氏　　　　　名	道山　知成
学位(専攻分野)	博士(理学)
学 位 記 番 号	総研大甲第 2059 号
学位授与の日付	平成 31年 3 月22日
学位授与の要件	物理科学研究科　天文科学専攻 学位規則第6条第1項該当
学 位 論 文 題 目	*Revealing Star Formation Activity and Feedback Mechanisms in Nearby Merging Galaxies*
論 文 審 査 委 員	主　査　　教授　本間　希樹 教授　臼田　知史 准教授　Espada, Fernandez, Daniel 助教　江草　芙実　東京大学大学院 理学系研究科 助教　Pettitt Alexander Robert 北海道大学　 高等教育推進機構

（様式３）

博士論文の要旨

氏　　名 Tomonari Michiyama 道山知成

論文題目

Revealing Star Formation Activity and Feedback Mechanisms in Nearby Merging Galaxies

要旨

A galaxy-galaxy merger is a fundamental process for galaxy evolution since it is a common event in the universe. The ultimate question in this thesis is ***"what happens during a galaxy-galaxy merger"***. Astronomers have been studying a merger process theoretically and observationally. It is obvious that collisions affect the morphology of galaxies. Furthermore, many studies have addressed that a merger process affects activities of galaxies, i.e., triggering starburst and/or active galactic nucleus (AGN) activities. However, it remains unknown ***how such activities are enhanced by a galaxy-galaxy merger and subsequently affect galaxy evolution (feedback process).*** I approach these issues by using sub/millimeter telescopes; Atacama Submillimeter Telescope Experiment (ASTE) and Atacama Large Millimeter/submillimeter Array (ALMA). I performed a series of separate projects as follows.

[1st project] At first, I investigated "global" properties of merging galaxies through survey observations. The main goal of the first project is to reveal the evolution of the merging galaxies in terms of star formation relation. Star formation relation is a global relation between properties of star formation activity (i.e., star formation rate: SFR) and material for star formation (i.e., molecular gas mass: M_{H2}). The relation has been studied over ~50 years and still be a big issue in astronomy since the relation is essential to understand and model the galaxy evolution. Several investigations have demonstrated that there is a bi-modal sequence for isolated disk galaxies and starburst galaxies; long-lasting star formation in disk galaxies and rapid mode in starburst galaxies. This means that star formation efficiency (SFE=SFR/M_{H2}) is higher in starburst galaxies than disk galaxies. ***My working hypothesis is that a galaxy-galaxy merger can explain the bi-modality, which means that merging galaxies fill the gap between two sequences.*** In order to confirm this idea, it is necessary to investigate the exact location of interacting galaxies through systematic observations along the merger sequence from early stage (before coalescence) to late stage (after coalescence) with a various SFR range. However, previous studies are biased to late stage mergers that have intense starburst activity. In my project, ***I conducted ASTE CO (3–2) survey observations for merging galaxies*** (total observation time 120 hours). I increase the number of early stage merging galaxies without intense starburst activities. I investigated the relation between the CO (3–2) luminosities ($L_{CO} \propto M_{H2}$) and the far-infrared luminosity ($L_{FIR} \propto$ SFR) (which is a

fundamental relation to determine star formation relation) in a sample of 29 early- and 31 late-stage merging galaxies and 28 nearby isolated spiral galaxies. I found that normal isolated spiral galaxies and merging galaxies have different slopes (α) in the $\log L_{\rm CO} - \log L_{\rm FIR}$ plane: α ~ 0.8 for disk galaxies and ~ 1.1 for merging galaxies. This means that merging galaxies fill the gap between disk- and starburst-sequence. In addition, I found that the star formation efficiency (SFE ∝ $L_{\rm FIR}/L_{\rm CO}$) gradually increases from isolated galaxies, merging galaxies, and to high-z active galaxies.

[2nd project] Second, I investigated details of star formation activity in a merging galaxy. As shown in the first project, a galaxy collision plays an important role for global star formation activity in galaxies. The goal of second project is to answer the question of ***"Where are starbursts triggered in merging galaxies?"***. In this project, I use both optical integral field units (MUSE mounted on Very Large Telescope) to obtain Hα and Hβ image which can trace diffuse disk-wide starbursts and ALMA to obtain H40α and H42α image which can trace extremely dusty nuclear starbursts. As a kickoff study, I selected one merging galaxy NGC 3256 that consists of two galaxies; one is the northern starburst galaxy and the other is the southern dusty galaxy hosting a low luminosity AGN. Optical observations show many star forming blobs outside of nuclear regions, and these regions are categorized as starbursts. In addition, ALMA shows that there is a star forming region at the southern nucleus where optical recombination lines are undetected due to strong dust extinction ($A_{\rm V}$ ~18). The missed SFR in the southern dusty star forming region is ~12% of total SFR expected from extinction corrected Hβ map. Including both optical and sub-mm recombination observation, I found that the ***contribution of SFR from nuclear and spatially extended starburst is ~27% and 73%*** respectively. Therefore, I conclude that disk-wide starbursts are more important than dusty nuclear starbursts in NGC 3256.

