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研究課題名（和文）Disentangling the Molecular Gas Properties of the Nuclear Disk/Torus in Powerful Radio Galaxies with ALMA

研究課題名（英文）Disentangling the Molecular Gas Properties of the Nuclear Disk/Torus in Powerful Radio Galaxies with ALMA

研究代表者

エスパダ　ダニエル（Espada, Daniel）

国立天文台・アルマプロジェクト・特任准教授

研究者番号：２０７８４０８６

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研究成果の概要（和文）：超巨大ブラックホールへのガス供給メカニズムを調べることを目的に、ALMA望遠鏡を用いて、最近傍の楕円電波銀河NGC5128 (Centaurus A)のダストレーンおよび高密度ガス円盤(circumnuclear gas disk; CND)に対して高空間分解能観測(>1秒角 ;18pc相当)を行った。結果、CND領域においてガスの非円運動が発見され、それに伴う衝撃波が銀河中心部への物質供給に大きな役割を果たしていることを示した。また、CNDでは、分子ガスの物理特性や星形成活動が、他の円盤銀河と比べて大きく異なり、活動銀河核の活動がそれらに大きく影響している可能性を明らかにした。

研究成果の学術的意義や社会的意義
This is basic research important to understand how supermassive black holes are fed and affect their environment, which is essential to understand galaxy evolution.
The research achievements were disseminated to the astronomical community through refereed publications as well as in conferences.

研究成果の概要（英文）：We present in this project ALMA observations toward the dust lane and circumnuclear disk (CND, at radii <200 pc) of the nearest elliptical and radio galaxy, NGC 5128 (Centaurus A), with high angular resolutions of ~1" (or 18 pc) or better. In this project we study: 1) the properties of the CND and mechanisms driving molecular gas to the center of the galaxy down to pc scale, 2) The physical and chemical properties of the molecular gas in this giant elliptical galaxy, 3) the relation between molecular gas and star formation rate, including the CND, and 4) the properties of Giant Molecular Clouds as a function of galacto-centric radii and environments. We find that non-circular motions and subsequent shocks play a major role to drive gas to the center. The molecular clouds and SF activities in the circumnuclear gas have different properties than those in disk galaxies, with higher velocity dispersions, lower SFEs, and a larger X factor than average values in disk galaxies.

研究分野：Galaxies

キーワード：ISM: clouds　galaxies: ISM　galaxies: nuclei　　galaxies: elliptical　　ISM: molecules

１．研究開始当初の背景

It is still unclear what are the mechanisms that feed gas into the Super Massive Black Holes in the most powerful galaxy jets, usually located in the centers of elliptical galaxies. It is believed that accretion events are one of the principal causes to replenish the gas in these otherwise old stellar systems. However, it is not clear how the gas from recent accretion events evolves with time in these systems, how much and how fast gas is converted to stars or destroyed, and finally how it reaches the center.

２．研究の目的

The original main objectives of the research proposal are to probe the: 1) physical properties of the Giant Molecular Cloud in NGC5128 as a function of galacto-centric radii, 2) mechanisms fueling the molecular gas to the center of the galaxy, 3) comparison with the properties of the gas properties obtained from state-of-the-art numerical simulations, and 4) Super Massive Black Hole mass in the elliptical NGC 5128. We have addressed all of them except objective 4). This is because no emission was found close to the sphere of influence of the SMBH in any of the observed transitions. Instead we investigated further the physical properties and star formation laws in the molecular disk of Centaurus A, for the first time with this level of detail in a giant elliptical galaxy. In this research program for the closest elliptical and prototypical radio galaxy (Cen A) we found that non-circular motions and subsequent shocks play a major role to drive gas to the center. The molecular clouds and SF activities in the circumnuclear gas have different properties than those in disk galaxies, with higher velocity dispersions, lower SFEs, and a larger X factor than average values in disk galaxies.

３．研究の方法

The methodology in this research project is based on the analysis of ALMA observations obtained with high resolution of several molecular transitions. We target the closest radio powerful and elliptical galaxy, Centaurus A, as well as other similar galaxies located at larger distances. First, we study the distribution and kinematics of the molecular gas tracers, near and far from the active galactic nucleus. Second, we obtained the star formation law by comparing molecular gas with star formation rate using Spitzer data, and derive a catalog of Giant molecular clouds. The observations include 12m, 7m and TP array data, and thus the maps capture information from large to small spatial scales.

