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研究課題名（和文）Star Formation Rates in the Galactic Center of the Milky Way

研究課題名（英文）Star Formation Rates in the Galactic Center of the Milky Way

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研究成果の概要（和文）：高解像度の干渉計観測を使用して、銀河中心を取り巻く分子雲(いわゆるCentral Molecular Zone, CMZ)における星形成活動を研究した。本研究により、CMZ全体での星形成率は、この領域のほとんどの個別分子雲の星形成率と同様に、観測されている分子雲から期待される星形成率の10分の1以下であることが判明した。一方で、CMZにおける（0.3光年未満の）小さな空間スケールの星形成は正常であることもわかった。したがって、CMZにおける非効率な星形成を理解する鍵は、（数光年以上の）大きな空間スケール、たとえば雲が崩壊するのを妨げる強い乱流の存在、にあると言える。

研究成果の学術的意義や社会的意義
The research provides new insights into star formation in the extreme environments in the Central Molecular Zone, and changes the preconception that the Central Molecular Zone around our Galactic Center is not suitable for star formation.

研究成果の概要（英文）：I used high resolution interferometer observations to study the star formation activities in the so-called Central Molecular Zone around the center of our Galaxy. I found that the star formation rate of the whole Central Molecular Zone as well as those of most individual molecular clouds in the Central Molecular Zone are at least 10 times lower than expected. I also found that star formation at small spatial scales (smaller than 0.3 light years) in this zone is just normal. Therefore, the key of the inefficient star formation in this zone must be in the large spatial scales (a few light years and larger), for example, strong turbulence that presents the clouds from collapsing.

研究分野：Astronomy

キーワード：Galactic Center　Star Formation Rate　Central Molecular Zone

１・研究開始当初の背景

The Central Molecular Zone (CMZ) refers to the inner 500 parsecs of our Galaxy, which contains a large amount of dense molecular gas (~10^7 solar masses). However, although there are a few star-forming clouds such as the well-known Sagittarius B2 cloud, most of the other molecular clouds in the CMZ are thought be inactive in terms of star formation. The overall star formation rate of the CMZ is estimated to be at least 10 times lower than expected from the dense gas star formation relation that is well established towards nearby molecular clouds and external galaxies (e.g., Longmore et al. 2013; Barnes et al. 2017; Kauffmann et al. 2017). In other words, the star formation efficiency (star formation rate per unit gas mass) in the CMZ is at least 10 times lower than expected.

However, high angular resolution and high sensitivity observations using radio and (sub)mm interferometers toward the CMZ have been rare. Only a few clouds have been observed using the Submillimeter Array (SMA) or ALMA before this research (e.g., Johnston et al. 2014; Lu et al. 2015; Kauffman et al. 2017), which suggest an overall inefficient star formation in these clouds, consistent with previous conclusions.

Two questions are still to be answered: i) Is there a very early phase of star formation that has been missed by previous studies? To address this question, we need to estimate the star formation rate and star formation efficiency of clouds in the CMZ using indicators such as masers and ultra-compact HII regions, which trace very early stages of star formation. ii) Is there an even earlier phase of star formation, not even seen in masers or HII regions, but can be seen in prestellar dense cores?

These two questions are important for understanding the star formation activities deeply embedded in the CMZ clouds as well as the future of the CMZ, for example, whether there is an increasing trend of star formation in CMZ.

２・研究の目的

The objectives of the research, corresponding to the two questions above, are: i) to systematically survey several representative molecular clouds in the CMZ as well as the whole CMZ, and use masers and ultra-compact HII regions to estimate the star formation rates and efficiencies of the CMZ clouds. This is the first systematical assessment of the star formation at very early phase (before the classic HII region phase, with ages less than 1 million years) in the CMZ. ii) to resolve individual prestellar or protostellar dense cores in the CMZ clouds to study the potential of future star formation.

