สัญญาเลขที่ MRG6080294

รายงานวิจัยฉบับสมบูรณ์

โครงการ การศึกษาโครงสร้างบริเวณให้กำเนิดดาวฤกษ์ของดาราจักรในยุคก่อตัว

วิภู รุโจปการ
จุฬาลงกรณ์มหาวิทยาลัย

สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัยและสำนักงานคณะกรรมการการอุดมศึกษา

บทคัดย่อ

รหัสโครงการ: MRG6080294

ชื่อโครงการ: การศึกษาโครงสร้างบริเวณให้กำเนิดดาวฤกษ์ของดาราจักรในยุคก่อตัว

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โครงการวิจัยนี้มุ่งศึกษาโครงสร้างของบริเวณก่อกำเนิดดาวฤกษ์ในยุคก่อตัวของดาราจักร ซึ่งอยู่ในช่วง 10,000 ล้านปีแรกของเอกภพ ระยะเวลาดังกล่าวเป็นช่วงเวลาที่มีดาวฤกษ์เกิดใหม่ขึ้นอย่างรวดเร็ว และเป็นระยะเวลาไล่เลี่ยกับการก่อรวมตัวของหลุมดำยักษ์ที่ใจกลางดาราจักร ซึ่งปรากฏให้เห็นในรูปของดาราจักรกัมมันต์ ผู้วิจัยได้พัฒนาวิธีการใหม่ในการระบุตำแหน่งและการกระจายตัวของบริเวณให้กำเนิดดาวฤกษ์และแก่นดาราจักรกัมมันตะอย่างเป็นเอกเทศ กรรมวิธีใหม่นี้มีความละเอียดถึงระดับมิลิอาร์ควินาที คิดเป็นความแม่นยำระดับ 200 พาร์เซค (650 ปีแสง) ในดาราจักรที่อยู่ห่างไปกว่า 10,000 ล้านปีแสง การวิเคราะห์ข้อมูลร่วมจากการสังเกตในช่วงคลื่นวิทยุและมิลิเมตรทำให้สามารถส่องทะลุฝุ่นที่หนาทึบของดาราจักรในยุคนี้ได้ การศึกษาตำแหน่งของปรากฏการณ์ทั้งสอง ช่วยให้เราเข้าใจธรรมชาติพหุสัมพันธ์ของหลุมดำยักษ์และดาราจักร อันเป็นส่วนสำคัญยิ่งขององค์ความรู้ด้านวิวัฒนาการของดาราจักร เนื่องจากปัจจุบันเป็นที่ทราบกันแล้วว่าดาราจักรทั่วไปมีหลุมดำยักษ์อยู่ตรงศูนย์กลาง แต่ยังไม่เป็นที่ทราบแน่ชัดว่าหลุมดำดังกล่าววิวัฒนาการขึ้นอย่างไรและการก่อตัวของหลุมดำยักษ์มีผลต่อวิวัฒนาการของดาราจักรอย่างไร งานวิจัยนี้ชี้ให้เห็นเป็นครั้งแรกว่าหลุมดำยักษ์กำลังก่อตัวขึ้นในปริมณฑลของบริเวณให้กำเนิดดาวฤกษ์ และมีความเป็นไปได้สูงว่าทั้งสองปรากฏการณ์วิวัฒนาการร่วมกันขึ้นจากมวลก๊าซเดียวกัน และอาจเป็นพหุสัมพันธ์ที่เกิดขึ้นกับดาราจักรโดยทั่วไป ผู้วิจัยกำลังดำเนินการวิจัยต่อยอดเพื่อยืนยันการค้นพบนี้ด้วยการสังเกตจากหอสังเกตการณ์ที่มีประสิทธิภาพสูงที่สุดในโลกในช่วงคลื่นต่าง ๆ

คำหลัก: วิวัฒนาการของดาราจักร, ดาราจักรยุคก่อตัว, แก่นดาราจักรกัมมันต์

Abstract

Project Code: MRG6080294

Title: Dissecting the Structure of Star Formation at the Peak of Galaxy Assembly

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Project Period: 1 August 2017 – 30 April 2019 (2 years)

The goal of our program is to study the structure of star-forming regions during the peak epoch of galaxy assembly, the cosmic era encompassing the first 10 billion years of the Universe. This epoch is characterized by rapid formation of both stellar masses (i.e., star formation) and the rapid growth of supermassive black holes (i.e., massive black hole accretion, which appears as active galactic nuclei or AGN). Understanding the co-evolution of these phenomena in this cosmic epoch is, therefore, key to breakthroughs in galaxy evolution study. We have developed a new technique to independently capture the spatial distributions of star-forming regions and the site of AGN with an unprecedented, milliarcsecond resolution, corresponding approximately to a 200-parsec scale (650 light-year) at a distance of 10 billion light-years by combining radio and submillimeter observations. Early results from the application of this technique indicate that the AGNs are located within the compact regions of gas-rich, heavily obscured, intense nuclear star formation. This is consistent with a picture of *in situ* galactic bulges and SMBH growth and may represent the dominant process regulating the bulge - SMBH relationship through which all massive galaxies may pass. We are vigorously pursuing additional observations across the electromagnetic spectrum using best-in-class facilities worldwide to apply the technique developed in this work to definitively constrain the in-situ star-formation/AGN co-evolution picture.

Keywords: galaxy: evolution, galaxy: starburst, galaxy: active galactic nuclei

1. Introduction to the Research Problem

The convergence of theory and observation in galaxy evolution is a major milestone in astrophysics. With appropriate sets of parameters, models of galaxy formation can reproduce, for instance, the luminosity and mass distributions of today's galaxies and the cosmic star formation rate (SFR) history since the formation epoch of first stars. However, many of the most fundamental processes in the model are not well understood, especially down to galactic scales, where the current frontier questions in galaxy evolution lie: *How did galactic spheroids form? How did galaxies and their massive black holes (MBH) co-evolve?*

A crucial aspect of improving our understanding of the link between MBHs and star formation requires high-resolution imaging to capture, within galaxies, where MBHs are growing and the details of the distributions of cold gas and star formation to corroborate or challenge the models predicting the intermediaries. Theorists have put forward a picture that clumpy star formation at kpc-scale resulting from violent instability in gas-rich disks fed by cold gas inflows could migrate inward to coalescence into a central starburst (e.g., Bournaud et al. 2014). Simulations suggest that once cold gas falls within a ~few 100 of parsec from the MBH, a cascade of self-propagating instability could fuel the active galactic nuclei (AGN), characterized by the rapidly rising gas surface density near the MBH (Hopkins & Quataert 2010). Observing both the SF clumps and the rapid increase in gas surface density requires gas and dust to be traced from the ~kpc scale to ~100 pc scale from the location of the AGN.

Indeed, UV-bright star-forming clumps are ubiquitous in z ~ 1-3 star-forming galaxies (SFGs). They appear to be ~1 kpc in size, contain 10^8-10^9 solar masses of stellar mass, form stars at 1-30 solar masses per year, and reside in kinematically-ordered systems. Their size, mass, SFRs, and age gradients are broadly consistent with the clump-facilitated bulge formation scenario. However, observational evidence is now mounting that the apparent kpc-clumps are due to the limited observing resolutions around ~1 kpc of the Hubble Space Telescope (HST) and ground-based optical facilities. The Atacama Large Millimeter/submillimeter Array (ALMA) sub-kpc images of SFGs at z ~ 3 show that clumps account for only a minority of the total SFR and in some cases the galaxies are even smooth with no apparent clumps (Hodge et al. 2019; Rujopakarn et al. 2019). The relatively small role of clumps of the star formation at 200-400 pc scale is consistent with the new generation of simulations that the apparent kpc-sized clumps originate from clusters of <100-pc ``sub-clumps" blending together

(Mandelker et al. 2014; Behrendt et al. 2016; Tamburello et al. 2017). However, the existence of sub-clumps has to be established in the typical (i.e., heavily dust-obscured) SFGs before predictions on their roles in bulge/MBH formation can be made.

