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学位論文題目 Chemical Evolution of Galaxies through Observational
Statistics and Empirical Modeling

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博士論文の要旨

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論文題目：Chemical Evolution of Galaxies through Observational Statistics and Empirical Modeling

Understanding the cosmic evolution of the baryon cycle is a central goal of modern astrophysics. The baryon cycle describes the complex interplay of gas inflow from the intergalactic medium, the consumption of gas through star formation, and the expulsion of metal-enriched gas via galactic outflows. In the local universe, these processes are observed to be in an equilibrium state, manifesting as tight scaling relations such as the mass-metallicity relation and the fundamental metallicity relation (FMR). These relations suggest that the metallicity of a galaxy is regulated by its stellar mass and star formation rate. However, a fundamental question remains regarding when and how this equilibrium was established in the history of the universe. Investigating the gas-phase metallicity of galaxies in the early universe was historically challenged by observational limitations. Prior to the launch of the James Webb Space Telescope (JWST), rest-frame optical diagnostic lines necessary for accurate metallicity measurements were inaccessible for galaxies at redshifts $z > 4$. Consequently, understanding the physics of early galaxies often relied on studying local counterparts. With the advent of JWST and the development of sophisticated empirical models, it is now possible to directly measure the chemical properties of early galaxies and interpret them within a physical framework. This thesis combines statistical studies of local metal-poor galaxies, direct observations of high-redshift galaxies using JWST, and a novel empirical model to elucidate the evolutionary history of the baryon cycle.

In Chapter 2, we investigate extremely metal-poor galaxies (EMPGs) in the local universe to understand the low-metallicity limit of galaxy formation and the equilibrium state of chemically primitive systems. We develop a machine-learning selection technique to identify EMPG candidates from the photometric data of the Sloan Digital Sky Survey (SDSS). The algorithm is trained to distinguish the unique colors of EMPGs from other objects. We apply this method to SDSS photometric catalogs and select candidates. We conducted spectroscopic screening of candidates using the Seimei and Nayuta Telescopes to distinguish galaxies from stars, followed by deep spectroscopy of ten selected targets with the Magellan Telescope to measure the metallicities. We derive gas-phase metallicities using the direct method based on the detection of the auroral oxygen line, which provides a temperature-sensitive and

accurate abundance measurement. Although we successfully identified three new EMPGs, our systematic search did not yield any galaxies with metallicities below one percent of the solar value. This non-detection places a stringent constraint on the metallicity floor in the local universe, suggesting that galaxies with lower metallicities are either extremely rare or do not exist at the present epoch. We then analyze the chemical properties by constructing a statistical sample of 80 confirmed EMPGs. We found that the mass-metallicity-SFR relation of these local EMPGs can be explained by the same equilibrium model that describes more massive and metal-rich galaxies. This result indicates that the baryon cycle in the local universe operates in an equilibrium state even in the most metal-poor systems known.

In Chapter 3, we extend this selection methodology to the high-redshift universe to identify primitive galaxies in the early universe. We utilize deep near-infrared imaging data obtained by JWST NIRC*am*. By adapting the color selection criteria to the redshifted photometric bands available in the JWST fields, we search for galaxies at redshifts $z \sim 4 - 5$ that exhibit photometric signatures similar to local EMPGs. This search results in the identification of 17 promising candidates that show extremely blue colors indicative of low metallicity and young stellar populations. To validate these candidates, we conducted spectroscopic follow-up observations using FOCAS on the Subaru Telescope. While the spectroscopic validation of the selection technique remains to be achieved, the identification of the candidates provides a valuable target list for future analysis with JWST spectroscopy.

In Chapter 4, we perform a direct investigation of the chemical evolution of galaxies across a wide redshift range from $z = 2 - 10$ using spectroscopic data from JWST. We combine data from the DREAMS, JADES, CEERS, and ERO surveys to construct a large sample of 292 galaxies. The primary objective is to measure gas-phase metallicities using the robust direct method rather than relying on empirical calibrations that may not be applicable to high-redshift galaxies. Since the auroral oxygen line at 4363 angstroms is intrinsically faint, especially in distant galaxies, we employ a spectral stacking technique. We group galaxies based on their redshift and stack their spectra to increase the signal-to-noise ratio. This approach allows us to successfully detect the auroral line and derive electron temperatures and metallicities. We then examine the evolution of the mass-metallicity relation and the FMR. Our analysis reveals that galaxies up to redshift $z \sim 6$ generally follow the FMR established in the local universe. However, we discover a significant deviation at redshifts $z \gtrsim 8$. Galaxies at the earliest epochs exhibit gas-phase metallicities that are systematically lower than predicted by the stellar mass and star formation rates. Specifically, we observe a metallicity deviation of approximately 0.3 to 0.5 dex compared to the FMR prediction. This breakdown of the scaling relation suggests that

the baryon cycle in the early universe, within the first 600 million years of cosmic history, had not yet reached the equilibrium state observed today.

