A REDLINE STARBURST: CO(2−1) OBSERVATIONS OF AN EDDINGTON-LIMITED GALAXY REVEAL STAR FORMATION AT ITS MOST EXTREME

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ABSTRACT

We report observations of the CO(2−1) emission of SDSS J1506+54, a compact (re ∼ 135 pc) starburst galaxy at z = 0.6. SDSS J1506+54 appears to be forming stars close to the limit allowed by stellar radiation pressure feedback models: the measured LIR/L\textsubscript{CO} ∼ 1500 is one of the highest measured for any galaxy. With its compact optical morphology but extended low surface brightness envelope, post-starburst spectral features, high infrared luminosity (L\textsubscript{IR} > 10\textsuperscript{12.5} L\textsubscript{☉}), low gas fraction (M\textsubscript{H}/M\textsubscript{⋆} ∼ 15%), and short gas depletion time (tens of Myr), we speculate that this is a feedback-limited central starburst episode at the conclusion of a major merger. Taken as such, SDSS J1504+54 epitomizes the brief closing stage of a classic model of galaxy growth: we are witnessing a key component of spheroid formation during what we term a “redline” starburst.

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

Online-only material: color figures

1. INTRODUCTION

Theoretical studies suggest that the majority of the stellar mass in the central regions of massive spheroids forms in situ in powerful, compact starbursts (e.g., Narayanan et al. 2010). In these systems, radiative feedback from stars is expected to produce an upper limit on the star formation rate (SFR) density (Σ\textsubscript{⋆}) by limiting the density of the star-forming gas (Σ\textsubscript{gas}; Thompson et al. 2005; Murray et al. 2005). One explanation for the small range in central stellar surface densities observed in the cores of local spheroids is that they formed in compact starbursts where the bulk of the gas reservoir formed stars at the Eddington limit (Hopkins et al. 2010); however, observations have only just begun to probe the most extreme Σ\textsubscript{⋆}−Σ\textsubscript{gas} in distant powerful starbursts that are the antecedents of massive galaxies today.

Diamond-Stanic et al. (2012, hereafter DS12) reported the discovery, with the Wide-field Infrared Survey Explorer (WISE), of a population of moderate-redshift (z ∼ 0.5) galaxies that appear to be among the highest density starbursts yet observed. The Hubble Space Telescope (HST) imaging reveals that these systems are remarkably compact in the optical bands, with re ∼ 100 pc (DS12; P. H. Sell et al. 2013, in preparation), while the optical spectra and UV−IR spectral energy distributions (SEDs) imply high SFRs approaching 10\textsuperscript{3} M\textsubscript{☉} yr\textsuperscript{−1} (and thus very high Σ\textsubscript{⋆}), with little or no contribution from an active galactic nucleus (AGN). The galaxies also exhibit extremely blueshifted (1000 km s\textsuperscript{−1}) Mg\textsubscript{II} λλ2796, 2803 interstellar absorption lines (Tremonti et al. 2007) indicative of powerful feedback.

In order to test if these compact galaxies represent the formation of a massive stellar bulge via a feedback-limited starburst, we require a measurement of the cold gas reservoir, since Eddington-limited star formation places a theoretical upper limit on Σ\textsubscript{⋆}/Σ\textsubscript{gas} for the actively star-forming gas. In this Letter we present new observations at 2 mm of the most extreme galaxy in the DS12 sample with the Institut de Radioastronomie Millimétrique (IRAM) Plateau de Bure Interferometer (PdBI). We measure the CO(2−1) molecular emission line and derive the gas properties of this remarkable system to test the picture of Eddington-limited star formation in a compact starburst galaxy.