On the MBH side, localizing where exactly the AGN is growing in relation to the sites of intense SF is extremely challenging with conventional AGN indicators at z ~ 1-3. The X-ray resolution is ~1" whereas 0.01" is needed; the spatially-resolved optical diagnostics at 0.05" at z ~ 2 needs 40-meter-class telescopes; the mid-infrared AGN tracers are limited to ~5" resolution (i.e., 40 kpc). To add to the already immense challenge, the potentially extreme A_V of ~few 10-100 magnitudes toward the center of rapidly star-forming galaxies at this epoch (e.g., Simpson et al. 2017; Calabro et al. 2018) virtually precludes optical avenues. As such, spatially-resolved, extinction-independent images that capture both the growing stellar masses and MBH have never been possible at z ~ 2.

A breakthrough requires dissecting the dust-obscured central intensely star-forming disk at ~100 parsec scale within z ~ 1-3 galaxies, and specifically within galaxies where the location of an AGN is known precisely, which will shed light on the size and distribution of their star-forming substructures and the gas distribution down to the central 100 parsec of the MBH.

2. Objectives

2.1 To develop a technique to capture the spatial distribution of star formation and supermassive black hole growth in typical galaxies at the peak epoch of their assembly. The fundamental obstacles to overcome are (a) the strong dust extinction; (b) the extremely high angular resolution of sub-arcsecond required.

2.2 To apply the novel technique to study the co-evolution of star formation and supermassive black hole growth.

2.3 To identify future high-impact avenues for galaxy evolution studies that maximally synergizes high-resolution radio and millimeter interferometric observations.

3. Methodology

3.1 Identify radio-dominated AGN with strong star-forming activities. This involves compiling and extracting observations from the radio and sub/millimeter bands, process the data in a self-consistent manner, and identify radio sources whose synchrotron emission from AGN far exceeds the level corresponding to their star-forming activities. As such, radio emission pinpoints the location of AGN; the sub/millimeter emission is virtually free of AGN and, therefore, provide independent localization for the intense star-forming regions.

3.2 Prepare all necessary ancillary data from multiwavelength observations; cross reference their positional accuracies. This includes verifying their astrometric accuracy against the common reference frame, compiling multiwavelength ancillary data to measure their physical properties, e.g., stellar mass, star formation rate, stellar population properties, and their stellar mass distribution where applicable from the optical morphologies.

3.3 Accurately measure their position and morphology from radio and sub/millimeter interferometric observations. This allows establishing the spatial distributions of star formation and AGN phenomena down to the unprecedented accuracy of ~200 parsec at z ~ 3.

3.4 Examine their position and morphologies to study implications on galaxy evolution scenarios. Interpretations of the *in-situ* co-evolution scenario is tentatively proposed, to be definitively tested with a larger sample expected from observations described in Section 5.

3.5 Apply the new techniques on new observations; explore avenues to push the technique to even higher resolution with the augmentation of gravitational lensing. These activities will be supported by an upcoming TRF-MRG62 program (Section 5.4).

4. Results

Our pilot results have been published in The Astrophysical Journal Letters (Rujopakarn et al. 2018, 854, 4). The paper examined the existing ALMA observations of dust continuum of radio sources in the GOODS-S and COSMOS JVLA images at 6 and 3 GHz (Rujopakarn et al. 2016 and Smolcic et al. 2017). The search turned up three objects with >5x radio excess over the level predicted by the far-infrared/radio correlation, and with the observations being taken with sufficiently extended arrays to resolve the sub/millimeter emission. In all three galaxies, the AGNs are located within the compact regions of gas-rich, heavily obscured, intense nuclear star formation, with effective radii of 0.4 - 1.1 kpc and SFRs of ~100 - 1200 solar masses per year.

If the star-formation and AGN-driven outflows that may be present (e.g., Mullaney et al. 2013) do not completely disrupt the cold gas supply, and both types of activity proceed for the duration of their host's typical stellar mass doubling time of ~0.2 Gyr, then the newly formed stellar mass within the central kpc will be of order 10^{11} solar masses. Likewise, if the MBH is allowed to accrete at a rate predicted by the correlation between SFR and the average black hole accretion rate relation (Chen et al. 2013) for the same duration, the accreted MBH mass will be $10^{6.7}$ - $10^{7.8}$ solar masses, similar to those found in local massive galactic bulges. That is, the ongoing episode of SF and MBH growth in these galaxies is potentially capable of producing bulge stellar masses and MBH masses on the local scaling relations. This is consistent with a picture of *in situ* galactic bulge and MBH growth, and may represent the dominant process regulating the bulge – MBH relationship through which all massive galaxies may pass.

5. Future Works

The new technique developed in this work has led to a number of follow-up studies involving multiple programs to successfully pursue competitively-obtained observing time on the best-in-class facilities. These follow-up programs include:

5.1 Atacama Large Millimeter/submillimeter Array (ALMA), Cycle 6 program *"Testing to ~100 parsec the co-spatiality of intense star formation and supermassive black hole growth at z ~ 2"* (PI: W. Rujopakarn). This will expand the Rujopakarn et al. (2018) sample from three to 55 galaxies.

5.2 Jansky Very Large Array (VLA), Semester 2019A program VLA/19A-242 *"Capturing Radio AGNs at Cosmic Dawn with JVLA and JWST"* (PI: W. Rujopakarn). This will conduct the ultra-deep radio survey required to capture high redshift AGNs.

5.3 Large Binocular Telescope Observatory (LBTO), Semester 2019A program *"LBT/LUCI redshift survey of proto-bulge/SMBH candidates"* (G. Rieke & W. Rujopakarn). This will use near-infrared spectroscopy on the LBTO, which is currently the fastest facility of its kind in the world, to measure spectroscopic redshifts of the co-spatial SF/AGN objects.

5.4 TRF-MRG62 *program "Testing the co-evolution of the bulge–supermassive black hole at the peak of galaxy assembly"* (PI: W. Rujopakarn) is a continuation of this program.

6. Conclusions

We have developed a new technique to capture extinction-independent sub-kpc structures of star formation and localizing the sites of supermassive black hole accretion in $z \sim 3$ galaxies. In the pilot sample demonstrating the feasibility of the technique, we found AGN to occur within the region of intense star formation. This is consistent with an *in-situ* co-evolution between the two phenomena. We are vigorously pursuing multiple avenues to definitely confirm this evolutionary picture.

1. Output

Twenty-two publications were furnished under the support from this program; 13 of these are published in refereed journals (one first-author) and nine are submitted to journal for review. The published and submitted papers are listed in Sections 1.1 [items 1 - 13] and 1.2 [items 14 - 22], respectively.

1.1 The following journal publications carry acknowledgment for program MRG6080294, listed in a reverse chronological order. We note that the first-author publication is [3]. The latest available impact factors for relevant journals are following.

