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科研費 KAKENHI

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研究課題名（和文）Understanding formation of supermassive black hole seeds at high-redshift via direct collapse

研究課題名（英文）Understanding formation of supermassive black hole seeds at high-redshift via direct collapse

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研究成果の概要（和文）：ガス球を直接ブラックホールに崩壊させるダイレクトコラプスは、早期宇宙において巨大ブラックホールの種を作るのに有力なシナリオです。崩壊するガス球の中心付近では密度が非常に高くなるため、光学的に分厚くなり、輻射輸送計算が必要になります。そこで、我々はflux-limited拡散近似を用いて、孤立系ハローと宇宙論的シミュレーションの両方において、流体力学と輻射輸送をカップルさせたダイレクトコラプスシミュレーションを世界で初めて実行しました。その結果、中心にコアができ始めると光球が半径1e-6 pc付近から外側に向かって広がり、輻射圧によって非等方的なアウトフローが生まれることを見出しました。

研究成果の学術的意義や社会的意義
巨大ブラックホールは銀河進化と密接な関係を持っていることが知られており（SMBHと銀河の共進化）、すなわち、SMBHの形成と進化をよりよく理解することは宇宙の構造形成をより深く理解することにつながります。究極的には、宇宙の構造形成を理解することが、「我々はどこからきたのか？」という疑問に答えることに繋がります。また、本経費によって若手研究員を数人雇用して、彼らのキャリア形成にも貢献しました。これらの業績は日本の学術界を世界標準に押し上げ、日本という国の文化・社会を発展させる一助にもなっております。また、若手研究者の育成を通じて、世界の科学界にも貢献していることになります。

研究成果の概要（英文）：Direct collapse is a promising path to form supermassive black hole (SMBH) seeds at high redshifts. The innermost region of the collapse is expected to become optically thick and requires us to follow the radiation field. We apply radiative transfer in the flux-limited diffusion (FLD) approximation to solve the evolution of coupled gas and radiation, for both isolated halos and cosmological zoom-in simulation. We find that the photosphere forms at 1e-6 pc and rapidly expands outward. A strong anisotropic outflow forms. Typical radiation luminosity emerging from the photosphere is 1e+38 to 1e+39 erg/s, of the order of Eddington luminosity. The comparison run with the adiabatic approximation differs profoundly from the FLD run, by forming a central geometrically-thick disk. Overall, an adiabatic equation of state is not a good approximation to the advanced stage of direct collapse, mainly because the radiation is capable to escape due to a local anisotropy in the optical depth.

研究分野：宇宙物理学

キーワード：理論天文学　流体力学　銀河形成　巨大ブラックホール　輻射輸送　ダイレクトコラプス

１．研究開始当初の背景

In 2016, our understanding of the formation of supermassive black holes (SMBHs) included a list of options: the remnants of Population III stars, compact stellar clusters and direct collapse in dark matter (DM) halos. Each of the possibilities had problems. It was clear however, that the direct collapse option is the most feasible one. We have pursued this road. The main problem was that no model has included radiation transfer on the fly. The scientific community used different approximations in order to understand and circumvent the problems with the direct collapse. Most of the literature on this subject included adiabatic approximation when the collapsing flow became optically thick. This assumption precluded a meaningful analysis of the kinematics and dynamics of the accretion flow. The important force --- radiation force, has been neglected as well.

The prevailing view was also that the collapsing flow leads to the formation of a supermassive star, which powered by thermonuclear reactions. The role of the angular momentum was completely ignored. By the end of the main sequence time, the core collapse of the stellar core would cool by neutrini and form a seed black hole. However, the mass of this seed black hole was not determined, and could vary by more than four order of magnitude.