2. SDSS J150636.30+540220.9

SDSS J150636.30+540220.9 at z = 0.608 (hereafter “SDSS J1506+54”) was targeted because it is the most extreme system in the DS12 sample in terms of its SFR density. The effective radius measured in HST WFC3 F814W (rest-frame V-band) imaging is re ∼ 135 pc (Figure 1), and even the most conservative estimates for the SFR result in densities of Σ\textsubscript{⋆} ≈ 3000 M\textsubscript{☉} yr\textsuperscript{−1} kpc\textsuperscript{−2}. Fitting to the WISE 12 and 22 μm photometry, the integrated 8–1000 μm luminosity of SDSS J1506+54 is estimated to be in the range log(L\textsubscript{IR}/L\textsubscript{☉}) = 12.6−13.1, assuming a representative range of SEDs appropriate for star-forming galaxies (Chary & Elbaz 2001; Dale & Helou 2002; Rieke et al. 2009). The dispersion in rest-frame 24 μm luminosity using this range of templates is just 0.1 dex. A complementary estimate of L\textsubscript{IR} is therefore made using L\textsubscript{24} using the empirical correlation L\textsubscript{24−L\textsubscript{8−1000}} found by Rieke et al. (2009); we find log(L\textsubscript{IR}/L\textsubscript{☉}) = 12.78 ± 0.06, consistent with the estimate above. The SFR of SDSS J1506+54 is estimated to be in the range 340–1400 M\textsubscript{☉} yr\textsuperscript{−1} assuming the calibration of Kennicutt (1998), scaled to a Chabrier initial mass function. This is in good agreement with the SFR estimated from stellar population fits to the UV−optical−IR photometry (DS12).

The stellar mass is estimated from stellar population template fits to the 0.1−3 μm photometry, with log(M\textsubscript{⋆}/M\textsubscript{☉}) = 11.12 ± 0.07 (assuming a 0.1−100 M\textsubscript{☉} Chabrier initial mass function;
see Moustakas et al. 2013). Finally, the outflow velocity of the galactic wind is traced by the interstellar medium (ISM) Mg II λ2796, 2803 absorption lines, which indicate a maximum \( v_{\text{abs}} \approx -1210 \) km s\(^{-1}\) (Tremonti et al. 2007; DS12).

### 2.1. Comments on Possible AGN Contribution

The source does not appear to be dominated by an AGN. Although SDSS J1506+54 has the most luminous \([\text{O}III]\) λ5007 and \([\text{Ne} v]\) λ3426 emission of the DS12 sample (log(\(L_{[\text{O}III]}/\text{erg s}^{-1}\)) = 42.1 and log(\(L_{[\text{Ne} v]}/\text{erg s}^{-1}\)) = 41.1), only four counts were detected with Chandra in the 2–10 keV X-ray band, corresponding to a luminosity of \(L_X = 2.9\times10^{39} \text{ erg s}^{-1}\). Assuming typical ratios between X-ray, \([\text{O}III]\) λ5007, and \([\text{Ne} v]\) λ3426 luminosities, and accounting for possible small ~30% dust attenuation of the narrow-line region based on the reddening derived from our fit to the SED (DS12), the Chandra limits imply an X-ray absorption factor of ~10–20 for a buried AGN (DS12; Heckman et al. 2005; Gilli et al. 2010). However, as DS12 argue, even if the X-ray attenuation factor was as high as 100, the AGN would contribute less than half of the observed 2 \(\mu\)m luminosity (Diamond-Stanic et al. 2009; Gandhi et al. 2009). Thus, star formation is likely to be the dominant power source of the bolometric emission of SDSS J1506+54.

### 3. IRAM PLATEAU DE BURE 2 mm OBSERVATIONS

Observations were conducted with IRAM PdBi over 2012 June–July in configuration D, using five antennas and the WideE correlator. We targeted the CO(2–1) 230.54 GHz rotational transition at \(v_{\text{obs}} = 143.37 \text{ GHz (2 mm band)}\) in the direction of SDSS J1506+5402. The total (on source) integration time was 6.2 hr (after flagging; scans on-source were discarded for which the phases deviated by more than 45° from the solution), during which time the system temperature ranged between \(T_{\text{sys}} = 100 \text{ and } 400 \text{ K } (T_{\text{sys}}) \approx 200–250 \text{ K}\) for precipitable water vapor in the range \( \text{pwv} = 4–12 \) mm. Bandpass calibrators were the sources 3C84, 2200+420, or 3C273, gain calibration was performed with the sources 1418+546 and J1604+572, and the source MWC349 was used for flux calibration. The flux calibration accuracy is ~5%–10% at 2 mm. Data were calibrated, mapped, and analyzed using GILDAS (Guilloteau & Lucas 2000).

### 4. RESULTS

Figure 1 shows the velocity integrated CO(2–1) map of SDSS J1506+54 and Figure 2 presents the 2 mm spectrum around \(v_{\text{obs}} = 143.37 \text{ GHz}\). The CO(2–1) line is detected with high confidence at \(>8\sigma\) in the integrated map. The integrated line flux is \(\Delta V = 0.97 \pm 0.19 \text{ Jy km s}^{-1}\), corresponding to a luminosity of \(L_{\text{CO(2–1)}} = (4.8 \pm 0.9) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2\). Uncertainties are conservative; they are estimated via a bootstrap analysis, where we generate a series of realizations of the spectrum, adding noise to each 40 km s\(^{-1}\) channel, selected from a Gaussian distribution with \(\sigma = 1.1\) mJy. The standard deviation of the ensemble of integrated spectra is taken to be the 1\(\sigma\) error of the measured line flux.

