様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

# 科学研究費助成事業　　研究成果報告書

令和　４ 年　８ 月 ２６ 日現在

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研究課題名（和文）Can Baryon-Dark Matter Streaming Motion Explain Supermassive Blackholes in the Early Universe?

研究課題名（英文）Can Baryon-Dark Matter Streaming Motion Explain Supermassive Blackholes in the Early Universe?

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　2,200,000円

研究成果の概要（和文）：宇宙の再結合時には、バリオンとダークマター(DM)の間に超音速の相対運動が一般的に存在する。本研究では、この相対運動を考慮した流体シミュレーションを実行し、相対運動が宇宙初期の構造形成に及ぼす影響を調べる。結果として、第一世代天体の形成が遅れ、星形成ガス雲の質量が増大し、超大質量ブラックホールの種となる。また、速度差でガスがダークマターハローの外側で収縮し、球状星団へ進化する天体も調査中である。

研究成果の学術的意義や社会的意義
宇宙初期の天体形成は、宇宙進化を理解する上で最重要の課題の一つである。現在の宇宙に存在する銀河やブラックホールといった天体をシミュレーションで再現するには、137億年の宇宙史の間での複雑な効果を取り入れる必要があり、困難を伴う。対して本研究では宇宙開闢から約10億年を対象とするので正確に再現しやすい。ガスと暗黒物質の速度差を考慮した本研究を橋渡しとして、将来的には近傍宇宙の天体の再現が可能となる。

研究成果の概要（英文）：During the first billion years of cosmic history, a relative streaming motion between baryon and dark matter impeded gas accretion in dark matter clumps. We explored how this affected the structures of the early universe. We developed a code to accurately generate the initial gas/dark matter density field in the presence of the streaming. Then, we ran numerical simulations to evolve the density fluctuations into structures. We found that the streaming velocity can suppress the formation of small gas structures and reduce the recombination rate, thereby accelerating the ionization of the intergalactic gas by early galaxies. We are also finding that the streaming can cause a sudden collapse of gas into massive blackholes, which can be a progenitor of the supermassive blackhole we find at galactic centers. Lastly, we are investigating whether the streaming can create groups of stars completely devoid of dark matter, just like the globular clusters in today's galaxies.

研究分野：Computational astrophysics

キーワード：Astrophysics　Cosmology　Reionization　Hydrodynamics　Numerical simulation　Intergalactic medium

１．研究開始当初の背景

In 2010, it was theoretically discovered that, in the early universe, gas and dark matter had a relative streaming velocity of several km/s, which made it more difficult for structures like stars and blackholes to form than previously thought. The strength of this streaming velocity is known to have varied from place to place, possibly introducing a significant spatial inhomogeneity to the early structure formation that we did not think of before 2010.

Gas clouds started collapsing into dark matter halos when the universe was roughly 108 years old. This is when the streaming velocity comes into play. We think the relative motion between gas and dark matter made it more difficult for gas to fall into the gravitational well of the halo. The formation of the first galaxies should have been delayed. Some recent studies suggest the delayed collapse can lead to more abrupt infall of gas, resulting in the gas directly collapsing into a massive blackhole with tens of thousands solarmasses. Recent studies suggest that streaming velocity removed dark matter in globular clusters.

In order to tackle the above-mentioned processes, we need to update the numerical simulations of structure formation by adding the streaming motion effect. Understanding these first structures is a crucial stepping stone to understanding how the universe evolved into what we see today. We may explain how the supermassive blackhole at the galactic centers formed, why globular clusters lack dark matter, and when the first galaxies started shining and heating the universe.

２．研究の目的

Our goal was to run simulations of gravity and hydrodynamics to study the condensation of gas in dark matter halos in the early universe while accounting for the baryon-dark matter streaming velocity. The target quantities are the amount of gas captured in halos and the temperature of the captured gas. These quantities tell us how many stars and blackholes form in the halos and whether the gas cloud can directly collapse into a massive black and form globular clusters.

３．研究の方法

Our primary method for this research project is numerical simulations of gravity and gas dynamics plus radiative transfer of ultraviolet light. Since galaxy formation involves a complex interplay among these components, it is necessary to run numerical simulations with different levels of streaming velocity and local density to estimate the galaxy properties accurately.

４．研究成果

[1] Park H., Ahn K., Yoshida N., Hirano S., 2020, ApJ, 900, 30

We first worked on establishing an accurate method to simulate the gas structures in the presence of the streaming velocity. Typically, simulations of structure formation are initialized around several million years after the Big Bang, when the density field starts to become nonlinear. Until now, most studies simply added an artificial velocity to gas in old initial conditions created without the streaming velocity. This method misses the effect happening before the start of the simulation, underestimating the overall effect.

