Correlation between SFR Surface Density and Thermal Pressure of Ionized Gas in Local Analogs of High-redshift Galaxies

Tianxing Jiang, Sangeeta Malhotra, Huan Yang, and James E. Rhoads

1 School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA; tianxing.jiang@asu.edu
2 Department of Astronomy, University of Maryland, College Park, MD 20742, USA
3 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
4 Las Campanas Observatory, Carnegie Institution of Washington, La Serena, Chile

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Abstract

We explore the relation between the star formation rate surface density (ΣSFR) and the interstellar gas pressure for nearby compact starburst galaxies. The sample consists of 17 green peas and 19 Lyman break analogs (LBAs). Green peas are nearby analogs of Lyα emitters at high redshift and LBAs are nearby analogs of Lyman break galaxies at high redshift. We measure the sizes of green peas using Hubble Space Telescope Cosmic Origins Spectrograph near-UV images with a spatial resolution of ~0.05". We estimate the gas thermal pressure in H II regions by \( P = N_{\text{total}}T_kB \approx 2n_eT_kB \). The electron density is derived using the [S II] doublet at 6716,6731 Å and the temperature is calculated from the [O III] lines. The correlation is characterized by \( \Sigma SFR = 2.40 \times 10^{-3} M_\odot \text{yr}^{-1} \text{kpc}^{-2} (\frac{P}{kB})^{1.33} \). Green peas and LBAs have high ΣSFR up to 1.2 \( M_\odot \text{yr}^{-1} \text{kpc}^{-2} \) and high thermal pressure in the H II region up to \( P/kB \sim 10^{7.2} \text{K cm}^{-3} \). These values are at the highest end of the range seen in nearby starburst galaxies. The high gas pressure and the correlation are in agreement with those found in star-forming galaxies at \( \zeta \sim 2.5 \). These extreme pressures are shown to be responsible for driving galactic winds in nearby starbursts. These outflows may be crucial in enabling Lyα and Lyman-continuum to escape.

Key words: galaxies: evolution – galaxies: ISM – galaxies: starburst – galaxies: star formation

1. Introduction

Understanding the physical factors that control or affect star formation in galaxies is one of the most critical aspects of understanding galaxy evolution. Star formation is linked to the interstellar medium. On galactic scales, cold clouds collapse under their own gravity, fragment into small dense cores, and eventually stars form there. Stars inject energy, momentum, metals, and gas into the interstellar medium by stellar feedback (e.g., stellar winds, radiation, and supernova explosion), and ionize and heat the interstellar medium. Hot, ionized gas then cools and converts to cold gas again. Empirical star formation scaling relations are essential input for models and simulations of galaxy evolution (e.g., Springel & Hernquist 2003), due to the complexity of star formation physics.

Observationally, on galactic scales, the star formation rate surface density (ΣSFR) in galaxies correlates with the neutral gas (atomic and molecular gas) surface density by the empirical “Kennicutt–Schmidt law” (e.g., Schmidt 1959; Kennicutt 1989, 1998). This correlation has also been investigated on sub-galactic scales (e.g., Wong & Blitz 2002; Blitz & Rosolowsky 2004, 2006; Bigiel et al. 2008; Roychowdhury et al. 2015). ΣSFR is also proposed to be related to the galactic orbital time \( \Omega \) (e.g., Kennicutt 1998; Wong & Blitz 2002; Daddi et al. 2010; Genzel et al. 2010; García-Burillo et al. 2012), or to the stellar mass surface density (e.g., Boissier et al. 2003; Shi et al. 2011; Rahmani et al. 2016). However, these relations are often more complex than a simple mathematical expression and can vary in different types of galaxies. How the star formation in galaxies is controlled and regulated is still not quite clear. Based on numerical simulations of multiphase gaseous disks, Kim et al. (2011) discussed the relation between ΣSFR and the total midplane pressure of diffuse interstellar medium for star-forming disk galaxies in the regime where diffuse atomic gas dominates the interstellar medium (see also Ostriker & Shetty 2011). Among many physical properties they explored using numerical simulations, the best star formation correlation they have found is with the total midplane pressure of diffuse interstellar medium. They argued that this correlation should also apply to the starburst regime (generally where gas density \( \Sigma \sim 10^{-7} - 10^{-8} M_\odot \text{pc}^{-2} \)), such as (ultra)luminous infrared galaxies and galactic centers.

The question naturally arises of what the observations tell us about the potential relation between the star formation and the gas pressure in galaxies. Is there a good correlation? One way to measure the pressure is from the gas density and gas temperature. For ionized gas, the thermal pressure \( P = N_{\text{total}}T_kB \sim 2n_eT_kB \), where the electron density \( n_e \) is not hard to measure with more and more available high-quality high-resolution rest-frame optical spectra for both \( \zeta \sim 0 \) and \( \zeta \sim 2 \) galaxies (e.g., Hainline et al. 2009; Lehnert et al. 2009; Steidel et al. 2014; Sanders et al. 2016).