The line profile is adequately fit by a single-Gaussian profile \((\chi^2/\nu = 1.1)\), with a velocity width FWHM = 283 ± 31 km s\(^{-1}\) (Figure 2). Assuming the average inclination angle \(i = 30\)°, the true width could be as large as ~560 km s\(^{-1}\). Galaxy-integrated CO spectra often exhibit double-peaked line profiles, indicative of a rotating disc or ring (e.g., Downes & Solomon 1998). There are some hints of this in the current spectrum, and so we also fit a double-Gaussian profile (fixing the individual line peaks and individual dispersions to be equal). The fit is formally \(\chi^2/\nu = 0.9\), not significantly improved over the single component fit. The peak-to-peak velocity is \(AV = (147 \pm 12) \text{ km s}^{-1}\), and the line dispersion, which includes the one-dimensional turbulent velocity dispersion of the gas, is \(\sigma = (49 \pm 6) \text{ km s}^{-1}\).
At first glance, it seems puzzling that the line width is not even larger, if the mass distribution is as compact as suggested by the rest-frame UV morphology. There are two main possibilities: (1) the $r_e$ for the stellar mass is more widely distributed than $r_e$ of light measured in the F814W band (near-infrared observations at the same resolution will be required to test this) such that the environment dominated by star formation is compact ($r \approx r_e$), but molecular gas dominated, or (2) the CO-emitting gas is more widely distributed than the compact optical emission. The lack of size and orientation constraints for the CO(2–1) emission make any estimate of $M_{\text{gas}}$ uncertain; however, it would be unusual if the bulk of the gas reservoir (and presumably the concomitant dust) was beyond $r_e$ and configured in a way that did not completely obscure the UV-bright core.

5. INTERPRETATION AND DISCUSSION

5.1. Comparison with Other Galaxies

The measured $L_\text{IR}/L'_\text{CO} \approx 1500$ is one of the highest measured for any star-forming galaxy (Figure 3). Even if we accounted for an AGN contribution of 25% to our lowest estimate of $L_\text{IR}$, SDSS J1506+54 is at the extreme tail of the $L_\text{IR}/L'_\text{CO}$ distribution, with $L_\text{IR}/L'_\text{CO} \approx 550$ in this case. There are a handful of other star-forming galaxies with similar $L_\text{IR}/L'_\text{CO}$ properties; for example, the $z = 0.575$ hyper-LIRG IRAS F00235+1024 (Combes et al. 2011) and the $z = 0.633$ ULIRG IRAS F10398+3247 (Combes et al. 2012) both have CO line luminosities measured in the 2–1 transition, and are also at the extreme end of the $L_\text{IR}/L'_\text{CO}$ distribution (Figure 3). Several galaxies in the sample of Combes et al. (2012) have $L'_\text{CO}$ upper limits implying extreme $L_\text{IR}/L'_\text{CO}$ and of these, two are obviously hosting AGN, as evident from their optical spectra.

Like SDSS J1506+54, F00235+1024 is not dominated by an AGN, although it is thought to be a non-negligible ($\approx 30\%$) AGN contribution to its total infrared emission (Verma et al. 2002; Farrah et al. 2002). F10398+3247 could also contain a deeply buried AGN, as it has a deep silicate absorption feature ($\tau_{\text{SG}} > 3$; Dartois & Muñoz-Caro 2007), often associated with nuclei blanketed by a dense screen of carbonaceous and silicate grains.

5.2. Eddington-limited Star Formation

How do we interpret such extreme systems? Can $L_\text{IR}/L'_\text{CO}$ be driven to such high values through star formation alone? In individual galaxies, isolated star-forming cores might be Eddington-limited, which is to say $\Sigma$ is capped by radiation pressure from the recently formed O and B associations (e.g., Scoville 2004; Shirley et al. 2003). However, when taken as a whole, galaxies form stars at sub-Eddington rates due to intermittency—the fact that only a small fraction of the cold gas reservoir is actually forming stars (Downes & Solomon 1998; Murray et al. 2005; Andrews & Thompson 2011). Under certain conditions, however, one could envision a scenario where the majority of the gas reservoir could be driven to form stars at the Eddington limit. SDSS J1506+54 is an excellent candidate for this phenomenon.