The Astrophysical Journal: 5.551
The Astrophysical Journal Letters: 6.634
The Astronomical Journal: 4.150
Astronomy & Astrophysics: 5.567
Publications of the Astronomical Society of Japan: 2.244
Monthly Notices of the Royal Astronomical Society: 4.961

[13] Zanella, A.; Daddi, E.; ...; **Rujopakarn, W.**, et al., "The [C II] emission as a molecular gas mass tracer in galaxies at low and high redshifts", 2018, Monthly Notices of the Royal Astronomical Society, 481, 1976

[12] Roy, Namrata; Bundy, Kevin; ...; **Rujopakarn, W.** et al., "Detecting Radio AGN Signatures in Red Geysers", 2018, The Astrophysical Journal, 869, 117

[11] Hatsukade, B.; Kohno, K.; ...; **Rujopakarn, W.**, et al. "ALMA twenty-six arcmin2 survey of GOODS-S at one millimeter (ASAGAO): Source catalog and number counts" 2018, Publications of the Astronomical Society of Japan, 70, 105

[10] Franco, M.; Elbaz, D.; ...; **Rujopakarn, W.**, et al. "GOODS-ALMA: 1.1 mm galaxy survey. I. Source catalog and optically dark galaxies", 2018, Astronomy & Astrophysics, 620, 152

[9] Silverman, J. D.; Daddi, E.; **Rujopakarn, W.;** et al., “Concurrent Starbursts in Molecular Gas Disks within a Pair of Colliding Galaxies at z = 1.52”, 2018, The Astrophysical Journal, 868, 75

[8] Silverman, J. D.; **Rujopakarn, W.;** Daddi, E.; et al., “The Molecular Gas Content and Fuel Efficiency of Starbursts at z ˜ 1.6 with ALMA”, 2018, The Astrophysical Journal, 868, 75

[7] Elbaz, D.; Leiton, R.; ...; Rujopakarn, W., et al., “Starbursts in and out of the star-formation main sequence”, 2018, Astronomy & Astrophysics, 616, 110

[6] Fujimoto, Seiji; Ouchi, Masami; ...; **Rujopakarn, W.,** et al. "ALMA 26 Arcmin2 Survey of GOODS-S at One Millimeter (ASAGAO): Average Morphology of High-z Dusty Star-forming Galaxies in an Exponential Disk (n $\simeq$ 1)", The Astrophysical Journal, 861, 7

[5] McLure, R. J.; Dunlop, J. S.; ...; **Rujopakarn, W.,** et al. “Dust attenuation in 2 < z < 3 star-forming galaxies from deep ALMA observations of the Hubble Ultra Deep Field”, 2018, Monthly Notices of the Royal Astronomical Society, 476, 3991

[4] Nyland, K.; Harwood, J. J.; ...; **Rujopakarn, W.,** et al. “Revolutionizing Our Understanding of AGN Feedback and its Importance to Galaxy Evolution in the Era of the Next Generation Very Large Array”, 2018, The Astrophysical Journal, 859, 23

[3] Rujopakarn, W.; Nyland, K.; Rieke, G. H., et al., “Cospatial Star Formation and Supermassive Black Hole Growth in z ˜ 3 Galaxies: Evidence for In Situ Co-evolution”, 2018, The Astrophysical Journal Letters, 854, 4

[2] Ueda, Y.; Hatsukade, B.; ...; **Rujopakarn, W.,** et al., “ALMA 26 arcmin2 Survey of GOODS-S at One-millimeter (ASAGAO): X-Ray AGN Properties of Millimeter-selected Galaxies”, 2018, The Astrophysical Journal, 853, 24

[1] Barro, G.; Kriek, M.; ...; **Rujopakarn, W.,** et al. “Spatially Resolved Kinematics in the Central 1 kpc of a Compact Star-forming Galaxy at z ˜2.3 from ALMA CO Observations”, 2017, The Astrophysical Journal Letters, 851, 40

1.2 The following manuscripts carrying the MRG6080294 acknowledgment have been submitted for publications in refereed journals. We note that [16] and [17] are now in press.

[22] Dessauges-Zavadsky, M; ...; **Rujopakarn, W.**, et al. "Molecular clouds in the Cosmic Snake, a normal star-forming galaxy 8 billion years ago", submitted to Nature Astronomy

[21] Schramm, M.; **Rujopakarn, W.**, et al.; "A Catastrophic Failure to Build a Massive Galaxy around a Supermassive Black Hole at z = 3.84", submitted to The Astrophysical Journal

[20] Yamaguchi, Y; ...; **Rujopakarn, W.**, et al. "ALMA 26 arcmin2 Survey of GOODS-S at One-millimeter (ASAGAO): Millimeter Properties of Stellar Mass Selected Galaxies", submitted to The Astrophysical Journal

[19] Masters, K.; ...; **Rujopakarn, W.**, et al. "HI-MaNGA: HI Followup for the MaNGA Survey", submitted to Monthly Notices of the Royal Astronomical Society

[18] Alasdair, T.; ...; **Rujopakarn, W.**, et al. "Cosmic Ray Diffusion in Young Starbursts Explains the Spatially-Resolved Radio Spectra of ALMA-identified Submillimeter Galaxies", submitted to The Astrophysical Journal

[17] Yamaguchi, Y.; ...; **Rujopakarn, W.**, et al.; "ALMA Twenty-Six arcmin2 Survey of GOODS-S at One-millimeter (ASAGAO): Near-Infrared-Dark Faint ALMA Sources", accepted for publication in The Astrophysical Journal

[16] Su, K.; ...; **Rujopakarn, W.**, et al. "Extreme Debris Disk Variability -- Exploring the Diverse Outcomes of Large Asteroid Impacts During the Era of Terrestrial Planet Formation", accepted for publication in The Astronomical Journal

[15] Rodighiero, G.; ...; **Rujopakarn, W.**, et al. "AGN in Dusty Starbursts at z = 2: Feedback Still To Kick In", submitted to The Astrophysical Journal Letters

[14] Schulze, A.; ...; **Rujopakarn, W.,** et al., "ALMA reveals the star formation rate distribution of the most luminous quasars at z ~ 2", submitted to Monthly Notices of the Royal Astronomical Society

2. Broader impacts and applications

In addition to the academic output listed in Section 7 and the ongoing research efforts, the broader impacts of this work are following.

2.1 Two students at Chulalongkorn University directly work with the VLA radio observations during the period of the TRF support. One of them is currently a Research Assistant at the National Astronomical Research Institute of Thailand (NARIT).

2.2 The work of Rujopakarn et al. (2018) represents one of the science cases for Thailand, represented by the NARIT, to explore investments in THz instrumentation as in-kind contributions with broader impact on advanced technology developments to participate in world-class submillimeter facilities. Please kindly refer to the PI for specific details on this matter.

3. Selected oral presentations

3.1 Invited Review Talk on "Sub-galactic views at the peak of galaxy assembly: pushing the ~100 parsec frontier at z ~ 3" at the IAU Symposium 352 "Uncovering early galaxy evolution in the ALMA and JWST era" in Viana do Castelo, Portugal (scheduled)

3.2 Invited Talk on "Sub-galactic views at the peak of galaxy assembly: pushing the ~100 parsec frontier at z ~ 3" at the "Extremely Big Eyes on the Early Universe" in Tokyo, Japan; March 2019

3.3 Talk entitled "Smooth cold dust disks in typical star-forming galaxies at z ~ 3" at the "Dusting the Universe" conference in Tucson, USA; March 2019

Appendix

Appended herewith are the first pages of the refereed publications listed in Section 1.1 of the output.