２．研究の目的

The aim of our 3-year research project was to advance our understanding of formation of supermassive black holes (SMBHs) at high redshift. Recent detections of high-z quasars that harbor SMBHs provided a challenge to models of structure buildup in the universe. Main alternatives for the formation of SMBHs were (1) remnants of Pop III stars, and (2) direct baryonic collapse within DM halos, which could lead to the formation of `proto-AGN --- luminous pre-SMBH objects. By focusing on the late stage of the collapse, we proposed to investigate (i) trapping of radiation by collapsing gas, and (ii) its effect on angular momentum loss. Our main question was whether the SMBHs form as by-products of stellar evolution, or can by-pass it, forming radiatively-inefficient, geometrically-thick, self-gravitating disks --- precursors of AGN, to be observed by the upcoming JWST.

３．研究の方法

Our goal was to understand the formation of the SMBH seeds at high redshifts. Specifically, we focused on two main issues: (1) calculating the radiation transfer in the optically-thick part of the flow. As a corollary, we proposed to obtain the broad-band continuum emerging from the collapsing flow. (2) We proposed to study the nature of the collapsing flow at small radii --- formation of a supermassive star powered by thermonuclear reactions and the subsequent core collapse versus formation of a self-gravitating, geometrically-thick disk, characterized by a low energy-to-radiation conversion efficiency, collapsing as a result of a post-Newtonian instability. Below we provide the details.

We planned to start from the basic equations of radiation hydrodynamics, in the presence of internally-generated gravitational field. This was proposed to address both analytically and numerically. Our goal here was two-fold: (1) analyze analytically the ability of the accretion flow to get rid of its angular momentum by means of gravitational torques; and (2) calculate numerically all radiative and non-radiative ways for the gas to get rid of internal energy (e.g., formation of the preferred channel of radiation energy release along the rotation axis, and efficient turbulent virial convection). The crucial question for us to answer was: is radiation trapped by the flow, or is capable to escape? Does the flow remain radiation pressure- or thermal pressure-dominated? Both angular momentum and internal energy are the dynamical factors affecting the collapse in the most profound ways --- if the gas is unable to cool radiatively or mechanically, the collapse will be terminated. Hence, dynamics of the collapse in tandem with the energy transfer will determine the nature of the proto-AGN. Both options appear feasible and require careful modeling of the on-the-fly radiation transfer mechanisms, which is expected to be addressed in this proposal.

As a part of our strategy, we proposed to make use of the adaptive mesh refinement code (AMR) Enzo, where the fluid is discretized onto refined Eulerian grids. The non-public version that we used included a radiation transfer module HYPRE, which uses the flux-limited diffusion (FLD) approximation in the optically thick part of the flow. The PI and Co-PI had an extensive experience with Enzo over the last 5 years. We run high-resolution, zoom-in cosmological hydrodynamic simulations, which solves for gas and dark matter dynamics self-consistently. Mesh refinement can be continued to an arbitrary level, based on criteria involving a combination of DM and/or baryons overdensity, Jeans length, cooling time-scale, etc. We used the MUSIC code to generate multiscale initial conditions with multiple levels of refinements for cosmological zoom-in simulations. This method uses an adaptive convolution of Gaussian white noise with a real-space transfer function kernel together with an adaptive multi-grid Poisson solver to generate displacements and velocities.

Modifications that we planned to introduce into the code are as following: (1) The point sources of radiation will be replaced by the diffuse source of radiation. Hence every grid cell is the source of radiation depending on its temperature and density; (2) we have already added electron scattering, bound-free and free-free opacities (in addition to the H photo-ionization opacity already incorporated in Enzo); (3) we shall modify the Euler equation, introducing the radiation energy density gradients as an additional force. These changes should allow us to follow the full radiation hydrodynamics of gravitational collapse, which is a novel approach not yet attempted by other researchers.

We proposed to resort to approximations that preserve the most important aspects of radiation transfer. Dynamics of collapse in the context of SMBH seed formation have never been combined with an on-the-fly radiation transfer, even simple models will be beneficial. Using the AMR code Enzo (with our modifications!), we plan to obtain the solution of the radiation transfer through a FLD approximation, with couplings to both the gas energy and chemical number densities. For this purpose, Enzo uses an implicit scheme, circumventing the problem of small time-steps. The FLD transitions smoothly between optically-thin and thick limits and is coupled to an ionization network of H or H+He --- a crucial point to resolve the radiation shocks. There are three features of particular interest that we resolve: the precursor (where the gas is preheated ahead of the shock front by the radiation wave), the Zel'dovich spike (the overshoot at the shock front), and the radiation relaxation region (the decline in temperature to far-field post-shock value).

