国立天文台天文学データ解析計算センター
大規模シミュレーションプロジェクト
平成12年度成果報告書

2001 年　4月　9日

氏名	釣部 通
所属 (職)	大阪大学大学院理学研究科
連絡先住所	〒 560-0043 豊中市待兼山町１－１
電話	06-6850-5482
ファクシミリ	06-6850-5504
E-mail	tsuribc@vcga.css.sci.osaka-u.ac.jp

以下の研究課題で計算機共同利用プロジェクトを行いました。
（該プロジェクト ID：ntt05 ）
研究課題名

(和文)	分子と原始銀河雲の分裂過程の研究
(英文)	Study of Fragmentation Process of Molecular Clouds and Pregalactic Clouds

プロジェクトの成果

はじめに

本研究は、星間ガスの自己重力収縮における分裂過程を調べ、現在また宇宙初期の原始星形成の物理過程に対する理解を深めることである。今年度は、（１）単体の回転球状雲の収縮とそれに伴う分裂のクライテリオンの導出、（２）宇宙論的な揺らぎの進化に伴う初代天体形成のシミュレーション、を行った。

計算機使用状況

審査によって450時間の計算時間を与えられ、実質的に約400時間の計算時間を利用した。

得られた結果と意義

以下に、２つの収録を添付するので、そちらを参照していただきたい。

Gravitational Collapse and Fragmentation of Sub-galactic Primordial Clouds

釣部 通 (天体核研究室 学振研究員)

ABSTRACT

原始ガス雲の分裂過程を考察した。まず、水素分子を考慮した宇宙論的3次元計算流体力学的計算によって、球的な領域が最初に収縮すること示す。次に中心核領域の暴走回転収縮の高精度計算、および簡単化した状態方程式を用いた回転収縮の系統的な計算によって、収縮する核の分裂条件を導出し、その結果を裏付ける半解析的モデルも構築する。水素分子形成にともなって冷えた収縮する核は回転していても収縮とともに分裂することなく単一の中心核を形成しやすいことがわかった。その後の質量降着を伴った進化と統計的な議論は今後の課題である。

1. はじめに

次世代の大型宇宙望遠鏡の打ち上げ計画などに刺激されて、宇宙における第一世代天体の形成を明らかにする動きが世界的に活発になっている (例えば、 Rees 1998; Loeb 1998; Larson 1998)。 Hierarchical Clustering 構造形成のシナリオ (例えば CDM Model) では、構造は小さなものから形成されるが、ガス成分にはジーンズの重力不安定性条件のため、収縮可能質量の下限が存在する。これらより、水素再結合以降、 $M_{\rm J} \sim 10^6 M_\odot$ の雲が最初に重力収縮して初代天体を形成すると考えられる。このような質量の原始ガス雲では、水素分子による冷却が系の進化に重要な役割を果すことが長い間議論されてきた (Matsuda, Sato, & Takeda 1969; Hutchins 1976; Palla et al. 1983; Susa et al. 1994; Uehara et al. 1996; Tegmark et al. 1997)。これらは、主に一様モデルを用いたタイムスケールの比較による議論であり、衝撃波などを考慮したより現実的なモデルが望まれていた。この問題は1次元の流体計算により解決する (Haiman et al. 1996; Omukai & Nishi 1998; Nakamura & Umemura 1998)。しかし、これらの方法では分裂についての情報は全系の進化に伴う最小 Jeans 質量を求めることで議論することのみに制約される。分裂過程は本質的に多次元の問題であるため、多次元の解析が不可避である。計算機能力の向上と計算技術の進歩によって、近年、ようやく多次元の直接数値計算の試みが行われるようになってきた (Gnedin & Ostriker 1997; Abel et al. 1998; Bromm, Coppi, & Larson 1999)。これらの直接計算は、分裂の結果を直接示す興味深いものであるが、現在のところ上記のガス雲が非線型重力収縮した結果、どのような天体を形成するのかと

いう問題に関する系統的な理解は、まだ十分には得られていないと思われる。原始銀河の大局的性質にとって重要な、形成天体の質量個数分布を考えるためには、収縮の結果1つの大質量天体になるのか、それとも分裂が繰り返されて数多くの小質量天体になるのかという疑問に答えておく必要がある。ここではこの問題に関連して、収縮に伴う分裂条件ついて調べる。