The Astrophysical Journal Letters, 851:L40 (6pp), 2017 December 20 https://doi.org/10.3847/2041-8213/aa9f0d

Spatially Resolved Kinematics in the Central 1 kpc of a Compact Star-forming Galaxy at $z \sim 2.3$ from ALMA CO Observations

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Abstract

We present high spatial resolution (FWHM $\sim 0\farcs14$) observations of the CO(8–7) line in GDS-14876, a compact star-forming galaxy at $z = 2.3$ with a total stellar mass of $\log(M_\star/M_\odot) = 10.9$. The spatially resolved velocity map of the inner $r \lesssim 1$ kpc reveals a continuous velocity gradient consistent with the kinematics of a rotating disk with $v_{\rm rot}(r = 1\,{\rm kpc}) = 163 \pm 5$ km s^{-1} and $v_{\rm rot}/\sigma \sim 2.5$. The gas-to-stellar ratios estimated from CO(8–7) and the dust continuum emission span a broad range, $f_{\rm gas}^{\rm CO} = M_{\rm gas}/M_\star = 13\%$–$45\%$ and $f_{\rm gas}^{\rm cont} = 50\%$–$67\%$, but are nonetheless consistent given the uncertainties in the conversion factors. The dynamical modeling yields a dynamical mass of $\log(M_{\rm dyn}/M_\odot) = 10.58^{+0.5}_{-0.2}$, which is lower, but still consistent with the baryonic mass, $\log(M_{\rm bar} = M_\star + M_{\rm gas}^{\rm CO}/M_\odot) = 11.0$, if the smallest CO-based gas fraction is assumed. Despite a low, overall gas fraction, the small physical extent of the dense, star-forming gas probed by CO(8–7), $\sim 3\times$ smaller than the stellar size, implies a strong relative concentration that increases the gas fraction up to $f_{\rm gas}^{\rm CO,1\,kpc} \sim 85\%$ in the central 1 kpc. Such a gas-rich center, coupled with a high star formation rate (SFR) $\sim 500\,M_\odot$ yr^{-1}, suggests that GDS-14876 is quickly assembling a dense stellar component (*bulge*) in a strong nuclear starburst. Assuming its gas reservoir is depleted without replenishment, GDS-14876 will quickly ($t_{\rm depl} \sim 27$ Myr) become a compact quiescent galaxy that could retain some fraction of the observed rotational support.

Key words: galaxies: high-redshift – galaxies: photometry

1. Introduction

Compact star-forming galaxies (SFGs) are frequently referred to as a population of massive, strongly SFGs at $z \gtrsim 2$, whose small sizes and high stellar-mass concentrations (e.g., Wuyts et al. 2011; Barro et al. 2013) closely resemble those of typical quiescent galaxies of the same mass and redshift (e.g., Daddi et al. 2005; Trujillo et al. 2007). These galaxies have been identified in sizable numbers and their properties: small stellar sizes, steep radial mass profiles, and obscured star formation rate (SFR) properties have all been confirmed by multiple studies (e.g., Barro et al. 2014a; van Dokkum et al. 2015). Moreover, NIR spectroscopic follow-up has allowed a characterization of the kinematic and dynamical properties of their ionized gas from the analysis of rest-frame optical emission lines (e.g., Barro et al. 2014b; van Dokkum et al. 2015; Nelson et al. 2016). These initial results revealed high integrated velocity dispersions ($\sigma \gtrsim 200$ km s^{-1}) and large dynamical masses, roughly consistent with their stellar masses, which imply relatively low gas (and dark matter) fractions and short depletion times. All of this evidence is consistent with the evolutionary picture in which compact SFGs are in a short-lived starburst phase, triggered by a dissipative event, which leads to the rapid formation of a compact core and subsequent quenching into a compact quiescent galaxy (e.g.; Wellons et al. 2015; Zolotov et al. 2015).

Nonetheless, tension with the dynamical constraints emerged when further spectroscopic follow-up of compact SFGs revealed that at least 20% have dynamical masses that are up to $10\times$ lower than their stellar masses (van Dokkum et al. 2015). The most likely explanation for such large discrepancies are the uncertainties on the dynamical modeling assumptions. For example, the line of sight inclination, the ratio between ordered and random motions of the gas (i.e., the amount of rotational support, $v_{\rm rot}/\sigma$), the extent of gas profile relative to the stellar-mass distribution, or the aperture corrections to scale the measurements within the slit to either galaxy-wide or effective ($r = r_e$) values can all contribute to the observed difference (e.g., van Dokkum et al. 2015; Price et al. 2016).

A way to reduce these uncertainties is obtaining emission line velocity maps with similar or better spatial resolution than the stellar-mass maps derived from *Hubble Space Telescope* (*HST*) data (e.g., Wuyts et al. 2012). These resolved maps can trace the kinematic properties of the gas and allow a more precise dynamical modeling by comparing the gas and

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ALMA 26 arcmin^2 Survey of GOODS-S at One-millimeter (ASAGAO): X-Ray AGN Properties of Millimeter-selected Galaxies

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Abstract

We investigate the X-ray active galactic nucleus (AGN) properties of millimeter galaxies in the Great Observatories Origins Deep Survey South (GOODS-S) field detected with the Atacama Large Millimeter/submillimeter Array (ALMA), by utilizing the *Chandra* 7-Ms data, the deepest X-ray survey to date. Our millimeter galaxy sample comes from the ASAGAO survey covering 26 arcmin^2 (12 sources at a 1.2 mm flux-density limit of $\approx$0.6 mJy), supplemented by the deeper but narrower 1.3 mm survey of a part of the ASAGAO field by Dunlop et al. Ofthe 25 total millimeter galaxies, 14 have *Chandra* counterparts. The observed AGN fractions at $z = 1.5$–3 are found to be 90^{+8}_{-19}% and 57^{+23}_{-25}% for the ultra-luminous and luminous infrared galaxies with $\log L_{\rm IR}/L_{\odot} = 12$–12.8 and $\log L_{\rm IR}/L_{\odot} = 11.5$–12, respectively. The majority ($\sim$2/3) of the ALMA and/or Herschel detected X-ray AGNs at $z = 1.5$–3 appear to be star-formation-dominant populations, having $L_{\rm X}/L_{\rm IR}$ ratios smaller than the "simultaneous evolution" value expected from the local black-hole-mass-to-stellar-mass ($M_{\rm BH}$–M_*) relation. On the basis of the $L_{\rm X}$ and stellar mass relation, we infer that a large fraction of star-forming galaxies at $z = 1.5$–3 have black hole masses that are smaller than those expected from the local $M_{\rm BH}$–M_* relation. This contrasts previous reports on luminous AGNs at the same redshifts detected in wider and shallower surveys, which are subject to selection biases against lower luminosity AGNs. Our results are consistent with an evolutionary scenario in which star formation occurs first, and an AGN-dominant phase follows later, in objects that finally evolve into galaxies with classical bulges.

Key words: galaxies: active – galaxies: high-redshift – galaxies: starburst – X-rays: galaxies

1. Introduction

A key issue in cosmic evolution is the growth history of supermassive black holes (SMBHs) in galactic centers and their stellar populations, leading to the tight bulge-mass-to-SMBH-mass correlation observed in the present universe (see Kormendy & Ho 2013 for a recent review; following them, we use the term "bulge" only for classical bulges and elliptical galaxies). Overall good agreement between the star formation and mass-accretion history from $z \sim 3$ to $z \sim 0$ (e.g., Boyle & Terlevich 1998; Marconi et al. 2004; Aird et al. 2015; Ueda

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Cospatial Star Formation and Supermassive Black Hole Growth in $z \sim 3$ Galaxies: Evidence for In Situ Co-evolution

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Abstract

We present a sub-kiloparsec localization of the sites of supermassive black hole (SMBH) growth in three active galactic nuclei (AGNs) at $z \sim 3$ in relation to the regions of intense star formation in their hosts. These AGNs are selected from Karl G. Jansky Very Large Array (VLA) and Atacama Large Millimeter/submillimeter Array (ALMA) observations in the Hubble Ultra-Deep Field and COSMOS, with the centimetric radio emission tracing both star formation and AGN, and the sub/millimeter emission by dust tracing nearly pure star formation. We require radio emission to be $\geqslant 5\times$ more luminous than the level associated with the sub/millimeter star formation to ensure that the radio emission is AGN-dominated, thereby allowing localization of the AGN and star formation independently. In all three galaxies, the AGNs are located within the compact regions of gas-rich, heavily obscured, intense nuclear star formation, with $R_e = 0.4$–1.1 kpc and average star formation rates of $\simeq$100–1200 $M_\odot$ yr^{-1}. If the current episode of star formation continues at such a rate over the stellar mass doubling time of their hosts, $\simeq$0.2 Gyr, the newly formed stellar mass will be of the order of $10^{11} M_\odot$ within the central kiloparsec region, concurrently and cospatially with significant growth of the SMBH. This is consistent with a picture of in situ galactic bulge and SMBH formation. This work demonstrates the unique complementarity of VLA and ALMA observations to unambiguously pinpoint the locations of AGNs and star formation down to $\simeq$30 mas, corresponding to $\simeq$230 pc at $z = 3$.