３・研究の方法

For the first objective, the systematic assessment of the star formation rates and efficiencies of CMZ clouds, I relied on the SMA and Very Large Array (VLA) observations. I used the K-band (22 GHz) receivers of VLA to observe water masers and free-free emission from ultra-compact HII regions in a sample of six clouds, and developed a Bayesian method to estimate the star formation rates of the clouds. Then I used the SMA 1.3 mm dust continuum data to estimate the amount of dense gas, from which the star formation efficiencies were derived. In addition, to assess the distribution of star formation and the star formation rate in the whole CMZ, I made C-band (6 GHz) VLA observations to survey the Class II methanol maser at 6.67 GHz and the free-

free emission from HII regions, which is by far the most comprehensive dataset in this respect toward the CMZ.

For the second objective, in order to study the fragmentation of gas and star formation activities at very small spatial scales (smaller than 0.1 parsec), I used ALMA observations to observe a sample of four representative CMZ clouds. I used the 1.3 mm dust continuum to resolve individual dense cores, and molecular lines such as SiO to reveal potential protostellar outflows associated with the dense cores.

４． 研究成果

I got three major results:

(1) In Lu et al. (2019a), I estimated the star formation rates and efficiencies of six CMZ clouds based on the SMA and VLA observations (Figure 1). I found that the star formation rates of four of the clouds are indeed about 10 times lower than expected. Two clouds, Sgr C and Sgr