４．研究成果

The main results of our work are summarized in the following subsections, as extracted from the refereed papers related to this KAKENHI program:

1) An inner molecular Ring, nuclear shocks, and the CO to Warm H2 Interface in the circumnuclear disk (CND) of Centaurus A (Espada et al. 2017, ApJ, 843, 136)

We present the distribution and kinematics of the molecular gas in the circumnuclear disk (CND, 400 pc x 200 pc) of Centaurus A with resolutions of ~5 pc (0.3'') and shed light onto the mechanism feeding the Active Galactic Nucleus (AGN) using CO(3-2), HCO^+(4-3), HCN(4-3), and CO(6-5) observations obtained with ALMA. Significant complexity is found in the distribution and kinematics of the molecular gas. Multiple filaments or streamers of tens to a hundred parsec scale exist within the CND, which form a ring-like structure with an unprojected diameter of 162 pc x 108 pc and a position angle PA ~ 155 deg. Inside the nuclear ring, there are two leading and straight filamentary structures with lengths of about 30 - 60 pc at PA ~ 120 deg on opposite sides of the AGN, with a rotational symmetry of 180deg and steeper

position-velocity diagrams, which are interpreted as nuclear shocks due to non-circular motions. Along the filaments, and unlike other nearby AGNs, several dense molecular clumps present low HCN/HCO^+(4-3) ratios (< 0.5). The filaments abruptly end in the probed transitions at r ~ 20 pc from the AGN, but previous near-IR H_2 (J=1-0) S(1) maps show that they continue in an even warmer gas phase (T~1000 K), winding up in the form of nuclear spirals, and forming an inner ring structure with another set of symmetric filaments along the N--S direction and within r ~ 10 pc.

The molecular gas is governed primarily by non-circular motions, being the successive shock fronts at different scales where loss of angular momentum occurs, a mechanism which may feed efficiently powerful radio galaxies down to parsec scales.

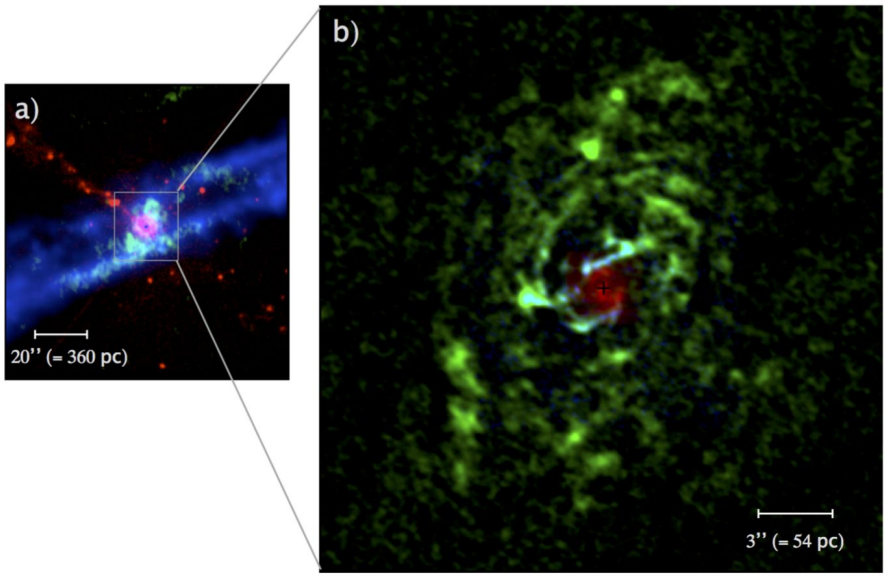

Fig. 1 kiloparsec to parsec scale view of the molecular disk of Cen A (NGC5128): a) Integrated CO(2-1) emission map (green) observed using the Submillimeter Array (SMA, Espada et al. 2009). The circumnuclear disk is just perpendicular to the X-ray/radio jet (red, Chandra). A more extended molecular gas component in form of spiral arms (Espada et al. 2012) is seen. b) Composite image of the CND of Cen A including the ALMA CO(3-2) (green) and CO(6-5) (blue) integrated intensity maps, as presented in Espada et al. (2017). The distribution of molecular hydrogen as traced by the H_2 line is mostly contained within a field of view of 54 pc.