Two studies indirectly suggest the association of star formation rate with the electron density in star-forming galaxies. This might also suggest the association of star formation rate with the thermal pressure of ionized gas, with the assumption that the temperature of ionized gas is comparable in these galaxies. Liu et al. (2008) showed histograms of the specific star formation rate (SFR/\( M_\odot \)) and SFR surface density (ΣSFR), and [S II] \( \lambda 6716,6731 \) ratio for SDSS Main sample (typical star-forming galaxies) and SDSS Offset-SF sample galaxies in their Figure 10. They have reported that the Offset-SF sample have both higher ΣSFR and higher electron density (thus higher pressure in H II regions) compared to SDSS Main sample. It was
claimed that the higher SFR surface density may account for the higher interstellar pressure seen in the H II regions of Offset-SF objects. Brinchmann et al. (2008) investigated the trends of SFR/M* vs ΣSF and [S II]λ6716/[S II]λ6731 ratio with their position in the [O III]λ5007/Hβ versus [N II] λ6583/Hα BPT diagram for SDSS galaxies. They have found that the galaxies farther away from the mean SDSS star-forming abundance sequence are characterized by higher SFR/M*, ΣSF and higher electron density. Neither studies directly presented the relation between ΣSF and electron density. Shimakawa et al. (2015) directly showed the correlation between ΣSF and the electron density ne and the correlation between the sSFR and ne for star-forming galaxies at z ~ 2.5, with a sample of 14 Hα emitters. Sanders et al. (2016) found no correlation between sSFR and ne using a larger sample at z ~ 2.3, but they did not investigate the correlation between ΣSF and ne. Bian et al. (2016) studied the median electron density in different sSFR and ΣSF bins. They have found that for typical SDSS star-forming galaxies, for a fixed sSFR, the electron density increases with increasing ΣSF, but for a fixed ΣSF, the electron density decreases with increasing sSFR. This trend was not found for their “local analogs.” Herrera-Camus et al. (2017) have found that the thermal pressure of the diffuse neutral gas increases with ΣSF in nearby galaxies.

In this work, we look into the relation between the SFR surface density ΣSF and the interstellar gas pressure on galactic scales. We seek to add observational constraints to the theories and simulations of the interplay between star formation and interstellar medium on galactic scales in the context of galaxy evolution. We study quantitatively the relation between ΣSF and thermal pressure of ionized gas for nearby compact starburst galaxies, with the sample of green peas and Lyman break analogs (LBAs). Green peas are nearby analogs of high-redshift Lyα emitters (e.g., Jaskot & Oey 2014; Henry et al. 2015; Yang et al. 2016, 2017b; Verhamme et al. 2017). LBAs are the counterparts in the nearby universe of the high-redshift Lyman break galaxies (LBGs) (Heckman et al. 2005). Both of them provide the best local laboratories for us to study the physical properties of the high-redshift star-forming galaxies, which is why we are particularly interested in these galaxies. We would like to see if there is a ΣSF–Pgas correlation for these galaxies, and if so, how it compares with that for z ~ 2.5 galaxies. We adopt the cosmological parameters of Ωm = 0.3, ΩΛ = 0.7 and H0 = 70 km s−1 Mpc−1 throughout this paper.

2. Data Sample

Green peas galaxies were first noted by volunteers in the Galaxy Zoo project (Lintott et al. 2008). They looked green and appeared to be unresolved round point sources in the gri composite color image (Cardamone et al. 2009) from the Sloan Digital Sky Survey (York et al. 2000, SDSS). Our sample of green peas is taken from the catalog in Cardamone et al. (2009). By defining a color selection in the redshift range 0.112 ≤ z ≤ 0.360, Cardamone et al. (2009) systematically selected 251 green peas with extreme [O III]λ5007 equivalent widths from the SDSS Data Release 7 (DR7) spectroscopic database. 80 out of 251 are star-forming objects that have high S/N SDSS spectra. These star-forming green peas are low-mass galaxies with high star formation rates and low metallicity. For these 80 star-forming green peas, 12 of them have near-UV (NUV) images taken with the Cosmic Origins Spectrograph (COS) in the HST archive (PIs: Henry (GO: 12928); Jaskot (GO: 13293); Heckman (GO: 11727)) and were discussed in Henry et al. (2015) and Yang et al. (2016, 2017a), and 19 of them have COS NUV images from our recent HST observation (PI: Malhotra (GO: 14201)). To get a well-measured size of the galaxies, the galaxies have to be spatially resolved. We emphasize that these COS NUV images offer a tremendous gain in resolution (of ~1″05) over that of SDSS images (PSF width ~1″4). The seeing of SDSS images is larger than the SDSS r-band half-light radii of green peas.

LBAs are supercompact UV luminous galaxies originally selected by Heckman et al. (2005) as local starburst galaxies that share typical characteristics of high-redshift LBGs. They are star-forming galaxies at z < 0.3 that satisfy the criteria LUV > 10^{42.3} L⊙ and IUV > 10^8 L⊙ kpc^−2. LBAs share similar stellar mass, metallicity, dust extinction, SFR, physical size, and gas velocity dispersion with LBGs. Our sample of LBAs is drawn from Overzier et al. (2009). We excluded 6 out of 31 LBAs as these 6 objects have dominant central objects and might be Type 2 AGNs. We used the optical half-light radius from their Table 1. The radii are either from HST WFPC2 F606W images (PSF FWHM ~0″11) or from HST ACS Wide Field Channel F850LP images (PSF FWHM ~0″12).

There are optical spectra in the SDSS Data Release 12 (DR12) spectroscopic database with well-resolved [S II] λ6716,6731 lines ( Alam et al. 2015) for the 31 green peas and for 24 LBAs out of the 25 LBAs. With visual inspection of the spectra, we excluded two green peas and two LBAs as the [S II] λ6716,6731 lines in SDSS spectra are badly contaminated by the sky lines. One of the green peas was also included as a Lyman break analog in Overzier et al. (2009). We include this one in the sample of LBAs in our work and do not count it twice. Of the remaining 50 objects, all but 3 have emission line measurements and SFR measurements in the public MPA-JHU catalogs, which are based on SDSS Data Release 8 (DR8). In total, we end up with 47 objects, 26 green peas and 21 LBAs. We refer to them as the “parent sample.” We decided to use MPA-JHU catalogs in our work instead of the pipeline measurements from SDSS DR12 for two primary reasons. First, the emission line fluxes are better measured in MPA-JHU measurements by using stellar population synthesis models to accurately fit and subtract the stellar continuum; while for SDSS pipeline measurements, the emission line fluxes are measured by fitting multiple Gaussian-plus-background models to the lines. We can get more accurate [S II] measurements as needed. Second, the total SFR (using the galaxy photometry as described in Salim et al. 2007) and fiber SFR (using Hα fluxes within the galaxy fiber aperture as described in Brinchmann et al. 2004) are provided by MPA-JHU measurement.