2. 初代天体の宇宙論的形成

全系の質量 $10^8 M_\odot$ に対して CDM と ガスの2成分系の3次元宇宙論的流体力学計算を水素分子の非平衡形成および冷却を考慮に入れて計算した。その結果、圧力と重力が釣り合ったフィラメント、および球状の knot が形成した。次に $10^5 M_\odot$ 程度の球状の knot が冷却に必要な水素分子を形成して、暴走的に収縮することがわかった(図1)。

次に、この knot が収縮する過程で再分裂が起こるかどうかを調べるために、中心領域を孤立系の回転雲でモデル化して幾つかの初期条件から再計算した。もっとも典型的な初期条件では中心に1つの $100 M_\odot$ 程度の回転によって支えられた円盤が形成した。一方、別の初期条件では、分裂が起こるものもあった。これらの定性的性質の違いは、中心領域の等密度面の軸比の違いから理解できることも分かった。また、いずれの場合にも、幅広い密度領域において、ほぼ等温、もう少し正確には、$T \propto \rho^{0.1}$ という依存性を示すことが分かった。

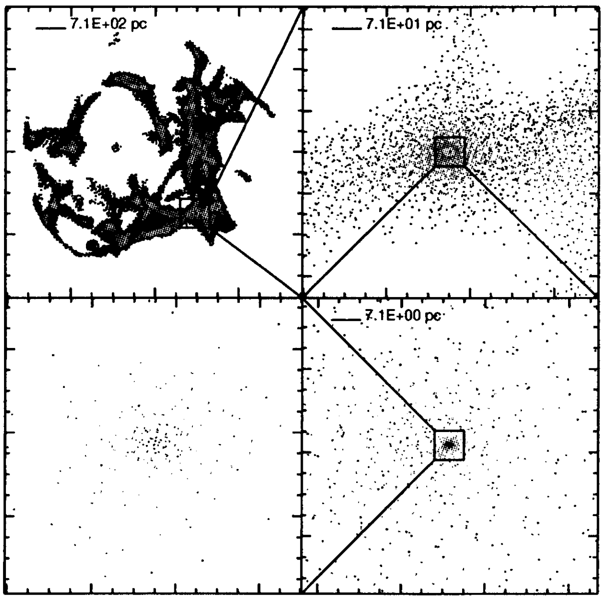

図. 1. 宇宙論的計算によるガス分布の例

3. 分裂の条件

ガス雲が収縮した結果に形成される状態を予言できるようになるため、様々な初期圧力の強さ、回転の強さから得られる結果を系統的に調べて分裂の条件を考察した。等温の場合は Tsuribe & Inutsuka (1999a,b) で詳しく議論した。ここでは、それを拡張して $T \propto \rho^{0.1}$ の場合についての分裂条件を求めた。温度の上昇を考慮に入れると、密度が発散する前に遠心力による障壁が収縮を止め、円盤が形成される。その後の円盤の進化は、収縮前の初期の密度の中心集中度に依存することがわかった。初期密度が一様である場合には、円盤の成長が速く、円盤は重力的に不安定になり分裂しやすく、分裂のクライテリオンは、円盤の中心領域からの円盤の質量の増大に伴い徐々に進化する。しかしながら、初期密度に中心集中度がある場合には、中心領域において渦状波が形成し、円盤半径の増大よりも中心領域の密度上昇の方が早かった。したがって、初期密度に中心集中があると分裂条件は円盤形成の後あまり変化しないと考えられる。図 2 は分裂のクライテイオンの例を示す。この図は、母天体もしくは分裂片が図中の線より上側に現れた場合には、その後、再分裂しないことを示している。宇宙論的計算により得られた球状の knot は、典型的には分裂条件の上側に位置し、その後、階層的に分裂する可能性は低いと考えられる。