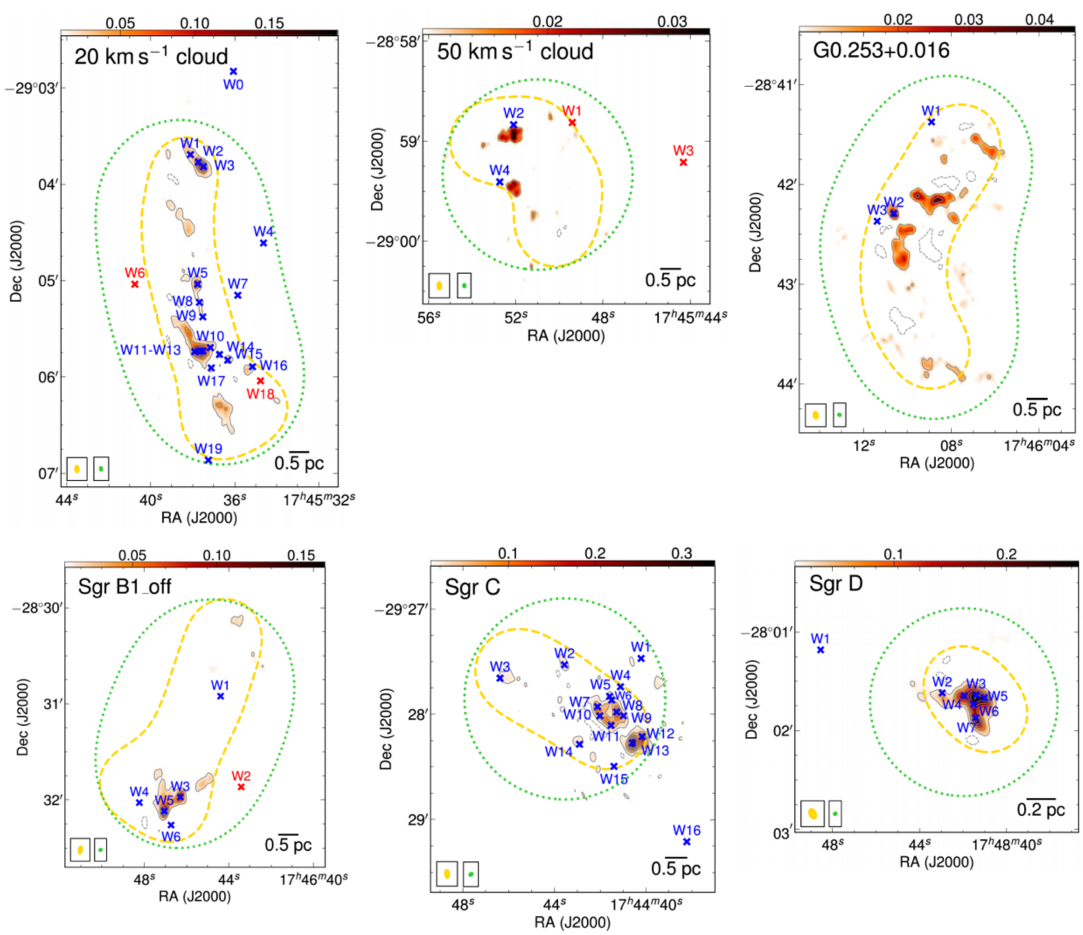

Figure 1: A summary of the SMA and VLA observations of the six clouds (from Lu et al. 2019a). The background images and contours show the SMA 1.3 mm continuum emission. VLA H2O masers are marked by crosses, among which red ones are those with AGB star counterparts and have been excluded in the analysis of star formation. The dashed and dotted loops show the mosaic field of the SMA and VLA, respectively.

B2, have higher star formation rates that are consistent with the dense gas star formation relation in Lada et al. (2010). However, if I consider the masses confined in gravitationally bound dense cores of ~0.2 parsec scale in each cloud, and compare them to the star formation rates, I found a good linear correlation. This suggests that although star formation in suppressed in the clouds generally, it is not affected and may proceed as normal in gravitationally bound cores. This result was highlighted in the July 2019 issue of the SMA newsletter (https://lweb.cfa.harvard.edu/sma/Newsletters/pdfFiles/SMA_NewsJuly2019.pdf).

(2) In Lu et al. (2019b), I systematically searched for signatures of high-mass star formation in the CMZ and estimated the star formation rate of the whole CMZ based on the VLA C-band observations. I identified 104 compact radio emission sources, among which 17 are likely HII regions. I detected 23 methanol masers, among which 6 are new detections. Based on these detections, I found that there are only seven isolated clouds in the CMZ where high-mass star formation is ongoing, and the overall star formation rate of the whole CMZ, even after taking these new evidence of star formation into account, is still about 10 times lower than expected.

In addition, I serendipitously detected two new formaldehyde (H_2CO) masers toward the Sgr C cloud, which belong to a very rare type of maser. This cloud is one of the nine regions in the Milky Way that contains this type of maser, which suggests unique physical and chemical properties in the CMZ.