We have derived our own star formation rates independently (see Section 3.3) but take advantage of the information in the MPA-JHU catalog to correct for the extended light outside the fiber as part of our procedure.

3. Method

3.1. Electron Density

The average electron density in a nebula can be measured by observing the effects of collisional de-excitation. This can be measured...
Figure 1. S II line ratio vs. electron density in H II region. The left panel shows green peas and the right panels show Lyman break analogs. The dashed line is a fit to the [S II] line ratio and electron density according to the IRAF routine “temden.”

done by comparing the intensities of two lines of a single species emitted by different levels with nearly the same excitation energy and different radiative transition probabilities or different collisional de-excitation rates (see, e.g., Chapter 5 of Osterbrock & Ferland 2006). The ratio of the intensities of the lines they emit depends on the relative populations of the two levels, which is dependent on the collision strengths of the two levels. So the ratio of the intensities of the lines is sensitive to the electron density. The most frequently used emission line doublets in rest-frame optical spectra are [O II] λλ3726,3729 and [S II]λλ6716,6731. Since the SDSS spectra do not properly resolve [O II]λλ3726,3729 but do resolve [S II]λλ6716,6731, we measured the electron density from [S II] doublets. The [S II] doublet ratio is a good measurement of the electron density for 10^{3.5} \text{ cm}^{-3} < n_e < 10^{4.5} \text{ cm}^{-3}. The program “temden” under the IRAF STS package NEBULAR is available for the measurement with input of the intensity ratio of the doublets and temperature. The output electron density is insensitive to the input temperature for 7500 K < T_e < 15000 K. When measuring Ne, we assumed T_e = 10^{4} \text{ K}, which is an order-of-magnitude estimate for H II regions. Sanders et al. (2016) have argued that the measurement of the electron density is different when using the most up-to-date collision strength and transition probability atomic data instead of the old values included in the IRAF routine temden. However, we notice that the measurements of n_e from [S II] doublets based on either the updated value in Sanders et al. (2016) or IRAF temden are very close to each other for 10^{3.5} \text{ cm}^{-3} < n_e < 10^{4.5} \text{ cm}^{-3}, with differences of n_e at a fixed [S II] ratio within ∼0.1 dex, as seen in Figure 1 in Sanders et al. (2016).

The line ratio is R = \frac{[S \text{ II}]6716}{[S \text{ II}]6731}. The lower uncertainty and upper uncertainty of the ratio are calculated separately: the lower uncertainty is \epsilon_{\text{err}} = R - \frac{[S \text{ II}]6716 - [S \text{ II}]6731}{[S \text{ II}]6716 + [S \text{ II}]6731}, and the upper uncertainty is \epsilon_{\text{err}} = \frac{[S \text{ II}]6716 + [S \text{ II}]6731}{[S \text{ II}]6716 - [S \text{ II}]6731} - R. We only measured the electron density for the objects that have more than 4σ detection of [S II]λ6716 and [S II]λ6731 and satisfy \frac{R}{\epsilon_{\text{err}}} > 3 and \frac{R}{\epsilon_{\text{err}}} > 3 (38 objects out of 47 objects in the “parent sample”). As seen from the dashed line in Figure 1, in both very high (with ratio lower than ∼0.44) and very low electron density regimes (with ratio higher than ∼1.38), the line ratio is not sensitive to the electron density at all, and the theoretical maximum of the line ratio is ∼1.43. Taking these into account, we classify the measurement of the electron density into four cases. (1) If the lower bound of the line ratio is higher than 1.38, we can only measure the upper limit of electron density, which corresponds to the line ratio of 1.38. (2) If the lower bound of the line ratio is between 1.10 and 1.38 and the upper bound of the line ratio is higher than 1.38, we can only measure the upper limit of electron density, which corresponds to the lower bound of the line ratio. (3) If the lower bound of the line ratio is less than 1.15 and the upper bound of the line ratio is higher than 1.38, the uncertainty of the electron density spans a wide range and thus the measurement is not useful. (4) If the upper bound of the ratio is not higher than 1.38, then we can safely measure the electron density and its (upper and lower) uncertainty. For the fourth case, the lower (upper) uncertainty of the electron density corresponds to the upper (lower) uncertainty of the line ratio. We throw away two objects that are classified in the third case. Therefore, there are 36 objects that have electron density measurements out of the 47 objects in the “parent sample.”

Figure 1 shows the line ratios and electron density measurements based on the IRAF “temden” package for the remaining 36 objects out of the “parent sample.” There are 17 green peas and 19 LBAs in Figure 1. We call them the “final sample.” Note that in Figure 4, the thermal pressure is only measured for the “final sample.” Furthermore, in Table 1, the properties are also for the “final sample” instead of the “parent sample.”

The dashed line in Figure 1 is the fitted function R(n_e) = a_{\text{fit}} + \frac{c}{n_e} between n_e and the line ratio R over a range of electron densities of 10^{-3} – 10^{4} \text{ cm}^{-3} for the temden package, similar to what has been done in Sanders et al. (2016). The result is R(n_e) = a_{\text{fit}} + \frac{c}{n_e} with a = 0.4441, b = 2514, and c = 779.3.
As seen from Figure 1, the electron densities for our “final sample” are mostly 100 ~ 700 cm⁻³. This is comparable to the typical electron densities for z ~ 2 star-forming galaxies (Steidel et al. 2014; Shimasawa et al. 2015; Sanders et al. 2016; Kashino et al. 2017) and much larger than the typical electron densities (~30 cm⁻³ or 10–100 cm⁻³) measured for SDSS star-forming galaxies (Brinchmann et al. 2008; Sanders et al. 2016).