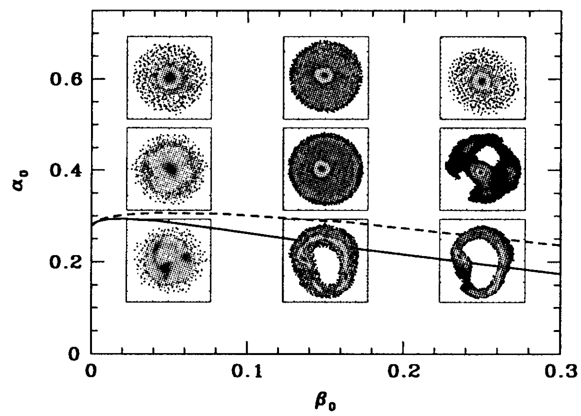

図 2. 初期に中心密度集中をもった回転する $\gamma = 1.1$ polytrope ガス球の Accretion Phase における分裂条件。α_0 は、暴走収縮初期の圧力の重力に対する比、β_0 は中心での回転エネルギーの重力エネルギーに対する比。実線、点線は半解析的モデルから予言される分裂条件。

4. 今後に向けて

中心に核が形成された後、回りに円盤が降着する。その円盤の分裂可能性と角運動量輸送については更なる考察が必要である。中心核と円盤が成長する過程は、 Tsuribe(1999) で求め

られた自己相似解に従う可能性もある。また、各々の核の合体、中心からの Feedback を受けた進化についても、さらに考察する必要がある。今後これらの過程を踏まえた上での統計的な議論を行う予定であるが、その際に、ここで求めたクライテリオンは役に立つであろう。

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THE PHYSICS OF GALAXY FORMATION
*ASP Conference Series, Vol. ***, 2001*
M. Umemura, and H. Susa, eds.

Fragmentation of Primordial Subgalactic Clouds

Toru Tsuribe

Department of Physics, Kyoto University, Kyoto, 606-8502, Japan

Department of Astronomy, Yale University, Box 208101, New Haven, CT 06520-8101, USA

Abstract. Fragmentation processes of primordial clouds are analyzed in detail. Cosmological hydrodynamical calculations demonstrate that quasi-spherical dense cores collapse first to form a dense object. A series of calculations of the rotating collapse of an initially spherical core shows that the equation of state is well approximated by a simple polytropic relation with $\gamma \sim 1.1$ over a wide range of central density. The criterion for fragmentation of rotating polytropic cloud cores with $\gamma = 1.1$ is derived numerically and semianalytically. Fragmentation during core collapse is not expected to take place if the cloud thermal energy is greater than 0.3 times its gravitational energy at the initial stage of runaway collapse. The collapse of the central small core will not be halted by centrifugal force since a nonaxisymmetric waves will appear and the flow will converge to the self-similar flow until γ exceeds 4/3. The possibility of fragmentation in the primordial circum-protostellar disk is also discussed.

1. Introduction

In the scenario of hierarchical structure formation (e.g., the Cold Dark Matter model), small scale dark matter structures are supposed to develop first due to their large initial amplitude of fluctuation. On the other hand, th gas component is controlled by the Jeans condition for gravitational instability against pressure gradient forces, predicting the minimum mass that can collapse. Considering these things, it can be suggested that the first astronomical structures develop as a result of gravitational collapse of high-σ fluctuations with $M_J \sim 10^6 M_\odot$ (Peebles & Dicke 1968). Since the virial temperature on this mass scale is several 1000K, and there is no metal nor dust, the main coolant is molecular hydrogen. Nonequilibrium formation of H_2 in a collapsing cloud keeps the temperature almost isothermal over a wide range of density at several hundred K (Matsuda, Sato, & Takeda 1969; Palla et al. 1984; Uehara et al. 1996). Recent direct multi-dimensional numerical calculations demonstrate the fragmentation of these structures (Abel et al, 2000; Bromm et al, 1999; Nakamura & Umemura 1999). However, the final outcome after the collapse is still not well understood, especially regarding the further possibility of fragmentation of the collapsing clumps formed in the dark matter potential wells. In this contribution, I investigate the condition for fragmentation during the collapse to help predict