[3rd project] Finally, I describe the feedback process. Starburst and AGN feedback occur in the form of galactic-scale outflows. The goal of the third project is to answer the question of ***"What kind of structure and properties do molecular outflows have?".*** Recently, a number of studies have reported identifications of molecular outflows in CO observations by using ALMA. They measured the mass and velocity of outflows. However, in order to include the feedback process into galaxy evolution model, the other properties of outflows (e.g., structure and physical and chemical properties) should be investigated. The originality of the third project is that ***I use multi-lines (e.g., CO, HCN and HCO+) to characterize the structure, density and temperature, and chemistry of the outflows***. NGC 3256 is an ideal target since two low J (J<3) CO outflows from the two nuclei (starburst and low-luminosity AGN) have already been reported. Two different types of outflow can be simultaneously investigated. I detected the high-density gas traced in HCN (1-0) and HCO^+ (1–0) in AGN triggered southern outflow. On the other hand, the same lines were undetected in the northern outflow triggered by starburst. In terms of the HCO^+(1–0)/CO(1–0) (i.e. dense gas fraction) and the CO(3–2)/CO(1–0) line ratio are larger in the outflow (0.20±0.04 and 1.3±0.2, respectively) than in the nucleus (0.08±0.01, 0.7±0.1, respectively). This means that the outflowing gas has a higher density and temperature compared to the nucleus. ***It is difficult to understand these results under an assumption of simple mass transportation*** (i.e., negative feedback). In addition, by investigating these line ratios for each velocity component in the outflow, I found that the dense gas fraction increases and the CO(3–2)/CO(1–0) line ratio decreases toward the largest velocity offset. This means that dense gas tracers and CO lines trace different part of the outflow; i.e., ***dense clumps traced by HCN and HCO+ and diffuse gas traced by CO lines***. Such clumps with large velocity offset are detected by high resolution (0.2") follow up CO(2-1) observation. One possible scenario to produce such a two-phase outflow is an interaction between the jet and the interstellar medium (ISM), which is seen in active AGNs (e.g., M51, IC5013).

[Conclusions] Through these three projects, I found mainly two important phenomena to answer the question of "what happens during a galaxy-galaxy merger" as follows.
(1) "nuclear starburst" and "disk wide starbursts" in merging galaxies: The classical idea of merger induced star formation activity is nuclear starbursts taking place in the central region (< 1 kpc) due to global gas inflow in the late stage. On the other hand, some theoretical models predict disk-wide starbursts (> 1 kpc) due to the fragmentation of dense gas in the early stage. The enhancement of SFE in merging galaxies seen in our ASTE survey supports the latter case. In addition, a case study of NGC 3256 shows the evidence of the larger contribution of disk-wide starburst than dusty nuclear starburst. The key of my project is that both diffuse disk-wide starbursts and dusty nuclear starbursts are investigated in a consistent manner by using hydrogen recombination lines by optical (MUSE/VLT) and mm wavelength (ALMA). In the future, it is necessary to investigate various types of merging galaxies (e.g., early/late stage, major/minor, wet/dry) with the same method in order to explain the mechanism of enhancement of star formation activity during a merger process. For example, more advanced merging galaxies are expected to have larger contribution of dusty nuclear starbursts than disk-wide starbursts.

(2) dense clumps in a molecular outflow: A case study of NGC 3256 shows the presence of dense clumps in the AGN triggered outflow. This has not been predicted by the typical merger scenario, where gas is simply expelled without any actions ("negative feedback"). The complex physical mechanisms are necessary to explain the formation of dense clumps in outflows, i.e., jet and ISM interaction by strong AGN feedback. Such clumps in the outflows can possibly become the sites of future star formation ("positive feedback"), affecting the long-term evolution of the host galaxy. However, the expected SFR derived from total dense gas mass in the outflow is not as high as the SFR of host galaxy. The conclusion from this study is that while the degree of star formation is likely small, the existence of "positive feedback" is possible and it is not completely ruled out. As a next step, it is necessary to investigate how outflows affect the star formation activity not only for high-velocity gas but also for the gas in the disk.