### 3.2. Electron Temperature

The electron temperature in a nebula can be determined from measuring the ratio of intensities of two lines of a single species emitted from two levels with considerably different excitation energies (Chapter 5 of Osterbrock & Ferland 2006). In rest-frame optical spectra, the most frequently used emission lines are [O III]λ5007, [O III]λ4363, and [O III]λ4363. Since these three lines are relatively close in wavelength, the effect of dust extinction on the ratio of $\frac{[O\text{ III}]}{[O\text{ III}]+\lambda4363}$ is small. In the “parent sample” of 47 objects, 36 objects have at least 2σ detection of [O III]λ5007, [O III]λ4363, and [O III]λ4363. For these 36 objects, the ratio of $\frac{[O\text{ III}]}{[O\text{ III}]+\lambda4363}$ was input to the program “temden” in IRAF to measure the temperature. Therefore, in the “parent sample” of 47 objects, 36 objects
have electron temperature measurements. For these 36 objects, the typical uncertainties are 200–1500 K and the median uncertainty is $-497$ K, $+612$ K. Among the “final sample” of 36 objects that have electron density measurements from Section 3.1, only 26 of them have electron temperature measurements. For the other 10 objects in the “final sample,” we assumed a temperature of 11,000 K. Among the 10 objects, there are two objects with at least 2σ detection of $[\text{O} \text{III}]\lambda5007$, $[\text{O} \text{III}]\lambda4959$, and S/N of $[\text{O} \text{III}]\lambda4363$ between 1.5 and 2 in our “final sample”, for which the electron temperature is 11, $300^{+1440}_{-1240}$ K and 11, $400^{+3740}_{-1420}$ K. The assumed 11,000 K for these 10 objects in our “final sample” is consistent with the temperature of these two objects, and with the uncertainties or the lower limits on the line ratios of these 10 objects. The assumed 11,000 K is also close to the median temperature of 12,391 K (11% difference) of the 36 objects in the “parent sample” but slightly lower, as befits a subset of objects with somewhat weaker $[\text{O} \text{III}]\lambda4363$ emission.

Figure 2 shows the distribution of the electron temperatures for 36 objects out of the “parent sample.” The electron temperature is mostly 10,000 K–15,000 K. Andrews & Martini (2013) measured electron temperature from O $^{++}$ for stellar mass-SFR stacks of SDSS galaxies, which is mostly between 10,500 and 12,000 K. In comparison, the electron temperature of our sample is slightly larger than the typical electron temperature in $z \sim 0$ SDSS star-forming galaxies.

### 3.3. Star Formation Rate

We measured the SFRs from the Hα fluxes in MPA-JHU catalogs. The line fluxes from MPA-JHU catalogs have been corrected for Galactic extinction following the O’Donnell (1994) attenuation curve. First, we derived dust extinction in the emitting galaxy assuming the Calzetti et al. (2000) extinction curve and an intrinsic Hα/Hβ value of 2.86:

$$E(B-V)_{\text{gas}} = \frac{\log_{10}(f_{\text{Hα}}/f_{\text{Hβ}})^{2.86}}{0.4 \times [k(\text{Hα}) - k(\text{Hβ})]}.$$

with $k(\text{Hα}) = 2.468$ and $k(\text{Hβ}) - k(\text{Hα}) = 1.163$. Then the SFR was calculated by SFR (M$_\odot$ yr$^{-1}$) = 10$^{-4.27} L(\text{Hα})_{\text{corr}}$ (erg s$^{-1}$) according to Kennicutt & Evans (2012). That is our own fiber SFR. The SFRs are not sensitive to the dust extinction law chosen, because the dust extinction is low ($E(B-V)_{\text{gas}} \sim 0.1$ mag) for our sample. The SFR will change no more than 0.03 dex if the extinction law from the Milky Way (MW) the Large Magellanic Clouds (LMC), or the Small Magellanic Clouds (SMC) is chosen instead of the Calzetti et al. (2000) extinction. We calculated the ratio of the total SFR to the fiber SFR that are both available in MPA-JHU catalogs. For green peas the ratios are typically less than 1.2, and for LBAs typically around 1.5. Then we corrected our own fiber SFR by applying the factor of this ratio. For LBAs, we compared the SFR based on MPA-JHU with the SFR measurements from Hα luminosity in Overzier et al. (2009). Note that Overzier et al. (2009) applied a small correction factor to Hα fluxes of typically ~1.7 due to the flux expected outside the SDSS fiber. We found good statistical agreement and no gross systematic differences between the SFR based on MPA-JHU and the SFR in Overzier et al. (2009).

### 3.4. Half-light Radius

GALFIT$^7$ is an image analysis algorithm that can model the light distribution of galaxies, stars, and other astronomical objects in two-dimensional digital images by using analytic functions. We measured the half-light radii of the green peas from COS NUV images using GALFIT version 3.0 (Peng et al. 2010). The Sersic radial profile, which is one of the most frequently used profiles for galaxy morphology analysis, was chosen in our measurement. The distribution of the UV

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Figure 2. Normalized histogram of the electron temperature measured for the “parent sample.” The curve shows the kernel density estimate with the normal (Gaussian) kernel function. The kernel density estimate (KDE) is normalized such as the area under the KDE curve is equal to 1. The kernel density estimate is complementary to the histogram in presenting the distribution of a quantity. The numbers of galaxies in each bin, from left to right, are 4, 6, 4, 4, 7, 3, 4, 1, 2, and 1, respectively.

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$^7$ http://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html
half-light radii for green peas is shown in Figure 3. The typical radii is ~0.19 arcsec, and ~0.7 kpc, as listed in Table 1.