2) Physical and chemical Properties of the molecular disk of Centaurus A (McCoy et al. 2017, ApJ, 851, 76). We present ALMA observations of low-J transitions of three CO isotopologues, HCN, HCO^+, HNC, CN, and CCH toward the inner projected 500 pc of NGC 5128. Our observations resolve physical sizes down to 40 pc. By observing multiple chemical probes, we determine the physical and chemical conditions of the nuclear interstellar medium of NGC 5128. This region contains molecular arms associated with the dust lanes and a circumnuclear disk (CND) interior to the molecular arms. The CND appears to be chemically distinct from the molecular arms. It is dominated by dense gas tracers while the molecular arms are dominated by ^{12}CO and its rare isotopologues. The CND has a higher temperature, elevated CN/HCN and HCN/HNC intensity ratios, and much weaker ^{13}CO and $C^{18}O$ emission than the molecular arms. This suggests an influence from the AGN on the CND molecular gas. There is also absorption against the AGN with a low velocity complex near the systemic velocity and a high velocity complex shifted by about 60 km s^{-1}. We find similar chemical properties between the CND in emission

and both the low and high velocity absorption complexes, implying that both likely originate from the CND. If the high velocity complex does originate in the CND, then that gas would correspond to gas falling toward the supermassive black hole.

3) Star Formation Laws at Giant Molecular Cloud Scales (Espada et al. 2019, ApJ, in press)
We present ALMA CO(1–0) observations toward the dust lane of the nearest elliptical and radio galaxy, NGC5128 (Centaurus A), with high angular resolution (∼ 1″, or 18pc) and including short spacings and single dish data to recover information from large to small spatial scales and total flux. We find a total molecular gas mass of 1.5×10^9 $M_\odot$ and we reveal the presence of filamentary components more extended than previously seen, up to a radius of 3kpc. We find that the global star formation rate (SFR) is ∼1 $M_\odot$ yr^{-1}. The star formation efficiency is 0.6 Gyr^{-1} (or depletion time $\tau = 1.5$ Gyr), a value that is similar to that in spiral galaxies. We show the most detailed view to date (40 pc resolution) of the relation between molecular gas and star formation (SF) within the stellar component of an elliptical galaxy and for a wide range of radii, from the outskirts at several kpc scale to the circumnuclear region (r = 200 pc) close to the powerful radio jet. We derive the resolved Kennicutt-Schmidt SF law in this object by comparing molecular gas and SFR surface densities, the latter from Spitzer/IRAC 8 μm data. Although on average the SFE on 40 pc scales is similar to that of spiral galaxies, the circumnuclear disk (CND) presents SFEs of 0.3 Gyr^{-1}, lower by a factor of 4 than the outer disk. The low SFE in the CND is in contrast to the high SFEs found in the literature for the circumnuclear regions of some nearby disk galaxies with nuclear activity, maybe as a result of stronger shocks and shear motions in Centaurus A and a more continuous period of AGN feedback. Because the molecular gas in low surface density regions (i.e. outskirts of the molecular disk) might be more easily ionized by massive star formation and/or destroyed under the hot interstellar medium within the elliptical galaxy, the molecular disk is expected to become more compact in ∼1 Gyr and only some central molecular gas or filaments with sufficient density and strong shear motions preventing SF will remain, which will result in the low SFEs previously seen in other giant ellipticals with cold gas.

4) A Giant Molecular Cloud Catalog of the molecular disk of Centaurus A (Miura, Espada et al. 2019, ApJ, submitted). We present the first census of giant molecular clouds (GMCs) down to 10^5 Msun and within the inner 4 kpc of the nearest giant elliptical and powerful radio galaxy, Centaurus A. To accomplish this, we used CO(1-0) data with 1″ spatial resolution (or ∼20 pc) and 2 km s^{-1} velocity resolution taken with ALMA. We identified 689 GMCs, which can be characterized by a median radius of 38 pc and median velocity dispersion of 6km s−1. The I(CO)-N(H2) conversion factor, based on the virial method, is $X_{CO} = (2 \pm 1) \times 10^{20}$ cm^{-2} (K km $s^{-1})^{-1}$ for the entire molecular disk, consistent with the disks of spiral galaxies including the Milky Way, and $X_{CO} = (5 \pm 2) \times 10^{20}$ cm^{-2} (K km $s^{-1})^{-1}$ for the circumnuclear disk (CND, within a radius of 200pc). The line width and mass-to-size relations of the resolved GMCs present an offset on average toward higher line widths and masses with respect to quiescent regions in other nearby spiral galaxies. The differences in the scaling relations reach their maximum offset for the GMCs associated with the CND. There, the velocity dispersions are ∼ 0.4 dex higher than those in the GMCs of the Milky Way disk. We obtained the GMC mass spectrum distribution and find that the best truncated power-law fit for the whole molecular disk (index $\gamma \simeq -2.41 \pm 0.02$ and upper cutoff mass ∼ 1.3