In the absence of nuclear heating, and assuming the model of momentum-driven feedback (e.g., Murray et al. 2005) the upper limit of $L_\text{IR}/L'_\text{CO}$ for star-forming galaxies is set by the Eddington luminosity. For optically thick dust emission ($\tau_{100\mu m} > 1$),

$$L_{\text{Edd}} = \frac{4\pi Gc}{\kappa} X_{\text{CO}} L'_\text{CO}$$  \hspace{1cm} (1)
powered by radiation pressure on dust grains intermingled with the ISM, and the ram-pressure of supernovae detonations (Murray et al. 2005). The strongly blueshifted Mg II lines are excellent evidence that this is the case (Tremonti et al. 2007; DS12).

The 2 mm spectrum of SDSS J1506+54 exhibits a marginally significant (3.2σ) narrow (σ < 40 km s$^{-1}$) spike close to the outflow velocity traced by Mg II (no RFI or telluric contaminant is expected at this frequency). We can draw no conclusions on such a low-significance feature, but we remark that if cold gas has become swept up in the outflow traced by Mg II absorption, and has survived shock-heating, then we might expect to detect entrained cold gas in this way.

6. SDSS J1506+54 AS AN EDDINGTON-LIMITED STARBURST INDUCED IN A LATE-STAGE MERGER

6.1. Formation

We speculate that SDSS J1506+54 is the remnant of a major merger. In this picture angular momentum losses caused by the dissipation of energy in shocks and gravitational torques cause the collapse of disk-gas to the central regions in each parent, and subsequently into a single merged core. This is a classic picture of galaxy growth that has been supported for many years by both theories, numerical simulations, and observations (Toomre & Toomre 1972; Sanders et al. 1988; Hernquist 1989; Barnes & Hernquist 1991; Sanders & Mirabel 1996; Schweizer 1996; Mihos & Hernquist 1996; Wyuts et al. 2010; Hopkins et al. 2013).

Tidal interactions in earlier stages of the merger might well be responsible for the faint extended (over several kiloparsecs) optical light (Figure 1; P. H. Sell et al. 2013, in preparation). Episodes of massive star formation must have occurred in the recent past (0.5–1 Gyr), with the A stars formed in (or moved to) relatively unobscured regions, in order to produce strong H$\alpha$ absorption observed in the optical spectrum. Indeed, the presence of post-starburst spectral features is entirely consistent with the typical timescales for equal-mass mergers (Lotz et al. 2008).

6.2. Fate

In the absence of additional cooling of gas, SDSS J1506+54 must be close to the cessation of star formation. At the current rate the gas will be consumed within a few tens of Myr, increasing the stellar mass by just $\sim 15\%$. This will place the galaxy in the exponential tail of the stellar mass function at $z \approx 0.5$ (Moustakas et al. 2013), but the current starburst contributes only a modest fraction of the total mass. Nevertheless, this small addition can have important consequences for the properties of the descendant (Robaina et al. 2009; Hopkins et al. 2010, 2013; Hopkins & Hernquist 2010).

Signatures of compact Eddington-limited starburst episodes could be found in the “fossil record” of local spheroids. Integral field observations of the cores of local elliptical galaxies reveal examples of compact ($\sim 100$ pc), “kinematically decoupled,” relatively young ($\lesssim 5$ Gyr) stellar components in a subset of the population (e.g., McDermid et al. 2006). The origin of these structures could well be found in powerful, compact starbursts such as the one we present. Star formation driven at extremely high $\Sigma$, could also have a critical impact on the form of the stellar initial mass function, due to the corresponding high cosmic-ray densities in such environments (Papadopoulos et al. 2011).
7. SUMMARY

We have presented observational evidence of what we term a "redline" starburst: a galaxy-forming star close to the Eddington limit assuming current models of stellar feedback. The measured $L_{\text{IR}}/L_{\text{CO}}$ $\sim 1500$ is one of the highest measured for any galaxy. Our conclusion is that the SDSS J1504+54 system is a final stage merger, undergoing a high-intensity circumnuclear starburst. If we are witnessing the intense—but fleeting—closing stages of the assembly of a massive stellar bulge, SDSS J1506+54 represents a unique opportunity to study the physics associated with this important evolutionary phase, and the mechanics of star formation at its most extreme.

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