To estimate the UV sizes of LBAs, the optical sizes of LBAs were divided by a representative value of 1.8, considering that the optical size is typically (about 2 times) larger than the UV size for LBAs (Overzier et al. 2008). We do not apply the PSF image in GALFIT for the size and sersic index measurement. The effects of PSF should be small, as the sizes we measured are more than 3 times bigger than the PSF FWHM, with only three exceptions whose sizes were overestimated by up to ~10%.

### 4. Results

For the 36 objects in the “final sample,” we measured the thermal pressure in the H II region by $P/k_B = N_{\text{total}}T$. If helium is singly ionized, then $N_{\text{total}} \simeq n_e + n_{\text{He}^+} \simeq 2n_e$. If some helium is doubly ionized, then the $N_{\text{total}}$ could be slightly less than $2n_e$. Since the number density of helium atom+ion is only around 8% of the H$^+$ density, this should be a minor effect. We also note that the ionization potential of sulfur is 10.36 eV, lower than the ionization potential of hydrogen. So [S II] doublets also exist beyond the boundary of H II regions, where there are neutral hydrogen atoms in addition to the electrons and protons. So $N_{\text{total}} = 2n_e$ is a lower limit of the total ion and atom density. We also calculated the $\Sigma$SFR by $\Sigma$SFR = $\frac{SFR}{\pi R_e^2}$.

The thermal pressure in H II regions and the $\Sigma$SFR are shown in Figure 4. We have included the uncertainties of the electron density and the temperature in the pressure uncertainty for each object. Note that for the 10 objects with an assumed temperature of 11,000 K, we took $-1460$ K, $+4090$ K (the average of $-1490$, $+4440$ K, and $-1420$ K, $+3740$ K) as representative uncertainties of the temperature. We find that our local analogs have high $\Sigma$SFR up to $1.2 M_\odot \text{yr}^{-1} \text{kpc}^{-2}$ and high thermal pressure in the H II region up to $P/k_B \sim 10^7.2 \text{K cm}^{-3}$.

The thermal pressure of our sample is higher than that for typical SDSS star-forming galaxies with thermal pressure around $P/k_B = 10^{5.8} \text{K cm}^{-3}$ (when $n_e = 30 \text{ cm}^{-3}$ and $T = 11,000 \text{ K}$ are taken). In addition, green peas have higher average $\Sigma$SFR and higher average thermal pressure than LBAs. The thermal pressures seen in green peas are near the upper end of pressures seen in starbursts by Heckman et al. (1990). In nearby starbursts, these extreme pressures are responsible for driving galactic outflows (Heckman et al. 1990), which are necessary for the resonantly scattered Ly$\alpha$ photons to escape.

To quantitatively describe the correlation, we used Spearman’s rank correlation, a nonparametric test for correlation. Spearman’s correlation coefficient $r_s$ measures the strength of association between two ranked variables, and the corresponding $p$-value tells you the significance level with which a null hypothesis that the variables are unrelated to can be rejected. Spearman’s rank correlation does not handle upper limits or error bars, so for the objects that only have upper limits for the electron density, we “re-measured” their electron density only for the purpose of applying Spearman’s rank correlation. For the objects with $R > 1.5$, we could not get a reliable electron density measurement, so we excluded them from the Spearman’s rank correlation analysis. For the objects with $R \leq 1.38$, we measured the electron density from the line ratio (without considering the error bars). For objects with $1.38 < R < 1.5$, we measured the electron density from a ratio of 1.38. See the column “$n_e$” in Table 1 for the measurements of the electron density that are used for Spearman’s rank correlation. Then we measured the pressure again combining the new electron density measurements here.
and the temperature measurements from Section 3.2. This is shown in Figure 5.

We calculated $r_s$ and p-value for the data points in Figure 5, and obtained $r_s = 0.615$ and $p = 0.02\%$. We checked that if we did not apply the correction factor (for the extended light outside of the fiber) to the SFR, we would obtain $r_s = 0.598$ and $p = 0.05\%$ and we would still see the correlation.

The next step is to fit a linear function between $\log \Sigma \text{SFR}$ and $\log (P/k_B)$, where $P/k_B$ denotes the thermal pressure. Since the relation between $[\text{S II}]$ line ratio and electron density is nonlinear, it is harder to know the distribution of the uncertainties of the electron density (obviously it is not appropriate to assume that the distribution of the uncertainties is close to Gaussian), and thus the distribution of the uncertainties of the thermal pressure. Moreover, it is hard to deal with the upper limits of the thermal pressure if fitting directly to $\log \Sigma \text{SFR}$ and $\log (P/k_B)$. Instead, we did a two-dimensional fitting to the $[\text{S II}]$ line ratio, the electron temperature, and $\log (\Sigma \text{SFR})$.

We assumed a linear relation between $\log (P/k_B)$ and $\log \Sigma \text{SFR}$,

$$\log (P/k_B) = f \times \log \Sigma \text{SFR} + g,$$

where $f$ and $g$ are two unknown parameters. Then

$$\log (2n_e T) = f \times \log (\Sigma \text{SFR}) + g,$$

$$n_e (\Sigma \text{SFR}, T) = \frac{10^{0.750 \times 5.966} \times 10^n}{2 \times T}.$$

Plugging this into $R(n_e) = a \frac{b + n_e}{c + n_e}$, we know

$$R(\Sigma \text{SFR}, T) = a \times \frac{b + 10^{0.750 \times 5.966} \times 10^n}{2 \times T}.$$