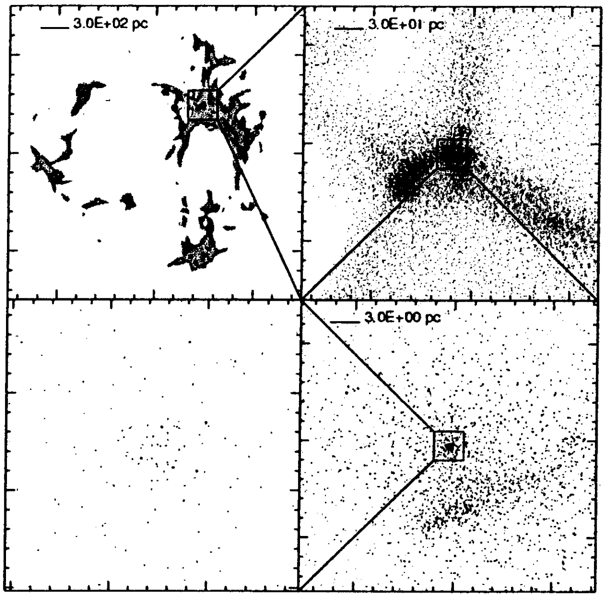

Figure 1. Result of cosmological formation of collapsing knots with Godunov SPH code with two million particles.

whether a large massive object or a cluster of small clumps forms as a result of the collapse.

2. Cosmological Formation of First Collapsing Objects

Firstly, before discussing the criteria for fragmentation of the runaway collapsing core, an example of the results of numerical calculations done with Godunov SPH code with two million particles for CDM and a gas component is presented. The calculation is started from a high redshift epoch $1 + z = 200$ when fluctuations on all scales are still in the linear stage. The three-dimensional Nbody + hydrodynamical evolution with nonequilibrium chemistry including hydrogen molecules is calculated for objects with $M_T = 10^8 M_\odot$. Figure 1 illustrates the resulting gas particle distribution and shows the formation of a lot of filamentary structures and spherical knots at the intersections of the filaments at a redshift around 35. They are dominated by dark matter gravity at first. Then inside quasi-spherical knots with $10^5 M_\odot$, a larger fraction of hydrogen molecules ($f_{H_2} \sim 10^{-3}$) is produced than elsewhere. These knots start to collapse leaving behind the outer filaments. This collapse starts at typically $T \sim 200$ and $n \sim 1000$ with small rotation, as was found in previous works.

Secondly, in order to resolve the detailed physics inside the collapsing core, rotating core collapse models starting from a spherical configuration with the above density and temperature are calculated for a variety of initial ratios of pressure gradient force and centrifugal force to gravitational force. All the models with $F_P/F_G > 0.2$ did not fragment during collapse. At the final stage of the calculation, the central core with a small fraction of the mass is still continuing to collapse with a decreasing mass. Therefore, the mass scale at the end of calculation at a specific density does not have significant relation with the mass of the first star. In a case with $F_P/F_G < 0.2$, fragmentation took place during the collapse. It is found that the difference between the fragmentation and non-fragmentation can be clearly classified by the evolution of the axis ratio of the isodensity contour in the central region. It is also worth noting that the thermal behavior is well approximated by a simple polytropic relation with $\gamma \sim 1.1$ over a wide range of density in the three-dimensional rotating core collapse. For the spherically symmetric collapse case, Omukai & Nishi (1998) had already pointed out this fact.

3. Criteria for Fragmentation

In order to systematically study the condition for fragmentation, we calculated the rotating collapse of a $\gamma = 1.1$ polytropic sphere from a variety of initial conditions that include rotation, initial thermal energy, and shape and amplitude of perturbations with $N = 10^5$ particles. As a result, a criterion for fragmentation during core collapse is found (c.f., Tsuribe & Inutsuka 1999a for isothermal clouds). Tsuribe & Inutsuka (1999b) derived the criteria for fragmentation of rotating collapsing isothermal clouds from a simple spheroid model with propagation of sound waves from outer boundary. Here, their analysis is extended to include a slow temperature increase as $T \propto \rho^{0.1}$. In Figure 2, the derived criteria for fragmentation for a $\gamma = 1.1$ polytrope and numerical results with initial 15are shown. The solid line shows the condition that the aspect ratio is 4π at the centrifugal bounce, above which fragmentation is not expected to take place. The dotted line shows the limit of arrival of the sound wave from the outer boundary at the centrifugal bounce for reference. The results of numerical calculations are well divided by lines predicted from the simple spheroid model. The derived criterion shows that fragmentation is not expected if the parameter $\alpha_0 = 5R_0P_0/2GM\rho_0$($\sim$ ratio of initial thermal energy to the initial gravitational energy) is greater than 0.3. The dependence on the rotation parameter ($\equiv \beta_0 = R_0^3\Omega_0^2/3GM$, ratio of the initial rotation energy to the gravitational energy) is small at least in the case of initial rigid rotation. The critical value $\alpha_0 = 0.3$ corresponds to $M = 1.8 \times 10^4 M_\odot$ for $n = 1000/\mathrm{cm}^3$ and $T = 200\mathrm{K}$. This criterion is also consistent with the results of previous core collapse calculations that included detailed thermal evolution.