In this work, we estimated the error from the approximation and provided an accurate initial condition generator for future use. We solved a set of proper equations to correctly estimate the streaming effect on the gas density field before starting the equation. We ran simulations to compare the results against the approximate simulations. We found that gas fraction in halos is not much affected by the approximation, justifying the approximation for studying early star formation. We, however, found that the abundance of gas structures (filaments, sheets, etc.) is overestimated in the approximate method, resulting in exaggerated recombination in the intergalactic gas. This work provides guidance for future works on the streaming velocity to avoid biasing the results. We published this work in a journal in 2020.

[2] A paper in preparation

As a follow-up project, we are simulating the fate of collapsing gas clouds in the early universe to estimate how many stars and blackholes were produced using the initial condition generator from the first work. We are investigating under what conditions direct collapse blackholes are produced instead of stars and the exact mechanism of the globular clusters forming without any dark matter. When this project is complete, we will be able to provide an observational forecast for the new upcoming space telescopes that target the early universe and gravitational wave experiments searching blackhole binaries. This work is still ongoing, and we plan to publish this work soon.

[3] Park H., Shapiro P. R., Ahn K., Yoshida N., Hirano S., 2021, ApJ, 908, 96

As another follow-up project, we investigated how the streaming velocity can affect reionization by modulating the abundance of small-scale gas structures around one billion years after the Big Bang. It has been known that small-scale gas structures delay the reionization of the universe by increasing the recombination rate. We were trying to see if the large-scale spatial variation in the streaming velocity can introduce a large-scale inhomogeneity in the reionization.

As was highlighted in the first project, we benefit from having an accurate initial condition generator when modeling small-scale gas structures in the presence of the streaming velocity. We first ran simulations of structure formation to see how many structures are formed at a given level of streaming velocity. We then ran simulations of ionizing radiation to calculate the amount of recombination from those small-scale structures. We found that the recombination rate does depend sensitively on the local streaming velocity magnitude. When the universe is one billion years old, our results show the hydrogen recombined 0.2, 0.4, and 0.6 times per atom for $+2\sigma$, average, and $-2\sigma$ levels of the streaming velocity. Thus, the streaming velocity can cause up to 0.4 difference in the ionizing photons needed to ionize the universe, creating a large-scale fluctuation in the reionization process. We expect this newly found phenomenon to be confirmed in the upcoming radio observations of hydrogen 21cm emission. We also think it will explain the large-scale fluctuations in the reionization suggested by the Lyman alpha forests of distant quasars.

[4] Park H., et al., 2021, ApJ, 922, 263; Park H., et al., 2022, Arxiv-eprint, 2202.06277 (accepted for publication)

As a side project, we studied the observability of Lyman alpha emitting galaxies from the early universe. The neutral hydrogen gas in the intergalactic medium of the early universe is expected to have scattered a significant portion of the Lyman alpha emission from galaxies. We downloaded output data of the Cosmic Dawn II simulation, a simulation of the cosmic reionization, and calculated the fate of Lyman alpha emission from the early galaxies.

Using the realistic simulation, we calculated the detailed scattering process of the photons and the fraction of scattered photons on their way to us. We provided a table giving the scattering fraction as the function of the global hydrogen neutral fraction and the luminosity of the source galaxies so that the upcoming observations of distant galaxies can constrain the neutral fraction of the early universe.

We have also investigated the fate of the scattered photons, which we expect to observe in the form of a diffuse halo around the source galaxy. We wrote a Markov Chain Monte Carlo simulation code to track the trajectory of Lyman alpha photons. We calculated how the scattered photons are distributed in the diffuse halo depending on their initial frequencies. We demonstrated that we would be able to reconstruct the original emission strength and line profile by analyzing the properties of the scattered light. We will soon start observing this scattered light using the James-Webb Space Telescope, scheduled to start observing later this year. Our insight will help recover the scattered portion, helping to understand the early galaxies in the first billion years of cosmic history.

5．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　2件）

| | |
|---|---|
| 1．著者名<br>Park Hyunbae、Shapiro Paul R.、Ahn Kyungjin、Yoshida Naoki、Hirano Shingo | 4．巻<br>908 |
| 2．論文標題<br>Large-scale Variation in Reionization History Caused by Baryon-Dark Matter Streaming Velocity | 5．発行年<br>2021年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>96～96 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/abd7f4 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Bianco Michele、Iliev Ilian T、Ahn Kyungjin、Giri Sambit K、Mao Yi、Park Hyunbae、Shapiro Paul R | 4．巻<br>504 |
| 2．論文標題<br>The impact of inhomogeneous subgrid clumping on cosmic reionization: II. Modelling stochasticity | 5．発行年<br>2021年 |
| 3．雑誌名<br>Monthly Notices of the Royal Astronomical Society | 6．最初と最後の頁<br>2443～2460 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/stab787 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Park Hyunbae、Shapiro Paul R.、Ahn Kyungjin、Yoshida Naoki、Hirano Shingo | 4．巻<br>908 |
| 2．論文標題<br>Large-scale Variation in Reionization History Caused by Baryon-Dark Matter Streaming Velocity | 5．発行年<br>2021年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>96～96 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/abd7f4 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>該当する |