We took the function $R(\Sigma \text{SFR}, T)$ in the two-dimensional fitting, to figure out the values of parameters $f$ and $g$ for the best fit. Note that the uncertainty of the temperature and the uncertainty of $\Sigma \text{SFR}$ are small, compared to the uncertainty of $R = \frac{[\text{S II}]6716}{[\text{S II}]6731}$. We applied weighted least-squares fitting to this two-dimensional fitting. This is only valid when the uncertainties of the line ratio $R$ are Gaussian. But it should not be a bad assumption to take the uncertainties of the ratio as approximately Gaussian just for a rough estimate of the parameters $f$ and $g$. Since the lower and upper uncertainties of the ratio are not symmetric, we used the larger one for each pair of lower and upper uncertainties in the weighted least-square fitting. The parameters $f$, $g$ for the best fit of $R(\Sigma \text{SFR}, T)$ are $0.750$, $5.966$, respectively. So the best fit in terms of $\log (P/k_B)$ and $\log \Sigma \text{SFR}$ is

$$\log (P/k_B) = 0.750 \times \log \Sigma \text{SFR} + 5.966.$$

This can be rewritten as

$$\Sigma \text{SFR} = 10^{-7.95} M_\odot \text{yr}^{-1} \text{kpc}^{-2} \times (P/k_B)^{1.33},$$

Figure 4. SFR surface density vs. pressure relation. The green filled circles and red stars (or green and red upper limits) are our sample. Note that in this figure, the thermal pressure of our sample is based on the electron density measurements that are listed in columns 8, 9, and 10 in Table 1, excluding the measurements labeled with e in column 8. Please refer to Section 3.1 for more details regarding the electron density measurements. The gray triangles are the H$\alpha$ emitters in Shimakawa et al. (2015). The best fit to our data is shown by the purple line. The correlation from the simulations in Kim et al. (2011) is the blue dashed line.
or

\[
\Sigma \text{SFR} = 2.40 \times 10^{-3} M_\odot \text{yr}^{-1} \text{kpc}^{-2} \\
\times \left( \frac{P/k_B}{10^4 \text{ cm}^{-3} \text{ K}} \right)^{1.33}.
\]

The best-fit exponent is 1.33, and the 68% confidence interval of this exponent is 1.08–1.74. The best fit is shown in Figure 4 as the purple line.

For the subset of data points that have 1σ uncertainties on the pressure (instead of upper limits) in Figure 4, the scatter (1σ standard deviation) of the pressure around the best fit is 0.268 dex, while the median pressure measurement uncertainty for this subset is $-0.300 \text{ dex} +0.248 \text{ dex}$. So the scatter is mostly due to the measurement uncertainties.

5. Discussion

5.1. Contribution from Diffuse Ionized Gas

In our work, we are interested in the pressure and the electron density inside H II regions. However, the [S II] fluxes we measured are from the spectra of the whole galaxy, including H II regions (and beyond the boundary of H II regions) and the diffuse warm ionized gas. Therefore, the estimated electron density based on the integrated-light galaxy spectra may not well represent the real electron density of H II regions. We treat the emission from diffuse ionized gas as contamination to [S II] fluxes in this work. It is hard to know exactly the effects of contamination from the diffuse ionized gas. Here we provide a rough estimate of the effects of [S II] fluxes from the diffuse ionized gas on the measurement of the electron density of the H II regions, based on the (unrealistic) assumption that there are purely two components emitting [S II] in the galaxy, each with a uniform electron density. The estimate here should be treated as a toy model. Previous works have studied the properties of the diffuse ionized gas in different galaxies, such as, Haffner et al. (1999) and Madsen et al. (2006) using the Galaxy, Hidalgo-Gámez & Peimbert (2007) using the dwarf irregular galaxy NGC 6822, Flores-Fajardo et al. (2009) using a set of 29 galaxies from the literature including 25 spirals and 4 irregulars, and Monreal-Ibero et al. (2010) using luminous and ultraluminous infrared galaxies. [S II]λ6716/Hα is higher in diffuse ionized gas compared to H II regions. For the Galaxy, [S II]λ6716/Hα in diffuse ionized gas and in H II regions is around 0.38 and 0.12 (Madsen et al. 2006), respectively. The difference of [S II]λ6716/Hα in diffuse ionized gas and H II regions is smaller in the dwarf irregular galaxy (Hidalgo-Gámez & Peimbert 2007) than in the Galaxy. We took $\frac{[\text{S II}]/\lambda6716}{H\alpha} = 0.125$ for diffuse ionized gas and $\frac{[\text{S II}]/\lambda6716}{H\alpha} = 0.090$ for H II regions as the representative values for our sample from the dwarf irregular galaxy NGC 6822 (Hidalgo-Gámez & Peimbert 2007) and take $\frac{[\text{S II}]/\lambda6716}{H\alpha} = 0.38$ for diffuse ionized gas and $\frac{[\text{S II}]/\lambda6716}{H\alpha} = 0.12$ for H II regions as the representative values for star-forming spirals. In addition, we have assumed that the ratio of Hα luminosity coming from H II region and diffuse ionized gas is 5:5 for spirals (Sb and Sc) and that the ratio is 7:3 for our sample (starbursts; Figure 8 in Oey et al. 2007). In our estimate, we took three different values for the electron density of diffuse ionized gas: $n_e,\text{DIG} = 0.5 \text{ cm}^{-3}, 10 \text{ cm}^{-3}, \text{ and } 50 \text{ cm}^{-3}$. Recall that we fitted a function $R(n_e) = a\frac{b + n_e}{c + n_e}$, so the theoretical line ratio in diffuse ionized gas (DIG) is $R_{\text{DIG}} = a\frac{b + n_e,\text{DIG}}{c + n_e,\text{DIG}}$. 

