Herschel sources is HATLASJ142935.3-002836 (Messias et al. 2014) (H1429-0028; G15v2.19 in
The lensed galaxy was detected in the GAMA-15 field of *Herschel-ATLAS* (Eales et al. 2010) with $S_{160,\mu m}=1.1 \pm 0.1$ Jy. The lensing models of the system using KeckII/NIRC2 laser guide star adaptive optics image and high-resolution ALMA imaging data are presented in Calanog et al. (2014) and Messias et al. (2014). The system includes a foreground edge-on disk galaxy $(z = 1.027)$ with a total magnification factor of $(1:2.8^{+1.2}_{−1.5})$. The two components have been used to suggest H1429-0028 may be undergoing a galaxy merger, but the two components of H1429-0028 are found to lie on top of each other. This also leaves the possibility that the compact bright component of H1429-0028 is a starbursting clump or a region within a galaxy. The full extent of the galaxy is traced by the extended features A, B, C and D are from the bright compact source near the inner cusp caustic while the diffuse ring is due to the extended component that is gravitationally lensed to an Einstein ring (Fig. 1). The lens model in Messias et al. (2014) shows that H1429-0028 is comprised of two components with a mass ratio of $(1:2)$. The background source is at $z = 1.027$ with a total magnification factor of $\mu = 7.9 \pm 0.8$ at infrared wavelengths (Messias et al. 2014). The K-band magnitude of H1429-0028 is 18.2 (Calanog et al., 2014) and is at the level that allows grism observations with just one or two HST orbits.

Here we report HST/WFC3 grism spectroscopic observations of H1429-0028 making use of G102 and G141 grism filters, covering the wavelength range of 0.8 to 1.7 $\mu$m. At the redshift of H1429-0028 these observations probe the rest-frame wavelength range of 0.4-0.8 $\mu$m allowing us to measure several photoionization emission lines. We use these measurements to explore the properties of this system in terms of several emission line diagnostic diagrams. We also establish the gas-phase metallicity in a star-forming galaxy. The *Paper* is organized as following: In Section 2 we describe the observations and our data reduction procedure. In Section 3 we present our results related to emission lines and emission line flux ratios and discuss them in the context of existing studies in the literature. We conclude with a summary in Section 4. When calculating luminosities we make use of the standard flat-$\Lambda$CDM cosmological model with $H_0=70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M=0.73$.

2. OBSERVATIONS

HST/WFC3 observations of H1429-0028 were completed with two orbits under GO program 13399 in Cycle 21 (PI:Cooray). We obtained a total of five exposures, including two direct images and three grism observations in two filters. The two direct images made use of WFC3/F160W and F105W filters for a total of 250 and 350 seconds, respectively. We obtained G102 and G141 grism observations over 1800 and 2900 seconds, respectively. The G141 grism covers 1.0 to 1.8 $\mu$m, while G102 grism covers 0.7 to 1.2 $\mu$m. At $z = 1.027$ these observations then allow important emission line studies of H1429-0028 involving Hα at 1.33 $\mu$m, Hβ at 0.985 $\mu$m, [OIII] at 1.015 & 1.005 $\mu$m, and [SII] at 1.364 & 1.361 $\mu$m. Due to the low spectral resolution of order 80 $\AA$ the data do not resolve the [SII] doublet or Hα from [NII].

We made use of the calibrated HST imaging and grism data from the CALWF3 reduction pipeline, as provided by the Space Telescope Science Institute. The spectra for individual objects in the image were extracted with the AXE software package (Kümmel et al. 2009). Briefly, we created an object catalog making use of the broad-band F160W and F105W images with the SExtractor package (Bertin & Arnouts 1996). A sky background subtraction was performed on the direct as well as the grism images. The core AXE marks spectral regions for each object in the SExtractor catalog, estimates contamination from nearby sources, and flat fields each of those regions or beams. A two-dimensional stamp of each grism beam is generated and then combined together with multiple observations of the same stamp to create a final two-dimensional image for scientific analysis. The data products include the two-dimensional combined grism stamp for each object as well as flux-calibrated one-dimensional spectra, contamination estimates, and error estimates.

We identified emission lines in the one-dimensional
In order to derive extinction corrections and line ratios, we measure the line intensities for detected bright regions of H1429-0028. In Fig. 1 we label the bright components following the scheme of Messias et al. (2014). In the G141 grism the brightest component C and (A+B) as well as parts of the Einstein ring had clear emission detections. For G102 only components (A+B) had a detectable [OIII] as well as Hβ. In G102 component C had clear detection of the [OIII] lines but only an upper limit on the Hβ line. Given the ratio of Hα to Hβ in knots (A+B), and the detected value of Hα in knot C, the expected value of Hβ in knot C is \(3.2 \pm 1.9 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\). We measured the Hβ line flux density to be \(1.4 \pm 3.8 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\). This value falls within the estimated range but is not robust enough to be used for scientific analysis.

