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研究課題名（和文）Measuring the growth history of galaxy outskirts

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研究代表者
Ｂｕｎｄｙ　Ｋｅｖｉｎ．Ａ（Bundy, Kevin Allen）

東京大学・カブリ数物連携宇宙研究機構・特任助教

研究者番号：２０６２４１４１

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研究成果の概要（和文）：本研究の目的は、楕円銀河が中心コアが早期に形成される一方でその外側は時間をかけて”隣の星々”からの降着によって2段階で形成されるシナリオを検証することであった。検証の過程で、Red Geysersと名付けた新タイプの銀河を発見する重要な結果を得た。これらの銀河内には予期しないAGNの風が存在し、銀河内の星形成が抑制されている可能性がある。この研究結果はNatureで出版された。さらに星の種族が銀河の住む環境にどのように依存しているかを調べた。最後に研究会で観測したスペクトルから星の性質を調べる様々な手法を比較し議論を深めた。本研究会は大変な成功を収め新たな解析手法の発展につながるものであった。

研究成果の概要（英文）：The purpose of this project was to test the 2-phase formation scenario for elliptical galaxies which states that their central cores are formed early while their outskirts build up through the accretion of "foreign stars" with time. Using the FIREFLY code, we have begun spectral fitting to determine stellar population properties.During this process, an important discovery was made of a new class of galaxy we call Red Geysers. These "red geysers" host unexpected AGN winds and may be a critical reason why star formation remains suppressed in these systems at late times. The resulting paper was published in Nature. Additionally, we returned to the primary analysis of the stellar populations and investigated their dependence on the local environment in which the galaxy lives.
Finally a workshop was held to deeply discuss and compare different approaches for measuring stellar properties from the observed spectra. This workshop was highly successful and will result in improved methods.

研究分野：　銀河形成

キーワード：　Spectral fitting　Stellar Gradients　AGN winds　Feedback

１．研究開始当初の背景

The surprising discovery of a factor of ~5 growth in the sizes of elliptical galaxies over the last 10 Gyr (since z~2) has triggered one of the most active topics in international astrophysics. The seminal paper by van Dokkum et al. (2008) with over 300 citations ended theories of "Monolithic Collapse" and raised a new fundamental question: How does galaxy growth occur? The most popular theory is the accumulation of "foreign" stars stripped away from lower mass, orbiting satellite galaxies and deposited at large radius (R). The satellites must be low mass (log M＊< 10.3) because 1) such galaxies are disk-like and extended, making them more easily stripped and shredded, 2) they are more vulnerable to the tidal forces of the larger galaxy. As a result, the spectra of these foreign stars should be chemically distinct. They should have lower metallicity ([Z/H]) because they formed in shallow potential wells, and their ages and element abundance patterns ([α/Fe]) should reveal a more extended star formation history, because most low-mass galaxies experience continuous star formation over cosmic time (Bundy et al. 2006). Unfortunately, small samples and poor coverage at large radius have prevented spectroscopic confirmation of accreted foreign stars in the outskirts of massive galaxies.

MaNGA (Mapping Nearby Galaxies at Apache Point Observatory) is a 6-year SDSS-IV survey of which I am the Principal Investigator (PI). We began on 1 July 2014 and will obtain resolved spectroscopy for 10,000 nearby galaxies, making it possible to test and quantify growth at large-R for the first time.

２．研究の目的

The spectroscopic measurements I proposed are similar to "galactic archaeology" (e.g., Arimoto & Yoshii, 1987, Chiba & Beers, 2000) studies of the Milky Way, but applied to other galaxies. Characterizing the metallicity, age, and star-formation timescale of stars in the outermost regions of galaxies will tell us about the physical processes that drive galaxy growth. For example, this will test "progenitor bias," the notion that the observed increase in average size is caused by the recent appearance of younger ellipticals that are intrinsically larger (see Belli et al. 2014), which will produce stellar metallicity gradients that will depend on the galaxy's age. An M＊dependence in the steepness of [Z/H] gradients (Pastorello et al. 2014), on the other hand, would result from early, rapid formation (e.g., Oser et al. 2010), perhaps followed by adiabatic size expansion (Fan et al. 2008).

Some evidence for foreign stars at large-R in a few individual galaxies has been reported by Coccato et al. (2011) and Weijmans et al. (2009), but with a mix of results. Indeed, the purpose here is to measure the deviation as well as the average trends in chemical gradients, thereby quantifying the history and mechanisms behind stellar accretion, across a range of galaxy types and environments. In this way we test claims that environmental effects at z~2 are required to pre-process (i.e., rapidly quench) the galaxies whose stars are later

accreted (Greene et al. 2013) by quantifying the age and star-formation history of stars in outer components. Finally, my MaNGA-based sample enables large-R comparisons between ellipticals and similarly massive disk galaxies that reside at their halo's center. Because satellite stripping and accretion are gravitational processes, foreign stars at large-R should be present regardless of the galaxy's morphological type.