Key words: galaxies: evolution – galaxies: starburst

1. Introduction

Multiple lines of evidence show a link between galaxy assembly and supermassive black hole (SMBH) growth, and that the accretion activity onto the SMBH leaves a lasting imprint on the evolution of its host galaxy (Kormendy & Ho 2013; Heckman & Best 2014 and references therein). Over the past decade, there has been considerable effort to determine how well galaxies that harbor active galactic nuclei (AGNs) are connected to the general galaxy population through large extragalactic surveys. A picture is emerging where there is a preference for AGNs, with moderate to high accretion rates, to reside in star-forming galaxies (SFGs) once selection effects are under control. This is seen across redshift from $z \lesssim 0.3$ (Kauffmann et al. 2003) up to $z \sim 1$ (Silverman et al. 2009) and beyond (Mullaney et al. 2012; Bongiorno et al. 2016). As a result, we have a clear association between accretion onto SMBHs and star formation, likely indicative of a co-evolution scenario on galaxy-wide scales.

However, a crucial aspect of improving our understanding of the link between SMBHs and star formation requires higher-resolution imaging to isolate, within galaxies, whether SMBHs are associated with the sites where the bulk of star formation is occurring. Yet, such images have been impossible at $z \sim 1$–3, potentially the formative era for the current relation. The commonly used tracers of AGNs do not have the required resolution, e.g., the resolution in the most sensitive *Chandra* X-ray observations of the Chandra Deep-Field South (Luo et al. 2017) is typically $\simeq 0\farcs7$–$3\farcs6$, corresponding to 5–27 kpc at $z = 3$. In addition, the strong dust extinction typical in rapidly assembling SFGs at this epoch (e.g., Dunlop et al. 2017) requires an extinction-independent tracer of star formation such as far-infrared, but again resolutions of $\sim 5''$, i.e., few tens of kiloparsecs, are typical.

Recently, the Atacama Large Millimeter/submillimeter Array (ALMA) now allows us to image the spatial distribution of the dust associated with star formation at sub-arcsecond resolution. The thermal continuum at, e.g., 870–1300 μm probes the rest-frame dust emission at 220–330 μm at $z = 3$, which is close to the peak of the spectral energy distribution (SED) of a typical dust-embedded star-forming galaxy. At the same time, this emission is largely free from any AGN contribution, which typically plummets rapidly longward of 40 μm (Elvis et al. 1994; Lyu & Rieke 2017). Likewise, sub-arcsecond centimetric radio observations (at, e.g., 1–10 GHz)

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Revolutionizing Our Understanding of AGN Feedback and its Importance to Galaxy Evolution in the Era of the Next Generation Very Large Array

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Abstract

Energetic feedback by active galactic nuclei (AGNs) plays an important evolutionary role in the regulation of star formation on galactic scales. However, the effects of this feedback as a function of redshift and galaxy properties such as mass, environment, and cold gas content remain poorly understood. The broad frequency coverage (1 to 116 GHz), high sensitivity (up to ten times higher than the Karl G. Jansky Very Large Array), and superb angular resolution (maximum baselines of at least a few hundred kilometers) of the proposed next-generation Very Large Array (ngVLA) are uniquely poised to revolutionize our understanding of AGNs and their role in galaxy evolution. Here, we provide an overview of the science related to AGN feedback that will be possible in the ngVLA era and present new continuum ngVLA imaging simulations of resolved radio jets spanning a wide range of intrinsic extents. We also consider key computational challenges and discuss exciting opportunities for multiwavelength synergy with other next-generation instruments, such as the Square Kilometer Array and the *James Webb Space Telescope*. The unique combination of high-resolution, large collecting area, and wide frequency range will enable significant advancements in our understanding of the effects of jet-driven feedback on sub-galactic scales, particularly for sources with extents of a few parsec to a few kiloparsec, such as young and/or lower-power radio AGNs, AGNs hosted by low-mass galaxies, radio jets that are interacting strongly with the interstellar medium of the host galaxy, and AGNs at high redshift.

Key words: galaxies: active – galaxies: nuclei – radio continuum: galaxies

1. Introduction and Motivation

Decades of observations of active galactic nuclei (AGNs) and their host galaxies have provided strong evidence that energetic AGN-driven feedback plays a pivotal role in influencing galaxy evolution. AGNs have been implicated in establishing the scaling relations between massive black hole (MBH) and host galaxy properties, regulating cooling flows in clusters, driving galaxy-scale outflows, and contributing to the build-up of the red sequence of massive galaxies (Kormendy & Ho 2013; Heckman & Best 2014). Cosmological simulations have provided further support for the importance of this paradigm by demonstrating the inability of models *lacking* energetic AGN feedback to produce the observed distribution of galaxy masses at $z = 0$ (e.g., Kaviraj et al. 2017).

The importance of AGN feedback in the context of galaxy evolution stems from the regulatory effect it may have on the star formation rate and efficiency of the host galaxy. AGN feedback may be driven by radiative winds launched by the accretion disks of powerful quasars ("radiative" or "quasar" mode feedback) or spurred by radio jets/lobes as they heat, expel, or shock their surroundings ("radio" or "jet" mode feedback). Observational evidence for both modes of feedback has been reported (e.g., Fabian 2012, and references therein). Villar Martín et al. (2014) show that on average, radio jets appear to be capable of producing more extreme gas outflows than accretion-disk winds. However, the relative importance of each mode, and the dependence on redshift, remains an open

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Dust attenuation in $2 < z < 3$ star-forming galaxies from deep ALMA observations of the *Hubble Ultra Deep Field*

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ABSTRACT

We present the results of a new study of the relationship between infrared excess (IRX $\equiv L_{\rm IR}/L_{\rm UV}$), ultraviolet (UV) spectral slope (β) and stellar mass at redshifts $2 < z < 3$, based on a deep Atacama Large Millimeter Array (ALMA) 1.3-mm continuum mosaic of the *Hubble Ultra Deep Field.* Excluding the most heavily obscured sources, we use a stacking analysis to show that $z \simeq 2.5$ star-forming galaxies in the mass range $9.25 \leq \log(M_*/{\rm M}_\odot) \leq 10.75$ are fully consistent with the IRX–β relation expected for a relatively grey attenuation curve, similar to the commonly adopted Calzetti law. Based on a large, mass-complete sample of $2 \leq z \leq 3$ star-forming galaxies drawn from multiple surveys, we proceed to derive a new empirical relationship between β and stellar mass, making it possible to predict UV attenuation (A_{1600}) and IRX as a function of stellar mass, for any assumed attenuation law. Once again, we find that $z \simeq 2.5$ star-forming galaxies follow A_{1600}–M_* and IRX–M_* relations consistent with a relatively grey attenuation law, and find no compelling evidence that star-forming galaxies at this epoch follow a reddening law as steep as the Small Magellanic Cloud (SMC) extinction curve. In fact, we use a simple simulation to demonstrate that previous determinations of the IRX–β relation may have been biased towards low values of IRX at red values of β, mimicking the signature expected for an SMC-like dust law. We show that this provides a plausible mechanism for reconciling apparently contradictory results in the literature and that, based on typical measurement uncertainties, stellar mass provides a cleaner prediction of UV attenuation than β. Although the situation at lower stellar masses remains uncertain, we conclude that for $2 < z < 3$ star-forming galaxies with $\log(M_*/{\rm M}_\odot) \geq 9.75$, both the IRX–$\beta$ and IRX–M_* relations are well described by a Calzetti-like attenuation law.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: starburst – galaxies: star formation – submillimetre: galaxies.