× 10^7 $M_\odot$) is consistent with that of nearby disk galaxies. There is a trend in the mass spectrum index from steep to shallow as we move to inner radii. Although the GMCs

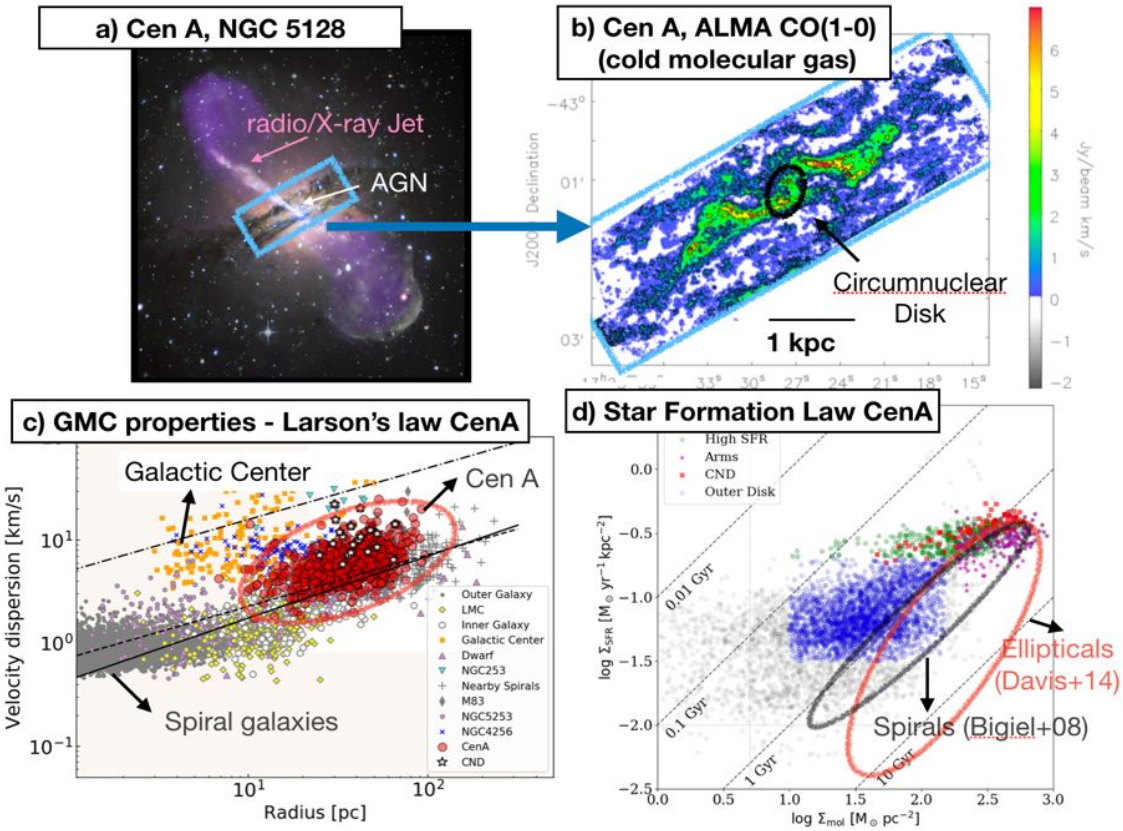

Figure 2. (a) The elliptical and radio galaxy in our pilot study, Cen A. **(b)** ALMA CO (1-0) integrated intensity map (20 pc resolution), extending ~5 kpc **(c)** Velocity dispersion- size (Larson's law) for identified GMCs. **(d)** Star Formation law (SFR vs. molecular gas surface densities) for regions of the molecular disk of Cen A. For comparison typical regions for disk galaxies (Bigiel et al. 2008) and other elliptical galaxies (e.g. Davis et al. 2014).

are in an elliptical galaxy, the general GMC properties in the molecular disk are as in spiral galaxies, including the GMC mass distributions. However, in the CND, large offsets in the scaling relations, a different XCO factor, and the shallowest GMC mass distribution shape ($\gamma = -1.1 \pm 0.2$) all suggest that there the GMCs are most strongly affected by the presence of the AGN and/or shear motions.