[Future prospects] The observational data presented in this thesis provides evidences of previously expected "disk-wide starbursts" and the new idea of "clumpy dense outflows" in merging galaxies, particularly in NGC 3256. The important next step is to expand our observation from individual case studies to a statistically significant sample that includes a wide range of merger stages, star formation rates, and nuclear properties.

Form8・Separate Sheet
（様式８・別紙）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名　　道山　知成

Title
論文題目　*Revealing Star Formation Activity and Feedback Mechanisms in Nearby Merging Galaxies*

宇宙の基本的な構成要素である銀河は、ビックバンから現在に至るまで長い時間をかけながら現在の形に進化してきた。特に、銀河進化の過程で起こる銀河の合体は、銀河内の星形成や銀河中心核の活性化を通して銀河進化に大きな影響を及ぼすと考えられている。しかし、銀河の合体過程において、いつどのように星形成や銀河中心核が活性化されるのか、また、それが母銀河にどのような影響を与えるのかは未解明であり、まだ研究の途上にある。

本研究は、合体銀河における星形成活動とそれが母銀河に与える影響の理解を目指し、主にミリ波帯の電波天文学観測から迫ろうとするものである。出願者はまず、合体途中の銀河の星形成効率を調べるため、星形成効率を調べる上で重要な指標となる Kennicutt-Schmidt 関係（銀河内の分子ガス量と星形成率の冪乗関係）に着目した。出願者は合体の進行度が異なる２つのグループ（Early stage/Late stage）に分けて観測ターゲットを選定し、その分子ガス量については国立天文台がチリに有する ASTE 望遠鏡を用いて観測を実行した。さらに、赤外線等のアーカイブデータも交え、Kennicutt-Schmidt 関係について調査した。その結果これらの合体途上の銀河が、活動性の弱い通常の銀河と非常に活動性の高い赤外線超過銀河の中間的な種族に対応することを見出し、通常の銀河にくらべて合体により星形成効率が上がる傾向を見出した。

さらに申請者は、合体銀河の中でも詳細観測が可能な近傍銀河 NGC3256 に着目し、ALMA による電離水素再結合線の電波観測と、VLT による赤外線の電離水素の観測を比較して、合体銀河内での星形成の様子について調べた。その結果、赤外線観測から銀河円盤領域に広がる爆発的星形成が行われるいることを見出すとともに、ALMA による電波観測からは中心核付近で強い吸収を受けている隠れた星形成の兆候も見出した。また両者を合わせた解析から円盤領域での星形成率と中心核での星形成率を比較し、前者が７割、後者が３割程度と、どちらも無視できないレベルで双方が共存することが明らかになった。

また申請者は NGC3256 の２つの中心核（合体する２つの銀河中心核に対応）の活動性を調べ、ALMA による分子輝線観測からそれぞれに付随するアウトフロー成分を検出した。ALMA の特性を生かして、CO の複数準位間の遷移や HCN など他分子の輝線のデータも取得し、その比較からアウトフロー内のガスの物理状態の診断を行った。その結果、南側に位置する活動的な領域からのアウトフローが、星形成ではなく活動銀河中心核によって駆動されていること、一方北側のアウトフローは星形成起源である可能性があることを見出した。さらに、南側の銀河中心核起源のアウトフローの詳しい解析から、その内部で密度の濃い領域がクランプ状に分布している可能性を見出した。この結果は、アウトフロー

の周辺で密度の濃い領域が生まれ、さらにそこで星形成が誘発されるという、”正のフィードバック”シナリオと合致しているものである。一方で、２つのアウトフローでは駆動源や高密度クランプの有無について異なる結果が示唆されており、必ずしも単一の描像で説明することができないことも示された。これらの結果は、今後さらなる観測的研究を触発する興味深い結果であり、銀河合体時の星形成や中心核活動性の研究に影響を与えるものである。

以上をまとめると、出願者の一連の研究は銀河進化における銀河合体の影響を評価するため、ASTE や ALMA などの最新のミリ波電波観測を中心に多波長観測も加えて展開された点において優れたものであり、銀河の合体で引き起こされる星形成や活動銀河核のアウトフローに新たな知見を与えるものである。また、出願者は観測からデータ解析、考察・議論に至るまで、本研究において主体的な役割を果たしている。よって審査委員会は全員一致で、本論文が博士論文に値するものであることを認め、合格であると判断する。