From Fig. 1 the lens models suggest two components for H1429-0028, one that is compact and bright and a second that is extended. The two components have effective radii of 0.18" ± 0.01 and 0.03" ± 0.01, for the source responsible for the ring and for knots, respectively. It is clear from the lensing models that the quadruply imaged knots A to D are from the same source. While it has been suggested that H1429-0028 is a merger, due to the presence of two components in the lens model, it is not clear from such a model if H1429-0028 is two separate galaxies or if the smaller component is a high star-forming region within a galaxy. Our spectral line data do not have the adequate velocity resolution but in the future this question can be addressed with an integral field unit (IFU) observations. In this work, for the line ratios, we only study the ratios of bright knots. Thus our line ratios capture the physical properties within the starbursting compact region or a compact galaxy. For the total Hα flux we add the flux from each component with their corresponding magnification from the lens model. The values are a magnification factor of \(\mu \sim 27\) for the compact component, which contributes to the bright knots, and \(\mu \sim 10\) for the larger component which contributes to the ring. We scale the observed line flux to a total estimate of the line intensity across the galaxy based on K-band photometry of the bright components and the diffuse rings. This correction results in a factor of 2.6±0.1 from the line fluxes measured for the sum of the components A+B+C to the galaxy as a whole assuming that the continuum fluxes detected for the other components and ring scale as the rest-frame optical magnitudes.

To correct for the [NII] contamination of Hα we make use of two independent methods to derive the expected [NII]/Hα line ratio and average them as the final value to use here. This follows the approach given in Domínguez et al. (2013). The first method from Sobral et al. (2012) estimates the [NII]/Hα ratio using the Hα + [NII] equivalent width (EWs). Using the measured EWs we estimate the ratio to be 0.27±0.07. However it could be that we are overestimating the EWs in our line fitting procedure due to systematic uncertainties associated with the model for the continuum, especially since the continuum is dominated by the residual fluxes from the foreground lensing galaxy. Thus we also employ a second method, but we find consistent estimates on the [NII]/Hα ratio.

The second method from Erb et al. (2006) relies on a relationship derived between stellar mass of a galaxy and the Hα/NII ratio of that galaxy. Here, instead of an independent estimate of the stellar mass, we make use of the SED modeling in Ma et al. (in prep) with a

<table>
<thead>
<tr>
<th>Line</th>
<th>Component</th>
<th>Flux[^1] (erg s^{-1} cm^{-2})</th>
<th>Eq. Width[^2] (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα + [NII]</td>
<td>(A+B)</td>
<td>45.8 ± 2.3</td>
<td>108.4 ± 5.4</td>
</tr>
<tr>
<td>Hα + [NII]</td>
<td>(A+B)</td>
<td>4.5 ± 2.6</td>
<td>15.1 ± 8.8</td>
</tr>
<tr>
<td>Hβ</td>
<td>(C)</td>
<td>1.4 ± 3.8</td>
<td>2.9 ± 8.0</td>
</tr>
<tr>
<td>[OIII]λ(5007)</td>
<td>(A+B)</td>
<td>6.4 ± 1.8</td>
<td>18.8 ± 5.2</td>
</tr>
<tr>
<td>[OIII]λ(4959)</td>
<td>(A+B)</td>
<td>4.1 ± 1.9</td>
<td>12.6 ± 5.9</td>
</tr>
<tr>
<td>[OIII]λ(5007+4959)</td>
<td>(C)</td>
<td>10.8 ± 2.2</td>
<td>22.6 ± 4.7</td>
</tr>
<tr>
<td><a href="doublet">SII</a></td>
<td>(A+B)</td>
<td>10.1 ± 1.8</td>
<td>23.7 ± 4.2</td>
</tr>
<tr>
<td><a href="doublet">SII</a></td>
<td>(C)</td>
<td>8.7 ± 2.1</td>
<td>14.1 ± 3.4</td>
</tr>
</tbody>
</table>

[^1]: Line fluxes are in \(10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}\), not corrected for lens magnification.
[^2]: Equivalent widths should be considered as an upper limit due to potential systematic uncertainties in the background continuum model.
Fig. 4.— $H\alpha$ luminosity vs. Far-infrared for H1429-0028 compared to the extinction corrected sample of IR luminous and sub-mm galaxies in Takata et al. (2006). For reference we also show the corresponding SFRs based on IR luminosity and $H\alpha$ luminosity to the top and left of the plot, respectively. We show H1429-0028 for two cases with and without extinction correction of $H\alpha$ luminosity. The dot-dashed line represents the case that SFRs from $H\alpha$ and far-infrared are equal. H1429-0028 falls below this trend line but the difference between IR and $H\alpha$-based SFRs is fully consistent with the observed scatter of previous measurements.