４．研究成果

Our results have been summarized in a number of publications in refereed journals, presented at the conferences, seminars and colloquia, as well as in public press release. Our biggest achievement was to introduce the radiation transfer into the problem of a direct collapse and to solve it on the fly.

First, we have addressed the radiation transfer in a direct collapse within DM halos to form the SMBH seeds at high redshifts. Our first approach was to use the isolated halos. The outer part of this collapse remains optically thin, and has been studied intensively using numerical simulations. For example, in our group, we first compared and examined the behavior of smoothed particle hydrodynamics (SPH) and AMR code in the context of direct collapse.

However, the innermost region of the collapse is expected to become optically thick, and it requires to follow the radiation field in order to understand its subsequent evolution. So far, the adiabatic approximation has been used exclusively for this purpose. We applied radiative transfer using the FLD approximation to solve the evolution of coupled gas and radiation, for isolated halos. For direct collapse within isolated DM halos, we find that (1) the photosphere forms at a 1e-6 pc and rapidly expands outwards. (2) A central core forms, with a mass of about one solar mass, supported by gas pressure gradients and rotation. (3) Growing gas and radiation pressure gradients dissolve it. (4) This process is associated with a strong anisotropic outflow, and another core forms nearby and grows rapidly. (5) Typical radiation luminosity emerging from the photosphere encompassing these cores is 1e+38 to 1e+39 erg/s, of the order the Eddington luminosity. (6) Two variability time-scales are associated with this process: a long one, which is related to the accretion flow within the central 1e-4 to 1e-3 pc, and 0.1 year, which is related to radiation diffusion. (7) Adiabatic models have been run for comparison and their evolution differs profoundly from that of the FLD models, by forming a central geometrically-thick disk. Overall, an adiabatic equation of state is not a good approximation to the advanced stage of direct collapse, because the radiation is capable of escaping due to anisotropy in the optical depth and associated gradients.

As a next step, we have modeled direct collapse of a primordial gas within DM halos in the presence of radiative transfer, in high-resolution zoom-in simulations in a cosmological framework, down to the formation of the photosphere and the central object. Radiative transfer has been implemented in the FLD approximation. Adiabatic models were run for comparison. We find that (a) the FLD flow forms an irregular central structure and does not exhibit fragmentation, contrary to adiabatic flow which forms a thick disk, driving a pair of spiral shocks, subject to Kelvin-Helmholtz shear instability forming fragments; (b) the growing central core in the FLD flow quickly reaches about 10 solar masses and a highly variable luminosity of 1e+38 to 1e+39 erg/s, comparable to the Eddington luminosity. It experiences massive recurrent outflows driven by radiation force and thermal pressure gradients, which mix with the accretion flow and transfer the angular momentum outwards; and (c) the interplay between these processes and a massive accretion, results in photosphere at ~10 AU. We conclude that in the FLD model, (1) the central object exhibits dynamically-insignificant rotation and slower than adiabatic case; the inner temperature rises rapidly with density; (2) does not experience fragmentation leading to star formation, thus promoting the fast track formation of an SMBH seed; (3) inclusion of radiation force leads to outflows, resulting in the mass accumulation within the central 1e-3 pc, which is 100 times larger than characteristic scale of star formation. The inclusion of radiative transfer reveals complex early stages of formation and growth of the central structure in the direct collapse scenario of SMBH seed formation.

５．主な発表論文等

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〔産業財産権〕
○出願状況（計　０件）

本研究は純粋な宇宙物理理論の理学研究のため、特許申請などはない。

○取得状況（計　０件）

〔その他〕
ホームページ等

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http://astro-osaka.jp/kn/

６．研究組織

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