３．研究の方法

MaNGA will obtain integral field spectroscopy from 3600—10300Å (R~2200) for 10,000 galaxies at z~0.03 and log M ▪> 9. Roughly 3000 galaxies have been observed, roughly 1200 of which will cover 2.5 Re (the remaining two-thirds of the MaNGA sample is designed to reach 1.5 Re). An overview of the survey is presented in Bundy et al. (2015). I am studying how spectral features sensitive to stellar age, [Z/H], and [α/Fe] vary with radius. The MaNGA reduction pipeline successfully processes the dithered 3-4 hour exposures obtained per galaxy into rectified datacubes soon after observations are obtained. As the MaNGA P.I., I oversee the team's development of an Analysis Pipeline which will perform emission/continuum decomposition, velocity rectification, and spectral fitting over all positions in the datacube. Postdocs at Kavli IPMU are working with me on this development, and a prototype fitting tool has already enabled a submitted publication on stellar chemistry maps using early MaNGA observations (Wilkinson et al., 2015). It is critical to bring other researchers together with similar expertise in order to build even better software, allowing me to measure the stellar age, [Z/H], and [α/Fe], in at least 5 radial bins to 2.5 Re for 500 elliptical and disk galaxies.

４．研究成果

As described in the Research Plan, an initial sample of several hundred galaxies was constructed and annular bins were established out to 2.5 Re. Using the FIREFLY code, we performed spectral fitting in these bins in order to determine stellar population properties such as age, metallicity, and alpha abundance. An important intermediate step was to verify that no star formation was apparent so that young (foreign) stars in the outskirts could be clearly detected. An analysis of the Ha equivalent width map (a proxy for star formation) was made for this sample. At this point an unexpected discovery was made. While the colors indicated these galaxies were "red and dead," their Ha gas profiles showed a surprising range of active behavior. Through a detailed analysis, we were able to prove that many of these ellipticals hosted ionizing gas outflows at a surprisingly high rate. These "red geysers" may be a critical reason why star formation remains suppressed in these systems at late times. This suppression is key to supporting the two-phase scenario that this proposal seeks to test.. Without suppression of star formation, the onion-shell like accretion of later-formed stars would never be possible to study. The resulting paper on this work was published in Nature. Two parallel paths were then pursued. On the one hand, the unexpected Red Geysers

discovery is very compelling and demands followup work. A more fulsome paper describing the sample properties of this new galaxy class is now being drafted. In addition, a more focused paper studying the radio AGN properties of Red Geysers in the context of radio activity in early-type galaxies is also being prepared. The second path is further development of tools to decode the observed spectrum and extract the properties of the stellar populations that contribute to it. FIREFLY was the initial tool used for this procedure. It was combined with the existing STARLIGHT code and papers using both to derive the stellar population gradients of MaNGA galaxies have now been submitted. One new aspect of this work is the analysis of how environment impacts these internal gradients. We have found that the effect of local environment is surprisingly minor. However, uncertainties in the methodology remain. This motivated a workshop at Kavli IPMU focused on building better tools for spectral fitting. A number of new ideas emerged from this workshop that will lead to direct improvements of extracting information from the MaNGA spectra and being able to identify foreign stars accreted at late times to the external regions of massive galaxies.

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 3 件）

① Belfiore F., Bundy, K., et al., 2016, MNRAS, Volume 461, Issue 3, p.3111, 10.1093/mnras/stw1234 "SDSS IV MaNGA - Spatially resolved diagnostic diagrams: A proof that many galaxies are LIERs"

② Penny SJ., Bundy, K., et al., 2016, MNRAS, 10.1093/mnras/stw1913 "SDSS-IV MaNGA: Faint quenched galaxies I- Sample selection and evidence for environmental quenching"

③ Cheung, E., Bundy, K., et al., 2016, Nature, 10.1038/nature18006, Volume 533, Issue 7604, pp. 504 "SUPPRESSING STAR FORMATION IN QUIESCENT GALAXIES WITH SUPERMASSIVE BLACK HOLE WINDS"

〔学会発表〕（計 4 件）

① Bundy, K., "MaNGA in Madison", SDSS Collaboration Meeting, July 27, 2016, Madison, USA

② Bundy, K., "MassAssembly Through Cosmic Time" The Interplay Between Local and Global Processes in Galaxies, Apr. 15, 2016, Cozumel, Mexico,

③ Bundy, K., "SDSS-IV MaNGA: Mapping Nearby Galaxies at APO", AAS Special Session, January 7, 2016, Florida, USA

④ Bundy, K., "MaNGA in Madrid: What's hot? What's Cookin?" SDSS Collaboration Meeting, July 20- July 23 2015, Madrid, Spain

〔図書〕（計　0 件）

〔産業財産権〕

○出願状況（計　0 件）

名称：
発明者：
権利者：
種類：
番号：
出願年月日：
国内外の別：

○取得状況（計　0 件）

名称：
発明者：
権利者：
種類：
番号：
取得年月日：
国内外の別：

〔その他〕
A press release was issued ahead of the publication of the discovery paper about Red　Geysers. The story was picked up by a number of international and Japanese news　outlets, triggered a “round table discussion” organized by the Kavli Foundation, and has　triggered a documentary segment to be filmed by the Discovery Science Channel.

Kavli IPMU
http://www.ipmu.jp/ja/20160526-redgeyser

朝日新聞
http://www.asahi.com/articles/ASJ5R63TJJ5RULBJ014.html

Phys.org
https://phys.org/news/2016-05-scientists-supermassive-black-holes-galaxies.html

Kavli **財団**
http://www.kavlifoundation.org/science-spotlights/why-dead-galaxies-rest-peace-never-form-stars-again#.WSUaQGfouJA

Discovery Science Channel
http://www.dailygalaxy.com/my_weblog/2016/05/red-geysers-new-phenomenon-creates-dead-galaxies-of-the-cosmos.html

６．研究組織
(1)研究代表者
バンディ　ケビンアレン（BUNDY, Kevin Allen）
東京大学・カブリ数物連携宇宙研究所・特任助教
研究者番号：20624141