![Figure 5. SFR surface density vs. thermal pressure (without error bars or upper limits) in H II regions for our sample, with green peas marked by green filled circles and Lyman break analogs marked by red stars. This figure is to show the data that are used in Spearman’s rank correlation analysis. The thermal pressure is based on the electron density measurements that are listed in column 8 in Table 1. Details: for the objects with $R > 1.5$, we could not get a reliable electron density measurement, so we excluded them for the Spearman’s rank correlation analysis (not shown in this figure). For the objects with $R \leq 1.38$, we measured the electron density from the line ratio (without considering the error bars). For objects with $1.38 < R < 1.5$, we measured the electron density from a ratio of 1.38.](image-url)
For dwarf irregular starbursts,

\[
R_{\text{observed}} = \frac{L_{\text{6716, DIG}} + L_{\text{6716, H II}}}{L_{\text{6731, DIG}} + L_{\text{6731, H II}}}
= \frac{0.125 \times L(\text{H}_\alpha, \text{ DIG}) + 0.090 \times L(\text{H}_\alpha, \text{ H II})}{R_{\text{DIG}}} + \frac{0.090 \times L(\text{H}_\alpha, \text{ H II})}{R_{\text{H II}}},
\]

so

\[
R_{\text{observed}} = \frac{0.125 \times 0.3 + 0.090 \times 0.7}{R_{\text{DIG}}} + \frac{0.090 \times 0.7}{R_{\text{H II}}},
\]

where \( L \) stands for luminosity. That is,

\[
R_{\text{H II}} = \frac{0.900 \times 0.7}{0.125 \times 0.3 + 0.090 \times 0.7} - \frac{0.125 \times 0.3}{R_{\text{DIG}}},
\]

where \( R_{\text{H II}} \) is the ratio of the fluxes of [S II] doublets that are emitted from H II regions. From the relation \( R(n_e) = \frac{b + n_e}{c + n_e} \), we know that the real electron density in H II regions is \( n_{e, \text{II}} = (c + R_{\text{H II}} - a \times b) \). So \( R_{\text{H II}} \) can be written as a function of \( R_{\text{observed}} \) and \( R_{\text{DIG}} \), and thus a function of \( R_{\text{observed}} \) and \( n_{e, \text{DIG}} \). For spiral galaxies, the demonstration process is the same. We compare the real electron density in the H II region and the electron density measured directly from the integrated luminosity in Figure 6. The left panels are for spiral galaxies, and the right panels are for dwarf irregular starbursts. According to Figure 6, for irregular dwarf starbursts (representative of our sample) the electron density in the H II region is underestimated by \( \sim 0.2 \)–\( 0.4 \) dex, for spirals it is underestimated by \( \sim 1.0 \) dex. For irregular dwarf starbursts, the three different assumptions of the electron density in DIG give roughly the same result, while for spirals this assumption matters when the measured electron density from integrated luminosity is lower than \( 10^{2.5} \) cm\(^{-3} \). We argue that we are not sure whether all the objects in our sample resemble the cases of a dwarf irregular starburst galaxy in the left panels of Figure 6, so we show the cases of star-forming spirals as well, as an extreme limit.

One way to get a good measurement of the electron density in H II regions is to use Integrated Field Unit (IFU) measurements or to use other line pairs that mainly originate from H II regions and are sensitive to \( 10^7 \) cm\(^{-3} \) \( < n_e < 10^8 \) cm\(^{-3} \), such as [O III] 88/52 μm, [S III] 33/19 μm in the infrared. In addition, we should note that the emission lines used for the electron density and electron temperature measurements for the whole galaxy is surface-brightness-weighted. Even inside the H II region or among different H II regions the electron density and the electron temperature can present a gradient. IFU measurement can help with this issue.

5.2. Diffuse Gas As a Possible Cause for Correlation?

Is it possible that the lower pressure in H II regions of lower ΣSFR galaxies is due to varying contribution of DIG in low SFR surface density galaxies and high SFR surface density galaxies? Below we discuss the possible different “extent of underestimate” of H II region pressure in galaxies with different ΣSFR.

If lower ΣSFR galaxies have a higher fraction of [S II] λλ6716,6731 emission coming from DIG than high ΣSFR galaxies, then lower ΣSFR galaxies will suffer a more substantial underestimate of the electron densities and pressure in H II regions. How should we compare this fraction in low ΣSFR galaxies and high ΣSFR galaxies? In the extreme case when all these galaxies have nearly the same [S II]λλ6716,6731/H\(_\alpha\) in DIG, and nearly the same [S II]λλ6716,6731/H\(_\alpha\) in H II region, the observed [S II]λλ6716,6731/H\(_\alpha\) normalized by metallicity for these objects should directly imply the fraction of [S II]λλ6716,6731 emission coming from DIG (the higher [S II]λλ6716,6731/H\(_\alpha\) is, the higher the fraction of [S II]λλ6716,6731 emission coming from DIG is). We measured direct T,λ-based metallicities for 19 objects out of the “final sample” (T. X. Jiang et al., 2019, in preparation). We find that there is no prominent anticorrelation between ΣSFR and observed [S II]λλ6716,6731/H\(_\alpha\) normalized by metallicity. However, given that starburst galaxies usually have a small fraction of DIG (Calzetti et al. 1999; Oey et al. 2007), we consider it unlikely that the whole trend in Figure 4 is driven by differential contribution of DIG in different galaxies.

5.3. Comparison with Correlation at High Redshift

Our study observationally indicates that the nearby compact starburst galaxies with higher SFR surface density tend to have higher thermal pressure in H II regions.

Shimakawa et al. (2015) presented the relation between electron density and ΣSFR for the H\(_\alpha\) emitters at \( z \leq 2.5 \). Note that [O II]\( λλ3726,3729 \) are used as tracers of the electron density in Shimakawa et al. (2015), while [S II] doublets are used in our work. We estimate the H II region thermal pressure for their sample using \( P = 2 \frac{n_e}{m_e} T_k R_{\text{HI}} \) where we assume \( T = 10^4 \text{K} \). We estimate these galaxies at \( z \sim 2.5 \) to our sample. As shown in Figure 4, the H\(_\alpha\) emitters at \( z \sim 2.5 \) obey very similar ΣSFR correlation with thermal pressure in H II regions to our starburst galaxies at \( z < 0.3 \). Note that our sample is larger than the sample in Shimakawa et al. (2015). For the same ΣSFR, the thermal pressure in H II regions in \( z \sim 2.5 \) galaxies is comparable to that in local \( (z < 0.3) \) analogs (green peas and LBAs). Since green peas and LBAs are the best analogs of high-redshift Ly\(_\alpha\) emitters and high-redshift LBGs, the high-redshift Ly\(_\alpha\) emitters and high-redshift LBGs might also have a similar correlation.