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|---|---|
| 1．著者名<br>Park Hyunbae、Ahn Kyungjin、Yoshida Naoki、Hirano Shingo | 4．巻<br>900 |
| 2．論文標題<br>First Structure Formation under the Influence of Gas-Dark Matter Streaming Velocity and Density: Impact of the “Baryons Trace Dark Matter” Approximation | 5．発行年<br>2020年 |
| 3．雑誌名<br>The Astrophysical Journal | 6．最初と最後の頁<br>30～30 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3847/1538-4357/aba26e | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>該当する |

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| 2．論文標題<br>The impact of inhomogeneous subgrid clumping on cosmic reionization - II. Modelling stochasticity | 5．発行年<br>2021年 |
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| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1093/mnras/stab787 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>該当する |

〔学会発表〕　計14件（うち招待講演　1件／うち国際学会　7件）

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|---|
| 1．発表者名<br>Hyunbae Park |
| 2．発表標題<br>Lyα Transmission in the Reionizing Intergalactic Medium |
| 3．学会等名<br>Reionization and Cosmic Dawn: Looking Forward To the Past（国際学会） |
| 4．発表年<br>2022年 |

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| 1．発表者名<br>Hyunbae Park |
| 2．発表標題<br>Lyα Transmission in the Reionizing IGM: Infall Motion, HII Bubble Size, and Self-shielded Systems |
| 3．学会等名<br>SAZERAC2（国際学会） |
| 4．発表年<br>2021年 |

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|---|
| 1．発表者名<br>Hyunbae Park |
| 2．発表標題<br>Scatter in Reionization History Induced by Baryon-Dark Matter Streaming Motion |
| 3．学会等名<br>Kavli IPMU Lunch Seminar |
| 4．発表年<br>2020年 |

１．発表者名
Hyunbae Park

２．発表標題
Scatter in Reionization History Induced by Baryon-Dark Matter Streaming Motion

３．学会等名
RESCEU summer school talk

４．発表年
2020年

１．発表者名
Hyunbae Park

２．発表標題
Scatter in Reionization History Induced by Baryon-Dark Matter Streaming Motion

３．学会等名
Kavli IPMU Colloquium

４．発表年
2020年

１．発表者名
Hyunbae Park

２．発表標題
Large-scale Variation in Reionization History Caused by Baryon-Dark Matter Streaming Motion

３．学会等名
Korea Institute for Advanced Study（国際学会）

４．発表年
2020年

１．発表者名
Hyunbae Park

２．発表標題
First Structure Formation under the Influence of Baryon-Dark Matter Streaming Motion

３．学会等名
Tohoku Univ. First Star Meeting

４．発表年
2020年

１．発表者名
Hyunbae Park

２．発表標題
Intergalactic Medium During the Epoch of Reionization

３．学会等名
Lawrence Berkeley National Lab Computational Cosmology Center Colloquium（招待講演）（国際学会）

４．発表年
2021年

１．発表者名
Hyunbae Park

２．発表標題
Impact of Baryon-Dark Matter Streaming Velocity on Reionization

３．学会等名
First Shanghai Assembly（国際学会）

４．発表年
2019年

１．発表者名
Hyunbae Park

２．発表標題
Implication of Baryon-Dark Matter Streaming Velocity on Reionization

３．学会等名
Kavli IPMU Lunch Seminar

４．発表年
2019年

１．発表者名
Hyunbae Park

２．発表標題
Implication of Baryon-Dark Matter Streaming Velocity on Reionization

３．学会等名
The 235th American Astronomy Society（国際学会）

４．発表年
2020年

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|---|
| １．発表者名<br>Hyunbae Park |
| ２．発表標題<br>Does Baryon-Dark Matter Streaming Motion Accelerate the Cosmic Reionization? |
| ３．学会等名<br>National Astronomical Observatory of Japan |
| ４．発表年<br>2020年 |

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| １．発表者名<br>Hyunbae Park |
| ２．発表標題<br>Can Baryon-Dark Matter Streaming Motion Accelerate the Cosmic Reionization? |
| ３．学会等名<br>University of Tokyo Astrophysics Seminar |
| ４．発表年<br>2020年 |

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|---|
| １．発表者名<br>Hyunbae Park |
| ２．発表標題<br>Impact of the Baryon-Dark Matter Streaming Motion  on the Epoch of Reionization |
| ３．学会等名<br>FirstStarIV（国際学会） |
| ４．発表年<br>2020年 |

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

| | 氏名<br>（ローマ字氏名）<br>（研究者番号） | 所属研究機関・部局・職<br>（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 | | | |
|---|---|---|---|---|
| 韓国 | Chungnam National University | KASI | Chosun University | |
| 米国 | NASA Goddard Center | University of Texas at Austin | University of California at Riverside | 他1機関 |
| フランス | Universite de Strasbourg | | | |
| 英国 | University of Sussex | | | |
| イタリア | Scuola Normale Superiore | | | |