1 INTRODUCTION

Obtaining an accurate measurement of the evolution of the cosmic star formation rate density (SFRD) remains a key goal in observational cosmology. A thorough, pre-Atacama Large Millimeter Array (ALMA), review of our understanding of the evolution of the cosmic SFRD from both the ultraviolet (UV) and far-infrared (FIR) was provided by Madau & Dickinson (2014). The data assembled for this review clearly demonstrate the dominant contribution made by obscured star formation over the redshift range $0 < z < 3$, and the

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ALMA 26 Arcmin^2 Survey of GOODS-S at One Millimeter (ASAGAO): Average Morphology of High-z Dusty Star-forming Galaxies in an Exponential Disk ($n \simeq 1$)

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Abstract

We present morphological properties of dusty star-forming galaxies at $z = 1$–3 determined with the high-resolution (FWHM $\sim 0\farcs19$) Atacama Large Millimeter/submillimeter Array (ALMA) 1 mm map of our ASAGAO survey covering a 26 arcmin^2 area in GOODS-S. In conjunction with the ALMA archival data, our sample consists of 45 ALMA sources with infrared luminosity ($L_{\rm IR}$) range of $\sim 10^{11}$–$10^{13}\,L_{\odot}$. To obtain an average rest-frame far-infrared (FIR) profile, we perform individual measurements and careful stacking of the ALMA sources using the *uv*-visibility method that includes positional-uncertainty and smoothing-effect evaluations through Monte Carlo simulations. We find that our sample has an average FIR-wavelength Sérsic index and effective radius of $n_{\rm FIR} = 1.2 \pm 0.2$ and $R_{\rm e,FIR} = 1.0$–1.3 kpc, respectively, additionally with a point-source component at the center, indicative of the existence of active galactic nuclei. The average FIR profile agrees with a morphology of an exponential disk clearly distinguished from a de Vaucouleurs spheroidal profile (Sérsic index of 4). We also examine the rest-frame optical Sérsic index $n_{\rm opt}$ and effective radius $R_{\rm e,opt}$ with deep *Hubble Space Telescope* (*HST*) images. Interestingly, we obtain $n_{\rm opt} = 0.9 \pm 0.3$ ($\simeq n_{\rm FIR}$) and $R_{\rm e,opt} = 3.2 \pm 0.6$ kpc ($> R_{\rm e,FIR}$), suggesting that the dusty disk-like structure is embedded within a larger stellar disk. The rest-frame UV and FIR data of *HST* and ALMA provide us with a radial profile of the total star formation rate (SFR), where the infrared SFR dominates over the UV SFR at the center. Under the assumption of a constant SFR, a compact stellar distribution in $z \sim 1$–2 compact quiescent galaxies (cQGs) is well reproduced, while a spheroidal stellar morphology of cQGs ($n_{\rm opt} = 4$) is not, suggestive of other important mechanism(s) such as dynamical dissipation.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: starburst – galaxies: star formation

1. Introduction

The size and morphology of high-redshift galaxies provide us with invaluable insights into galaxy evolution and formation. The Sérsic index n (Sérsic 1963, 1968) and the effective radius $R_{\rm e}$ are key quantities to evaluate the size and morphological properties.

In the rest-frame ultraviolet (UV) to optical wavelengths, the *Hubble Space Telescope* (*HST*) has revealed the n and $R_{\rm e}$ properties for the high-redshift galaxies up to $z \sim 6$ and even $z \sim 10$, respectively (e.g., Shen et al. 2003; Ferguson et al. 2004; Hathi et al. 2008; Oesch et al. 2010; Ono et al. 2013; van der Wel et al. 2014; Kawamata et al. 2015, 2018; Shibuya et al. 2015; Bowler et al. 2017). These *HST* studies show that star-forming and quiescent galaxies have an exponential-disk morphology with a Sérsic index in the rest-frame optical wavelength $n_{\rm opt} \sim 1$ and a spheroidal morphology with $n_{\rm opt} \sim 4$, respectively. Moreover, the quiescent galaxies are more compact than the star-forming galaxies at a given stellar mass. These *HST* results indicate that the transition from star-forming to quiescent galaxy may be associated with transformation in both size and morphology. However, the rest-frame

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Astronomy & Astrophysics

Starbursts in and out of the star-formation main sequence

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ABSTRACT

Aims. We use high-resolution continuum images obtained with the Atacama Large Millimeter Array (ALMA) to probe the surface density of star formation in $z \sim 2$ galaxies and study the different physical properties between galaxies within and above the star-formation main sequence of galaxies.

Methods. We use ALMA images at 870 μm with 0.2 arcsec resolution in order to resolve star formation in a sample of eight star-forming galaxies at $z \sim 2$ selected among the most massive *Herschel* galaxies in the GOODS-*South* field. This sample is supplemented with eleven galaxies from the public data of the 1.3 mm survey of the *Hubble* Ultra-Deep Field, HUDF. We derive dust and gas masses for the galaxies, compute their depletion times and gas fractions, and study the relative distributions of rest-frame ultraviolet (UV) and far-infrared (FIR) light.

Results. ALMA reveals systematically dense concentrations of dusty star formation close to the center of the stellar component of the galaxies. We identify two different starburst regimes: (i) the classical population of starbursts located above the SFR-$M_\star$ main sequence, with enhanced gas fractions and short depletion times and (ii) a sub-population of galaxies located within the scatter of the main sequence that experience compact star formation with depletion timescales typical of starbursts of ~150 Myr. In both starburst populations, the FIR and UV are distributed in distinct regions and dust-corrected star formation rates (SFRs) estimated using UV-optical-near-infrared data alone underestimate the total SFR. Starbursts hidden in the main sequence show instead the lowest gas fractions of our sample and could represent the last stage of star formation prior to passivization. Being *Herschel*-selected, these main sequence galaxies are located in the high-mass end of the main sequence, hence we do not know whether these "starbursts hidden in the main sequence" also exist below 10^{11} $M_\odot$. Active galactic nuclei (AGNs) are found to be ubiquitous in these compact starbursts, suggesting that the triggering mechanism also feeds the central black hole or that the active nucleus triggers star formation.

Key words. galaxies: evolution – galaxies: starburst – galaxies: active – galaxies: formation – galaxies: star formation – submillimeter: galaxies

1. Introduction

During the 6 billion years that passed between a redshift of $z \sim 2.5$ and 0.5, galaxies formed 75% of their present stellar mass (see Fig. 11 of Madau & Dickinson 2014) following a star-formation mode in which most of the ultraviolet (UV) starlight was absorbed by interstellar dust and re-radiated in the mid- to far-infrared (MIR and FIR, respectively, see e.g., Le Floc'h et al. 2005; Magnelli et al. 2009, 2013; Burgarella et al. 2013; Madau & Dickinson 2014 and references therein).