In Chapter 5, we construct a new empirical chemical evolution model named the `ChemicalUniverseMachine` to provide a physical interpretation of the observational results obtained in the preceding chapters. This model connects the metallicity evolution to the growth of dark matter halos. Unlike semi-analytic models that rely on numerous uncertain physical parameters, our empirical framework is designed to reproduce the observed evolution of the galaxy stellar mass function and the star formation rate density with minimal assumptions. The model incorporates a multiphase description of the interstellar medium and tracks the distribution of metals between the interstellar medium and the circumgalactic medium. By fitting the model to the observed mass-metallicity relation and its evolution, we constrain the key physical parameters governing the baryon cycle, such as the metal distribution fraction. The model successfully reproduces the observed metallicity evolution from redshift $z = 0 - 5$. Our analysis using this framework indicates that the metal distribution fraction into the interstellar medium is universally governed by the depth of the gravitational potential of the host dark matter halo, regardless of redshift.

Finally, in Chapter 6, we apply the `ChemicalUniverseMachine` model to interpret the breakdown of the FMR at redshifts $z \gtrsim 8$, as observed in Chapter 4. Our modeling quantitatively demonstrates that the observed metallicity deficit cannot be reproduced by standard extrapolations of local calibrations. Instead, reproducing the observations requires an evolution in the baryon cycle, specifically either an enhancement in outflow efficiency or an increase in gas inflow relative to star formation. This suggests that the baryon cycle in the early universe operates in a non-equilibrium state, distinct from the equilibrium established at lower redshifts. Consequently, this thesis presents a unified picture of the evolution of the baryon cycle, transitioning from a primordial, non-equilibrium state in the early universe to the equilibrium state established today.

博士論文審査結果

Name in Full
氏名 西垣 萌香

Title
論文題目 Chemical Evolution of Galaxies through Observational Statistics and Empirical Modeling

西垣氏の博士論文は、宇宙史を通じた銀河進化を支配する根源的な物理過程である「バリオン循環 (baryon cycle)」に注目し、観測と経験的モデルの両面からの研究成果をまとめたものである。

第2章では、近傍宇宙の極低金属量銀河(EMPG)に着目し、初期宇宙の銀河の類似天体として調査を行った。特に、太陽金属量の100分の1未満の銀河が観測されない「金属量フロア」の存在と、EMPGの物理的起源に焦点が当てられている。スローン・デジタル・スカイ・サーベイ(SDSS)のデータに対して機械学習を適用し、EMPGに特徴的な強い輝線の寄与がブロードバンドの測光値に現れる候補天体を選定し、複数の地上望遠鏡を用いて分光観測を行なった。その結果、新たなEMPGを3天体発見したが、金属量が太陽の100分の1以下である超低金属量銀河(HMPG)はやはり検出されなかった。そして先行研究で得られているEMPGサンプルも合わせて統計的解析を行い、近傍宇宙のEMPGがほぼ定常状態にあることを示した。

第3章では、この手法を JWST による高赤方偏移観測へ拡張する研究成果が記述されている。JWST/NIRCam による深観測データを用いて赤方偏移 4-5 の EMPG 候補天体を同定し、それらがきわめて低い($H\beta + [OIII]$)/ $H\alpha$ 比を示すことを明らかにした。これは近傍宇宙の EMPG よりもさらに低金属量、場合によっては HMPG クラスに相当する可能性を示唆しており、金属量フロアが初期宇宙では破れていた可能性を示す重要な結果である。

第4章では、JWST/NIRSpec による赤方偏移 2-10 の 294 天体の分光データをコンパイルしてスペクトルスタッキング解析を行うことで、微弱な $[OIII] \lambda 4363$ 線を検出し、直接温度法による金属量測定を実現した。その結果、銀河の金属量が初期宇宙に向かって低下し、特に赤方偏移8を超える宇宙では、星質量-星形成率-金属量関係(Fundamental Metallicity Relation; FMR) から低金属量側へ有意なオフセットが見られることが分かった。これは初期宇宙においてバリオン循環が非定常状態であった可能性を示す観測的証拠である。

第5章では、これらの結果を統一的に解釈するために、新たな経験的化学進化モデル「Chemical UniverseMachine」を構築した。このモデルでは、金属が分子ガス・中性ガス・銀河外に分配される割合をそれぞれ個別に扱い、過去のさまざまな観測研究を参照しながら、観測データの再現を試みるものである。解析の結果、初期宇宙では近傍宇宙の銀河とは異なり、より効率的なガス流出または大量のガス流入が必要であることが示された。

以上のように西垣氏の博士論文は、バリオン循環が初期宇宙の激しく非定常な状態から、現在の宇宙におけるほぼ定常的な状態へと進化してきた様子を明確に描き出し、銀河の進化とその化学進化の理解に新たな観測的・理論的基盤を提供する重要な研究であり、審査委員会は全員一致で本論文が博士の学位授与に値するものであると判断した。