Fig. 5.— Left: Balmer decrement vs. IR luminosity. The background data are from Takata et al. (2006). Middle: Balmer decrement vs. $H\alpha$ luminosity. The stars come from Dominguez et al. (2013) and the diamonds are from Takata et al. (2006). The contours show the galaxy population traced by SDSS. Right: Balmer decrement vs. galaxy stellar mass. The contours show the galaxy population traced by SDSS. The diamonds correspond to star-forming galaxies of $0.75 \leq z \leq 1.5$ presented in Dominguez et al. (2013), while the squares correspond to $z \sim 2$ from Sobral et al. (2012). We show the expected optical attenuation $A_V$ to the right of the right panel for corresponding values of $H\beta/H\alpha$. The dashed line represents the intrinsic value of the Balmer decrement.
consistent estimates on the extinction with SED modeling.\footnote{The extinction is lower than the background galaxy, including deblended IRAC data.} The background contours show the galaxy population traced by SDSS\footnote{Kewley et al. (2001).}. All data points from the literature (following Takata et al. 2006) are extinction corrected though we show extinctions. Though the apparent luminosity of H1429-0028 with and without extinction correction. When compared to the estimates based on the Balmer line ratios, the extinction is lower than $\tau_V \sim 1.9 \pm 0.5$. Once corrected for [NII] we find $\tau_V \sim 4.2 \pm 0.4$ consistent with the estimate of $\tau_V$ from the Balmer line ratios (Ma et al. in prep). In Fig. 4 we compare the extinction-corrected Hα luminosity of H1429-0028 with other star-forming galaxies. All data points from the literature (following Takata et al. 2006) are extinction corrected though we show the case for H1429-0028 with and without extinction correction. Though the apparent luminosity of H1429-0028 corresponds to that of a hyper-luminous infrared galaxy with $L_{IR} \sim 10^{13} L_\odot$, the intrinsic luminosity, once corrected for lensing magnification, is that of a ultra-luminous infrared galaxy (ULIRG). The galaxy falls between the SMGs and local ULIRGs studied by Swinbank et al. (2004) and Takata et al. (2006) with rest-frame optical spectroscopy at Keck and Subaru, respectively. We find the extinction-corrected SFR of H1429-0028, at $60 \pm 50 M_\odot$ yr$^{-1}$, to be lower than the instantaneous SFR implied by the total IR luminosity, with a value of $390 \pm 05 M_\odot$ yr$^{-1}$ using the Kennicutt (1998) relation. Given the scatter observed in Fig. 4, however, we do not find this difference to be statistically significant.

In Fig. 5 we compare the Balmer decrement of H1429-0028 against Hα, IR luminosity, and stellar mass for a sample of galaxies. As shown in Fig. 5 middle panel, for the sample of galaxies with both Hβ and Hα mea-
measurements in the literature, we find that the extinction-corrected Hα luminosity of H1429-0028 to be among the highest. The Domínguez et al. (2013) sample comes from HST/WFC3 grism observations of $z \sim 0.75$–1.5 galaxies. The SDSS-detected star-forming galaxies have L$_{H\alpha} < 10^{42}$ ergs s$^{-1}$, while for H1429-0028 L$_{H\alpha} > 10^{43}$ ergs s$^{-1}$. This is consistent with the fact that H1429-0028 is an ULIRG. The right panel shows the trend in the Balmer decrement with the stellar mass such that there is a slight decrease in the Hβ to Hα ratio with an increase in the stellar mass. The plotted points are the sample-averaged values from Domínguez et al. (2013) as diamonds and Sobral et al. (2012) as squares in three stellar mass bins in both studies. These data mainly probe the stellar mass below a few times 10$^{11}$ M$\odot$. H1429-0028 is massive with $M_* \sim 10^{11}$ M$\odot$ and has a Balmer decrement that is lower than the typical star-forming galaxies in the same redshift range of 0.75 to 1.5.

