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研究課題名（英文）Dust-free Insight into the Obscured Cosmic Accretion History and Modes of Galaxy Assembly

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研究成果の概要（和文）：本プロジェクトにより、電波による最も感度の高いハッブル探査領域の観測と解析が可能になりその結果を論文化することができた。我々は、米国の大型電波望遠鏡VLAを使い２－８GHzの周波数帯で、銀河の形成がピークを迎える赤方偏移１から３の距離にある星形成銀河を撮像した。結果として第一に、星形成銀河の形態は円盤状であり、冷たいガスの降着による銀河形成のシナリオと合致し、円盤の全体にわたって星形成が起きていることを明らかにした。第二に活動銀河核活動と星形成は赤方偏移３付近の銀河では同じ場所で起きていることがわかった。バルジと銀河中心のブラックホールが共に成長していくという描像と合致していることを確かめた。

研究成果の概要（英文）：The support from this program has enabled successful analysis and dissemination of results from the most sensitive astronomical survey at radio frequencies ever conducted. We used the Very Large Array radio observatory to conduct 2 - 8 GHz imaging of the Hubble Ultra-Deep Field at the sensitivities required to capture star-forming galaxies at z ~ 1-3, the peak epoch of galaxy assembly. We found that (1) the typical morphology of star formation (SF) in rapidly assembling galaxies at redshift z ~ 2 to be disk-wide, consistent with the scenario that galaxies assemble most of their stellar mass via accretion of cold gas, which leads to gas-rich, unstable disks and in-situ disk-wide star formation; and that (2) the active galactic nuclei (AGN) and SF are co-spatial at z ~ 3, consistent with a picture of in-situ galactic bulge and MBH growth. The program has spurred multiple new observing campaigns to definitively characterize the SF morphologies and the co-spatial nature of SF and AGN.

研究分野：　天文学

キーワード：　galaxy evolution　galaxy assembly　star formation　active galactic nuclei　SF - AGN coevolution

１．研究開始当初の背景

The research in the past 20 years have shown by the start of the 2010s that galaxy assembly activities, namely the cosmic star formation rate (SFR) and the cosmic massive black hole accretion rate (BHAR) peaked at redshift ~ 1-3. Both activities have since declined by an order of magnitude to the present level. These activities must have been linked since this epoch to preserve the local relation between the black hole and stellar mass in galaxy bulges, well known since the late 1990s. What has driven both processes at their peak was unknown and remains a major unsolved problem of this decade (as highlighted in, e.g., the 2010 US Decadal Survey). These open questions render this cosmic epoch to be of vital importance in our understanding of how galaxies were assembled.

However, it was also known by mid-2010s that galaxies undergoing most intense assembly are also the most dust-obscured ones. Galaxies forming stars at the rate as little as 10% of the typical SFR level at this epoch are completely obscured to the rest-frame ultraviolet light. That is, the sites of star formation in these galaxies can not be studied using our usual avenues to obtain high resolution imaging, e.g., using the Hubble Space Telescope. As a result, we did not know how intense star formation are distributed in these galaxies. The knowledge of this distribution is paramount to understand how intense SFR at this epoch are driven: nucleated and galaxy-wide star formation imply merger-driven and secular processes (such as the cold-mode accretion), respectively. Likewise, dust obscuration also hidden at least half of the active galactic nuclei (AGNs) populations, the sites of massive black hole accretion, at this epoch, further complicating the study of how SFR and BHAR are linked.

２．研究の目的

Our primary goals are to use the deepest sky survey at radio frequencies, which can peer through thick dust, to capture both the star formation and AGN activities at z ~ 1-3. We have proposed to (1) use the high resolution radio image to identify the typical mode of star formation, (2) find dust-obscured AGNs with the radio tracer and study the potential intermediary between SFR and BHAR.

３．研究の方法

The major enabling factor for this research is the advent of the US National Radio Astronomy Observatory's Jansky Very Large Array (VLA), where digitization and the resulting bandwidth increase of a factor of ~1,000 has increased the sensitivity of the array by an order of magnitude, thereby allowing a new generation of deep surveys to be conducted. This new generation of survey can, for the first time, capture z ~ 1-3 galaxies and AGNs at high sensitivity. The PI of this research program has led observing programs using the VLA to conduct deep radio imaging survey of the Hubble Ultra-Deep Field (HUDF) and the surrounding GOODS-S region at 2-8 GHz. We have used this data, along with the most sensitive multiwavelength information existed in the field to identify AGNs from star-forming galaxies, then study their properties in detail.

４．研究成果

The support from the program has enabled data analysis for the radio surveys to be carried out as proposed. At the time of this final report, the impact of this data has broadened beyond the proposed science goals, and also have played key roles in the publication and/or submission of eight refereed journal papers (and five more in preparation). We have successfully answered the key questions posed in the program's proposal.

Firstly, we have determined and reported in Rujopakarn et al. (2016) the typical morphology of star formation (SF) in rapidly assembling galaxies at redshift z ~ 2 to be disk-wide, consistent with the scenario that galaxies assemble most of their stellar mass via accretion of cold gas, which leads to gas-rich, unstable disks and in-situ disk-wide star formation.

Secondly, we have developed a new technique, reported in Rujopakarn et al. (2018), to identify and localize AGN in relation to the sites of intense SF at redshift z ~ 2 with ~100 parsec precision. This has not previously been possible due to the aforementioned extreme dust extinction typical near the center of rapidly star-forming galaxies at this epoch. Early results have shown the AGN and SF to be co-spatial. 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.
The source catalog from our VLA survey, has been widely distributed among collaborators and have been published, in part, in the aforementioned journal papers. Most notably, the resulting radio data was also used by the James Webb Space Telescope (JWST) NIRCam and NIRSpec Guaranteed Time Observations (GTO) teams, which the PI is a member, to target the GTO observations when the JWST is launched in 2019. Future students (including students at the Kavli IPMU, where the PI remain affiliated as a visitor) will have access to GTO data from JWST.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　7 件）

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⑦ Cheung, Edmond; Bundy, Kevin; Cappellari, Michele; Peirani, Sébastien; Rujopakarn, Wiphu; Westfall, Kyle; Yan, Renbin; Bershady, Matthew; Greene, Jenny E.; Heckman, Timothy M.; and 15 coauthors, Suppressing star formation in quiescent galaxies with supermassive black hole winds, Nature, Volume 533, Issue 7604, 2016, pp. 504-508, 10.1038/nature18006, Refereed

〔学会発表〕（計　2 件）

① Wiphu Rujopakarn, ALMA and JVLA imaging of intense galaxy-wide star formation in z ~ 2 galaxies in the HUDF: bridging SMGs to the main sequence, SMG20 - Twenty years of Submillimetre Galaxies: STAR-FORMING GALAXIES AT HIGH REDSHIFTS, 1 August 2017, Durham, UK

② Wiphu Rujopakarn, Probing the peak epoch of galaxy assembly with VLA and ALMA, Invited Colloquium, 19 January 2017, National Radio Astronomy Observatory, Charlottesville, USA

〔図書〕（計　0 件）

〔産業財産権〕

○出願状況（計　0 件）

名称：
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○取得状況（計　0 件）

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〔その他〕
ホームページ等

The Atacama Large Millimeter/submillimeter Array (ALMA) Observatory press release for Rujopakarn et al. (2016) results – http://www.almaobservatory.org/en/press-release/vla-and-alma-team-up-to-give-first-look-at-birthplaces-of-most-current-stars

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