5．主な発表論文等

〔雑誌論文〕（計　6　件）

1. The Molecular Disk of the Elliptical Galaxy NGC 5128 (Centaurus A): II. A Giant Molecular Cloud Catalogue. Miura, Espada et al., 2019, Astrophysical Journal, submitted. Peer review
2. The Molecular Disk of the Elliptical Galaxy NGC 5128 (Centaurus A): I. Star Formation Efficiencies at Giant Molecular Cloud Scales. Espada et al., 2019, Astrophysical Journal, in press. URL: https://ui.adsabs.harvard.edu/abs/2019arXiv190601237E. Peer review
3. Complex distribution and velocity field of molecular gas in NGC 1316 as revealed by Morita Array of ALMA. Morokuma-Matsui et al., 2019, Publications of the Astronomical Society of Japan, in press, URL: https://ui.adsabs.harvard.edu/abs/2019arXiv190511085M. Peer review

4. ALMA Observations of the Molecular Gas in the Elliptical Galaxy NGC 3557. Vila-Vilaro, Espada, et al., 2019, Astrophysical Journal, 870, 39. DOI: 10.3847/1538-4357/aaef7f. Peer review
5. ALMA Observations of the Physical and Chemical Conditions in Centaurus A. McCoy et al., 2017, Astrophysical Journal, 851, 76. DOI: 10.3847/1538-4357/aa99d6. Peer review
6. Disentangling the Circumnuclear Environs of Centaurus A. III. An Inner Molecular Ring, Nuclear Shocks, and the CO to Warm H2 Interface. Espada et al., 2017, Astrophysical Journal, 843, 136. DOI: 10.3847/1538-4357/aa78a9. Peer review

〔学会発表〕（計　7　件）

1. Conference: ALMA Science Workshop on Nearby Galaxies; Place: Mitaka, Japan; Date: Feb 28/Mar 1, 2019; Type: Oral contribution. Title: Star Formation Laws and GMC properties in the molecular disk of Centaurus A. Authors: D. Espada, on behalf of the ALMA Cen A collaboration
2. Conference: EA ALMA Science Workshop; Place: Osaka, Japan; Date: Dec 17 - 19, 2018; Type: Oral contribution. Title: Star Formation and Molecular Cloud properties along the Dust Lane of the Elliptical Galaxy NGC 5128 (Centaurus A). Authors: D. Espada, on behalf of the ALMA Cen A collaboration
3. Conference: EA ALMA Science Workshop; Place: Osaka, Japan; Date: Dec 17 - 19, 2018; Type: Poster contribution. Title: A First Giant Molecular Cloud Catalog for the Elliptical Galaxy NGC 5128 (Centaurus A). Authors: Miura, R. E. on behalf of the ALMA Cen A collaboration
4. Conference: Japanese Astronomical Society Meeting; Place: Himeji, Japan; Date: Sep 18 - 21, 2018; Type: Oral/poster contribution. Title: Star Formation Laws at GMC Scales along the Dust Lane of the Elliptical Galaxy NGC 5128 (Centaurus A). Authors: D. Espada, S. Verley, R. E. Miura, on behalf of the ALMA Cen A collaboration
5. Conference: Japanese Astronomical Society Meeting; Place: Himeji, Japan; Date: Sep 18 - 21, 2018; Type: Oral/poster contribution. Title: A GMC catalog for the Circumnuclear Disk of Centaurus A. Authors: R. E. Miura, D. Espada, Matsushita, S., on behalf of the ALMA Cen A collaboration
6. Conference: East Asian AGN workshop 2017; Place: Kagoshima, Japan; Date: Dec 4 - 6, 2017; Type: Oral contribution. Title: ALMA Observations of the Circumnuclear Disk of Centaurus A. Authors: D. Espada, on behalf of the ALMA Cen A collaboration
7. Conference: The Role of Gas in Galaxy Dynamics; Place: Valetta, Malta; Date: Oct 2 - 6, 2017; Type: Oral contribution. Title: Disentangling the Properties of the Circumnuclear Disk of Centaurus A with ALMA. Authors: D. Espada, on behalf of the ALMA Cen A collaboration

６．研究組織

(1)**研究協力者**
研究協力者氏名: **三浦　理絵**
ローマ字氏名：Miura, Rie E.