The galaxies that contributed most to the cosmic star formation rate (SFR) density therefore radiated most of their light in the infrared (IR) domain and at the peak epoch of cosmic star formation, the so-called "cosmic noon" around $z \sim 2$; these galaxies belonged to the class of luminous and ultraluminous infrared galaxies; LIRGs and ULIRGs ((U)LIRGs hereafter) respectively,

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Concurrent Starbursts in Molecular Gas Disks within a Pair of Colliding Galaxies at $z = 1.52$

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Abstract

We report on the discovery of a merger-driven starburst at $z = 1.52$, PACS-787, based on high signal-to-noise ALMA observations. CO(5–4) and continuum emission (850 μm) at a spatial resolution of 0."3 reveal two compact ($r_{1/2} \sim 1$ kpc) and interacting molecular gas disks at a separation of 8.6 kpc, indicative of an early stage in a merger. With an SFR of 991 $M_\odot$ yr^{-1}, this starburst event should occur closer to final coalescence, as is usually seen in hydrodynamical simulations. From the CO size, inclination, and velocity profile for both disks, the dynamical mass is calculated through a novel method that incorporates a calibration using simulations of galaxy mergers. Based on the dynamical mass, we measure (1) the molecular gas mass, independent from the CO luminosity, (2) the ratio of the total gas mass and the CO(1–0) luminosity ($\alpha_{\rm CO} \equiv M_{\rm gas}/L'_{\rm CO\,1-0}$), and (3) the gas-to-dust ratio, with the latter two being lower than typically assumed. We find that the high star formation triggered in both galaxies is caused by a set of optimal conditions: a high gas mass/fraction, a short depletion time ($\tau_{\rm depl} = 85$ and 67 Myr) to convert gas into stars, and the interaction of likely counter-rotating molecular disks that may accelerate the loss of angular momentum. The state of interaction is further established by the detection of diffuse CO and continuum emission, tidal debris that bridges the two nuclei and is associated with stellar emission seen by *HST*/WFC3. This observation demonstrates the power of ALMA to study the dynamics of galaxy mergers at high redshift.

Key words: galaxies: high-redshift – galaxies: ISM – galaxies: starburst – galaxies: star formation

1. Introduction

Our understanding of the physical properties of the interstellar medium in galaxies undergoing a merger that can induce star formation and accretion onto supermassive black holes is usually based on studies in the local universe. Representative examples include Arp 220, the Antennae, and NGC 6240, which belong to a class of Ultraluminous Infrared Galaxies (ULIRGs; Sanders & Dirabel 1996), which are unequivocally undergoing an extreme starburst (with a luminous active galactic nucleus—AGN—in many cases), triggered by a merger of two massive galaxies (e.g., Di Matteo et al. 2005; Hopkins et al. 2006; Volonteri et al. 2015). While such collisions accelerate the growth of galaxies (e.g., Scudder et al. 2012; Ellison et al. 2013), this mechanism appears to have a subdominant effect on the buildup of the global stellar mass and black hole mass density over a wide range of cosmic time (Rodighiero et al. 2011). Although, mergers likely represent a key phase (having a short duty cycle) through which every massive galaxy may pass (e.g., Lotz et al. 2008; Lackner et al. 2014). Moreover, galaxy mergers offer us a specialized laboratory to study the physics of the interstellar medium including the conversion of molecular gas into stars and the channeling of such gas to the central regions that can build up the central stellar bulge.

From seminal studies, local starbursts are characterized as having relatively large amounts of molecular gas (Sanders et al. 1986; Scoville et al. 1989), hence higher gas fractions relative

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Astronomy & Astrophysics

GOODS-ALMA: 1.1 mm galaxy survey

I. Source catalog and optically dark galaxies

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ABSTRACT

Aims. We present a 69 arcmin^2 ALMA survey at 1.1 mm, GOODS-ALMA, matching the deepest HST-WFC3 H-band part of the GOODS-South field.

Methods. We tapered the 0″24 original image with a homogeneous and circular synthesized beam of 0″60 to reduce the number of independent beams – thus reducing the number of purely statistical spurious detections – and optimize the sensitivity to point sources. We extracted a catalog of galaxies purely selected by ALMA and identified sources with and without HST counterparts down to a 5σ limiting depth of $H = 28.2$ AB (HST/WFC3 F160W).

Results. ALMA detects 20 sources brighter than 0.7 mJy at 1.1 mm in the 0″60 tapered mosaic (rms sensitivity $\sigma \simeq 0.18$ mJy beam^{-1}) with a purity greater than 80%. Among these detections, we identify three sources with no HST nor *Spitzer*-IRAC counterpart, consistent with the expected number of spurious galaxies from the analysis of the inverted image; their definitive status will require additional investigation. We detect additional three sources with HST counterparts either at high significance in the higher resolution map, or with different detection-algorithm parameters ensuring a purity greater than 80%. Hence we identify in total 20 robust detections.

Conclusions. Our wide contiguous survey allows us to push further in redshift the blind detection of massive galaxies with ALMA with a median redshift of $z = 2.92$ and a median stellar mass of $M_\star = 1.1 \times 10^{11}\,M_\odot$. Our sample includes 20% HST-dark galaxies (4 out of 20), all detected in the mid-infrared with *Spitzer*-IRAC. The near-infrared based photometric redshifts of two of them ($z \sim 4.3$ and 4.8) suggest that these sources have redshifts $z > 4$. At least 40% of the ALMA sources host an X-ray AGN, compared to ~14% for other galaxies of similar mass and redshift. The wide area of our ALMA survey provides lower values at the bright end of number counts than single-dish telescopes affected by confusion.

Key words. galaxies: high-redshift – galaxies: evolution – galaxies: star formation – galaxies: active – galaxies: photometry – submillimeter: galaxies

1. Introduction

In the late 1990s a population of galaxies was discovered at submillimeter wavelengths using the Submillimeter Common-User Bolometer Array (SCUBA; Holland et al. 1999) on the *James Clerk Maxwell* Telescope (see e.g., Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Blain et al. 2002). These "submillimeter galaxies" or SMGs are highly obscured by dust, typically located around $z \sim 2$–2.5 (e.g., Chapman et al. 2003; Wardlow et al. 2011; Yun et al. 2012), massive ($M_\star > 7 \times 10^{10}\,M_\odot$; e.g., Chapman et al. 2005; Hainline et al. 2011; Simpson et al. 2014), gas-rich ($f_{\rm gas} > 50\%$; e.g., Daddi et al. 2010), with huge star formation rates (SFR) – often greater than $100\,M_\odot\,{\rm yr}^{-1}$ (e.g., Magnelli et al. 2012; Swinbank et al. 2014) – making them significant contributors to the cosmic star formation (e.g., Casey et al. 2013), often driven by mergers (e.g., Tacconi et al. 2008; Narayanan et al. 2010) and often host an active galactic nucleus (AGN; e.g., Alexander et al. 2008; Pope et al. 2008; Wang et al. 2013). These SMGs are plausible progenitors of present-day massive early-type galaxies (e.g., Cimatti et al. 2008; Michałowski et al. 2010).

Recently, thanks to the advent of the Atacama Large Millimeter/submillimeter Array (ALMA) and its capabilities to perform both high-resolution and high-sensitivity observations, our view of SMGs has become increasingly refined. The high angular resolution compared to single-dish observations reduces drastically the uncertainties of source confusion and blending, and affords new opportunities for robust galaxy identification and flux measurement. The ALMA sensitivity allows for the detection of sources down to 0.1 mJy (e.g., Carniani et al. 2015), the analysis of populations of dust-poor high-z galaxies (Fujimoto et al. 2016) or main sequence (MS; Noeske et al. 2007; Rodighiero et al. 2011; Elbaz et al. 2011) galaxies (e.g., Papovich et al. 2016; Dunlop et al. 2017; Schreiber et al. 2017), and also demonstrates that the extragalactic background light (EBL) can be resolved partially or totally by faint galaxies ($S < 1$ mJy; e.g., Hatsukade et al. 2013; Ono et al. 2014; Carniani et al. 2015; Fujimoto et al. 2016). Thanks to this new domain of sensitivity, ALMA is able to unveil less extreme objects, bridging the gap between massive starbursts and more normal galaxies: SMGs no longer stand apart from the general galaxy population.