5.4. Interpretations of the Correlation

There could be different physical causes for the correlation between SFR surface density and thermal pressure in H II regions. We discuss them as follows.

1. As H II regions evolve, they expand because they are overpressured, and the H II region thermal pressure could drop. The ionizing photon rate due to the UV fluxes of massive stars also drops after around 5 Myr after the burst, thus the H\(_\alpha\) luminosity drops. This could play a role in the correlation observed in this work. We have measured the ages of the young starbursts in 19 objects out of the “final sample” by performing SED fitting to binned SDSS spectra (T. X. Jiang et al. 2019, in preparation). We do not find systematically older starburst ages among the galaxies having lower SFR surface density and lower thermal pressures. Therefore, this scenario should not be the primary cause of the observed correlation for local analogs. In fact the UV emission from the green peas in our sample is dominated by very young populations (mean age of 5–6 Myr).
2. The positive-correlation found in Section 4 between ΣSFR and thermal pressure in HII regions is expected if the thermal pressure is mainly driven by stellar feedback. For example, the mechanical energy injection due to stellar winds and/or supernovae in star-forming regions can increase the gas pressure (Strickland & Heckman 2009). Heckman et al. (1990) show that in case of starbursts with strong galactic outflows the pressure is dominated by thermal pressure.

5.5. Comparison with the Simulation Work

From the literature we found simulation work by Kim et al. (2011) that reported a correlation between ΣSFR and gas pressure. It is interesting to compare it with our work. Kim et al. (2011) conducted numerical simulations of multiphase gaseous disks in the diffuse-atomic-gas-dominated regime (Σ = 3–20 M⊙ pc−2). The simulations span a few hundred megayears, and the disks evolve to a state of vertical dynamical equilibrium and thermal equilibrium. From the simulations they have seen the nonlinear correlation between the SFR surface density ΣSFR and the total diffuse gas pressure at the midplane. They have argued that this correlation also applies to the starburst regime (the gas surface density Σ ∼ 10^2–10^4 M⊙ pc−2). We plot their correlation in Figure 4 as a comparison to the correlation of our sample. The slopes of the correlations are similar to each other. At a fixed ΣSFR, the thermal pressure in the HII region in our local analogs is somewhat smaller than the total midplane pressure in their simulations (by ∼0.3 dex). However, there are three main factors that we need to pay attention to when we do the
comparison, due to the differences between the physical properties in this work and in their simulations. First, the local analogs are compact starbursts of ages \(<10^7\) yr. They may not have had time to come into equilibrium yet. Second, we expect \(H\alpha\) regions this young to be overpressured. Third, the thermal pressure is only a fraction of the total pressure, which also includes contributions from turbulence (a factor of 2 or more for Mach numbers \(M > 1\); Elmegreen & Hunter 2000), magnetic fields, and cosmic-ray pressure. The effects of these other sources of pressure will be to lower our observed thermal pressures below the total pressure that Kim et al. (2011) use, as seen in Figure 4; while overpressure in the \(H\alpha\) regions will have the opposite effect. Overall, then, the correlation slope we have observed is broadly consistent with Kim et al. (2011), and a modest offset of the correlation zero-point (of either sign) appears physically plausible.

6. Summary

We have discussed the relation between the SFR surface density and the thermal pressure in \(H\alpha\) regions for nearby \((z < 0.30)\) compact starbursts, with the sample of green peas, the nearby analogs of high-redshift \(Ly\alpha\) emitters, and LBAs, the nearby analogs of high-redshift LBGs.

1. We have measured the electron densities for a large sample of local analogs, which are \(100 \sim 700 \text{ cm}^{-3}\), comparable to the typical values for \(z \sim 2\) star-forming galaxies and larger than the typical values measured for SDSS star-forming galaxies. We have found that the electron temperature in \(H\alpha\) regions for our sample is larger than the representative value of \(H\alpha\) regions in \(z \sim 0\) star-forming galaxies, with the median value around 12,000 K. We have measured the size of the green pea galaxies in the high-resolution \(HST\) COS NUV images with GALFIT. We have found that the typical size of green pea galaxies is \(\sim 0.19\) arcsec, and \(\sim 0.7\) kpc.

2. In our sample, green peas and LBAs have high \(\Sigma SFR\) up to \(1.2 M_{\odot} \text{ yr}^{-1} \text{kpc}^{-2}\) and high thermal pressure in the \(H\alpha\) region up to \(P/k_B \sim 10^{5-7} \text{ K cm}^{-3}\), similar to the high pressures seen in local starburst, which have massive outflows (e.g., M82). Large-scale outflows are necessary for the resonantly scattered \(Ly\alpha\) photons to escape.

3. More importantly, we have found a correlation between SFR surface density and the thermal pressure in \(H\alpha\) regions for the local analogs. This suggests a similar correlation in high-redshift \(Ly\alpha\) emitters and LBGs.

4. The correlation, as well as the range of pressures, is consistent with the results from \(H\alpha\) emitters at \(z \sim 2.5\) in Shimakawa et al. (2015).

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ORCID iDs

Tianxing Jiang https://orcid.org/0000-0002-2222-6129
Sangeeta Malhotra https://orcid.org/0000-0002-9226-5350
Huan Yang https://orcid.org/0000-0003-2260-7420
James E. Rhoads https://orcid.org/0000-0002-1501-454X

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