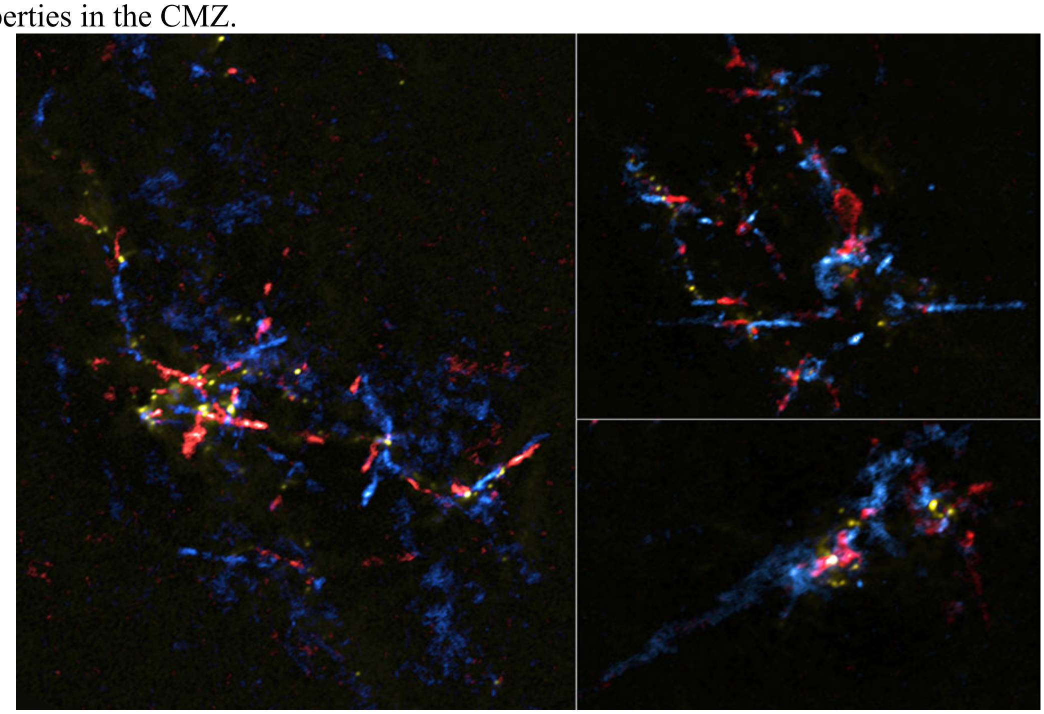

Figure 2: ALMA pseudo-color composite image of the gas outflows from dense cores in the CMZ clouds. The red and blue patches show the red/blue-shifted SiO line emission. The yellow blobs show the 1.3 mm dust emission from the dense cores. Credit: ALMA (ESO/NAOJ/NRAO), Lu et al.

(3) In Lu et al. (2020) and Lu et al. (2021), I used ALMA observations of 0.01 parsec resolution to resolve individual dense cores in four massive clouds in the CMZ. Based on the 1.3 mm dust continuum emission, I identified 835 compact dense cores. The spatial separation between these dense cores is consistent with the expectation of thermal Jeans fragmentation,

which is a surprising result given the highly turbulent environment in the CMZ. This result was highlighted in the ALMA science portal (https://almascience.org/alma-science/science-highlight-alma-finds-signatures-of-jeans-fragmentation-in-massive-clouds-around-the-galactic-center).

In addition, in Lu et al. (2021), I used several molecular lines, including SiO, SO, CH_3OH, HNCO, H_2CO, and HC_3N, to identify 43 protostellar outflows associated with the dense cores (Figure 2). Although our outflow sample is likely incomplete, it is probable that most of the 835 dense cores are not associated with outflows. On the one hand, the detection of the outflows suggests that star formation in the small spatial scales proceeds as usual (for example, with accretion disks that drive the outflows; and the relative abundances of the six molecular are also indistinguishable from those in nearby regions). On the other hand, the non-detection of any outflows in the majority of the dense cores may indicate that these cores are still in the prestellar phase, which may be able to actively form stars in the future. This result was highlighted in the NAOJ science news (https://www.nao.ac.jp/en/news/science/2021/20210329-alma.html), ALMA Observatory press release (https://www.almaobservatory.org/en/press-releases/stellar-eggs-near-galactic-center-hatching-into-baby-stars/), and many other websites.

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５．主な発表論文等

〔雑誌論文〕　計8件（うち査読付論文　8件／うち国際共著　8件／うちオープンアクセス　3件）

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２．論文標題 A Census of Early-phase High-mass Star Formation in the Central Molecular Zone	５．発行年 2019年
３．雑誌名 The Astrophysical Journal Supplement Series	６．最初と最後の頁 35-55
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３．雑誌名 The Astrophysical Journal Supplement Series	６．最初と最後の頁 35～35
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２．論文標題 Cloud-cloud collision as drivers of the chemical complexity in Galactic Centre molecular clouds	５．発行年 2020年
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2．論文標題 CMZoom. II. Catalog of Compact Submillimeter Dust Continuum Sources in the Milky Way’s Central Molecular Zone	5．発行年 2020年
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2．論文標題 Star formation in ‘the Brick’: ALMA reveals an active protocluster in the Galactic centre cloud G0.253+0.016	5．発行年 2021年
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2．論文標題 ALMA Observations of Massive Clouds in the Central Molecular Zone: Jeans Fragmentation and Cluster Formation	5．発行年 2020年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/2041-8213/ab8b65	査読の有無 有
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2．論文標題 ALMA Observations of Massive Clouds in the Central Molecular Zone: Ubiquitous Protostellar Outflows	5．発行年 2021年
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1．発表者名 Xing Lu
2．発表標題 Witnessing Formation of High-mass Star Clusters in the Central Molecular Zone
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2．発表標題 A Census of Early Phase High-mass Star Formation in the inner Central Molecular Zone
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関