In Fig. 6 we compare the line ratios of [OIII]/Hβ vs. [SII]/Hα. This is a variant of the more traditional BPT diagram (Baldwin et al. 1981) that involves [OIII]/Hβ vs. [NII]/Hα. Given that [NII] is blended with Hα in our low-resolution data we make use of [SII]/Hα ratio. We make extinction corrections for the [SII]/Hα ratio here given the two [SII] lines are somewhat separated in wavelength from Hα. In this diagram H1429-0028 is consistent with the low metallicity end of the star forming regions although the ratios have large uncertainties associated with measurement errors. The measurements are incompatible with AGN regions of galaxies from SDSS data at $z < 0.3$. While H1429-0028 is luminous this is primarily due to gravitational lensing: the intrinsic luminosity of H1429-0028 is compatible with a galaxy star forming at a rate of 200 to 400 M$\odot$ yr$^{-1}$. The lens models shown in Messias et al. (2014) are compatible with a merger system. Interestingly a value for [NII]/Hα of 0.27 ± 0.03 is higher than the average [NII]/Hα ratio of 0.19 ± 0.05 for the galaxies classified as star-forming in the SCUBA sample of Swinbank et al. (2004), and lower than the average for SMGs hosting AGN of 0.41 ± 0.05 from the same study.

In Fig. 7 we make use of the nebular line ratios, with the estimate of [NII]/Hα ratio, to make an estimate of the metallicity. Instead of an estimate based on [NII]/Hα ratio alone, we make use of the O3N2 ratio (Pettini & Pagel 2004) as the estimator here as it also involves the measured [OIII]/Hβ ratio. The metallicity value, as measured in terms of 12 + log(O/H) was found to be 8.49 ± 0.16. In Fig. 7 we compare the metallicity vs. the stellar mass. The figure shows the average metallicity vs. stellar mass relations for both local (Manucci et al. 2010) and $z \sim 2$ galaxies (Steidel et al. 2014). H1429-0028 has a metallicity comparable to galaxies at $z \sim 2$ despite being at $z = 1.027$. H1429-0028 has a high SFR, but shows no indication that it is hosting an AGN. H1429-0028 is metal poor despite its high stellar mass and argues for a scenario that it is still under a rapid formation phase.

Finally in Fig. 8 we show the location of H1429-0028 in comparison to the main sequence of galaxies at $z \sim 1$. Here we plot the total IR luminosity-based SFR of H1429-0028 vs. stellar mass. We find that H1429-0028 is above the $z = 1$ correlation from Elbaz et al. (2007). For comparison, we also show other dusty star-forming galaxies at $z \sim 1$ from the literature. Finally the average gas fraction $M_{ISM}/(M_\odot + M_{ISM})$ for the Tacconi et al. (2010) sample of star-forming galaxies is 0.34%. The gas fraction for H1429-0028 is 0.25 ± 0.1%, where we make use of the gas mass of $M_{ISM} = 4.6 \pm 1.7 \times 10^{10}$ M$\odot$ from ALMA CO observations reported in Messias et al. (2014).

H1429-0028 is one example of a grism observation with HST based on a galaxy that was first selected with the Herschel catalog as a lensed background source. Based on lensing models (Vadawal et al. 2013), we find that there should be roughly 0.25 deg$^{-2}$ lensed starburst galaxies in the redshift interval of 1 to 2. In the future such galaxies will be automatically included as part of the surveys that will be done with slitless grisms on Euclid and WFIRST. In the 2000 deg$^2$ High Latitude Deep survey we expect WFIRST will detect close to 500 lensed starbursts at $z \sim 1$ to 3. The study we have presented for one lensed galaxy can then be expanded to a large enough sample for detailed statistical study that probes the internal structure of lensed starbursts.

4. SUMMARY

We observed the Herschel-selected gravitationally-lensed starburst galaxy HATLASJ1429-0028, studied in detail in Messias et al. (2013) with some initial description in Calanog et al. (2014). We present Hubble/WFC3 G101 and G412 grisms of the HATLASJ1429-0028. The observations covered the wavelength regime of 0.8 to 1.7 μm and resulted in detections of Hα+[NII], Hβ, [SII], and [OIII] for several bright regions of the background galaxy. The Balmer line ratio $H\alpha/H\beta$ of 7.5 ± 4.4, when corrected for [NII], results in an extinction for the starburst galaxy of $E(B-V) = 0.8 ± 0.5$. The Hα based star formation rate, when corrected for extinction, is at the level of 60 ± 50 M$\odot$ yr$^{-1}$, lower than the star formation rate of 390 ± 90 M$\odot$ yr$^{-1}$ from the total IR luminosity. HATLASJ1429-0028 also has a low metallicity despite its high stellar mass at the level of 10$^{11}$ M$\odot$. The combination of high stellar mass, lack of AGN indicators, low metallicity, and the high star-formation rate of HATLASJ1429-0028 suggests that this galaxy is still going through a rapid formation.

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