However, many previous ALMA studies have been based on biased samples, with prior selection (pointing) or a posteriori selection (e.g., based on HST detections) of galaxies, or in a relatively limited region. In this study, we present an

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Detecting Radio AGN Signatures in Red Geysers

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Abstract

A new class of quiescent galaxies harboring possible AGN-driven winds has been discovered using spatially resolved optical spectroscopy from the ongoing SDSS-IV MaNGA survey. These galaxies, termed "red geysers," constitute 5%–10% of the local quiescent population and are characterized by narrow bisymmetric patterns in ionized gas emission features. Cheung et al. argued that these galaxies host large-scale AGN-driven winds that may play a role in suppressing star formation at late times. In this work, we test the hypothesis that AGN activity is ultimately responsible for the red geyser phenomenon. We compare the nuclear radio activity of the red geysers to a matched control sample with similar stellar mass, redshift, rest-frame NUV $-$ r color, axis ratio, and presence of ionized gas. We have used the 1.4 GHz radio continuum data from the VLA FIRST survey to stack the radio flux from the red geyser and control samples. In addition to a three times higher FIRST detection rate, we find that red geysers have a 5σ higher level of average radio flux than control galaxies. After restricting to rest-frame NUV $-$ r color >5 and checking mid-IR *WISE* photometry, we rule out star formation contamination and conclude that red geysers are associated with more active AGNs. Red geysers and a possibly related class with disturbed Hα emission account for 40% of all radio-detected red galaxies with log $(M_\star/M_\odot) < 11$. Our results support a picture in which episodic AGN activity drives large-scale, relatively weak ionized winds that may provide a feedback mechanism for many early-type galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: general

1. Introduction

The level of star formation in galaxies is known to be bimodal (Strateva et al. 2001; Blanton et al. 2003; Kauffmann et al. 2003), with star-forming galaxies often referred to as the "blue cloud" and galaxies without significant star formation falling under the "red-sequence" category. The latter is characterized by old stellar populations ($\gtrsim$6 Gyr) and short star formation timescales ($\lesssim$1 Gyr; Tinsley 1979; Worthey et al. 1992; Trager et al. 2000; Thomas et al. 2005; Graves & Schiavon 2008; Choi et al. 2014; Conroy et al. 2014; Worthey et al. 2014). The abundance of these quiescent galaxies has increased by several factors since $z \sim 2$ (Bell et al. 2004; Bundy et al. 2006; Faber et al. 2007; Ilbert et al. 2010; Moustakas et al. 2013), which implies that more and more galaxies are transitioning to quiescence. The increase in the red-and-dead population indicates that once galaxies shut off their star formation by some mechanism, they must stay quenched for a long time.

A permanent shutdown of star formation is hard to explain, because the quiescent population is not devoid of gas and is also capable of accreting new gas to eventually start forming stars again. Major surveys have shown an abundance of gas in quiescent galaxies (Demoulin-Ulrich et al. 1984; Buson et al. 1993; Binette et al. 1994), which if left to itself, should ultimately cool and form stars. This gas comes from a variety of sources like stellar mass loss from evolved stars (e.g., Mathews & Brighenti 2003; Ciotti & Ostriker 2007) or minor mergers. If all this gas formed stars, we would expect the global

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The [C II] emission as a molecular gas mass tracer in galaxies at low and high redshifts

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ABSTRACT

We present ALMA Band 9 observations of the [C II]158 μm emission for a sample of 10 main-sequence galaxies at redshift $z \sim 2$, with typical stellar masses ($\log M_\star/\mathrm{M}_\odot \sim 10.0$–10.9) and star formation rates ($\sim$35–115 $\mathrm{M}_\odot\ \mathrm{yr}^{-1}$). Given the strong and well-understood evolution of the interstellar medium from the present to $z = 2$, we investigate the behaviour of the [C II] emission and empirically identify its primary driver. We detect [C II] from six galaxies (four secure and two tentative) and estimate ensemble averages including non-detections. The [C II]-to-infrared luminosity ratio ($L_{[\mathrm{C\,II}]}/L_{\mathrm{IR}}$) of our sample is similar to that of local main-sequence galaxies ($\sim 2 \times 10^{-3}$), and $\sim$10 times higher than that of starbursts. The [C II] emission has an average spatial extent of 4–7 kpc, consistent with the optical size. Complementing our sample with literature data, we find that the [C II] luminosity correlates with galaxies' molecular gas mass, with a mean absolute deviation of 0.2 dex and without evident systematics: the [C II]-to-H_2 conversion factor ($\alpha_{[\mathrm{C\,II}]} \sim 30\ \mathrm{M}_\odot/\mathrm{L}_\odot$) is largely independent of galaxies' depletion time, metallicity, and redshift. [C II] seems therefore a convenient tracer to estimate galaxies' molecular gas content regardless of their starburst or main-sequence nature, and extending to metal-poor galaxies at low and high redshifts. The dearth of [C II] emission reported for $z > 6$–7 galaxies might suggest either a high star formation efficiency or a small fraction of ultraviolet light from star formation reprocessed by dust.

Key words: galaxies: evolution – galaxies: high redshift – galaxies: ISM – galaxies: star formation – galaxies: starburst – submillimetre: galaxies.

1 INTRODUCTION

A tight correlation between the star formation rates (SFRs) and stellar masses ($M_\star$) in galaxies seems to be in place both in the local Universe and at high redshift (at least up to redshift $z \sim 7$; e.g. Bouwens et al. 2012; Steinhardt et al. 2014; Salmon et al. 2015): the so-called 'main sequence' (MS; e.g. Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007; Stark et al. 2009, followed by many others). The normalization of this relation increases with redshift. At fixed stellar mass ($\sim 10^{10}\ \mathrm{M}_\odot$), $z \sim 1$ galaxies have SFRs comparable to local Luminous Infrared Galaxies (LIRGs); at $z \sim 2$ their SFR is further enhanced and they form stars at rates comparable to local Ultra Luminous Infrared Galaxies (ULIRGs). However, the smooth dynamical disc structure of high-redshift MS sources, together with the tightness of the SFR – $M_\star$ relation, disfavour the hypothesis that the intense star formation activity of these galaxies is triggered by major mergers, as by contrast happens at $z = 0$ for ULIRGs (e.g. Armus, Heckman & Miley 1987; Sanders & Mirabel 1996; Bushouse et al. 2002). The high SFRs in the distant Universe seem instead to be sustained by secular processes (e.g. cold gas inflows) producing more stable star formation histories (e.g. Noeske et al. 2007; Davé, Finlator & Oppenheimer 2012).

MS galaxies are responsible for $\sim$90 per cent of the cosmic SFR density (e.g. Rodighiero et al. 2011; Sargent et al. 2012), whereas the remaining $\sim$10 per cent of the cosmic SFR density is due to sources strongly deviating from the MS, showing enhanced SFRs and extreme infrared luminosities. Similarly to local ULIRGs, star formation in these starburst (SB) galaxies is thought to be ignited by major merger episodes (e.g. Elbaz et al. 2011; Nordon et al. 2012; Hung et al. 2013; Schreiber et al. 2015; Puglisi et al. 2017). Throughout this paper, we will consider as

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ALMA twenty-six arcmin^2 survey of GOODS-S at one millimeter (ASAGAO): Source catalog and number counts

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