4. Spiral Wave Formation

During core collapse with rotation, one might think that the centrifugal force halts the core collapse. Narita, Hayashi, & Miyama (1984) analyzed axisymmetric rotating collapse for isothermal cloud cores in detail. They showed that the collapse can not be halted due to the centrifugal force in the isothermal stage as a result of the property of the rotating self-similar collapse. This is because the divergence of the central density is earlier than the centrifugal bounce, forming an envelope with power-law density profile. Saigo & Hanawa (2000) showed that the this self-similar property does not hold in the case of axisymmetric

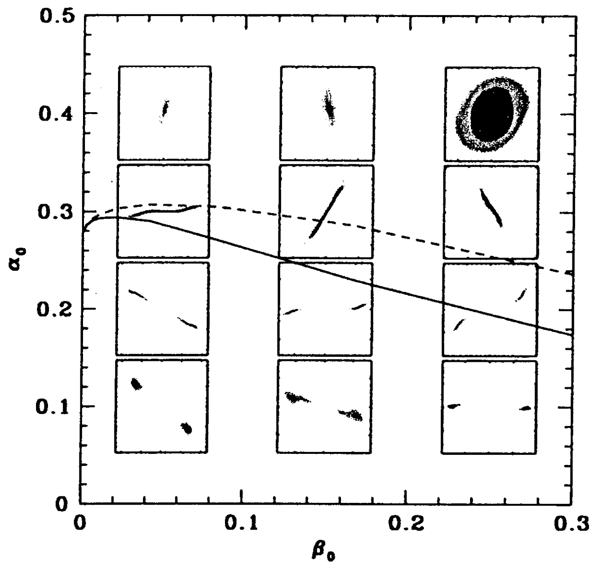

Figure 2. Criterion for fragmentation of rotating polytrope with $\gamma = 1.1$. Parameter α_0 corresponds to initial ratio of the thermal energy to the gravitational energy and β_0 is initial ratio of the rotational energy to the gravitational energy. Solid and dotted lines are criteria derived by simple spheroid model.

nonisothermal collapse. In the case of $\gamma > 1$, they showed that the collapse is halted due to the centrifugal bounce. The difference of the results can be explained by the evolution of the aspect ratio of the core during the collapse. If the collapse proceeds with isothermal equation of state, the aspect ratio in the central core can be constant. On the other hand, if the temperature increase exists, the flattening effect is not enough to enable gravity to overcome the pressure gradient plus centrifugal force at all the radii. We reinvestigated this behavior with the three-dimensional collapse calculations. As a result, it is found that the collapse in the center can not be halted by the centrifugal barrier even $\gamma = 1.1$. When the centrifugal barrier arises, the nonaxisymmetric instability appears to redistribute the angular momentum to enable the central region to collapse. As a result, collapse can continue as a self-similar manner. Analytic investigation shows the redistributed angular momentum distribution that can collapse infinitely as $J(\varpi) \propto M(\varpi)^n$, $n = (5\gamma - 7)/(3\gamma - 4)$, where ϖ is a cylindrical radius, J and M are cumulative angular momentum and mass.

The stability against the elongation of the core to the filament formation is also analyzed by direct numerical calculations for cases with $\alpha_0 > 0.3$. The result shows that it is marginally stable for $\gamma = 1.1$ and unstable for $\gamma = 1.0$. These results are consistent with the result of linear stability analysis (Hanawa & Matsumoto 2000). This result also shows that binary fragmentation does not take place due to the small temperature increase during the runaway collapse stage.

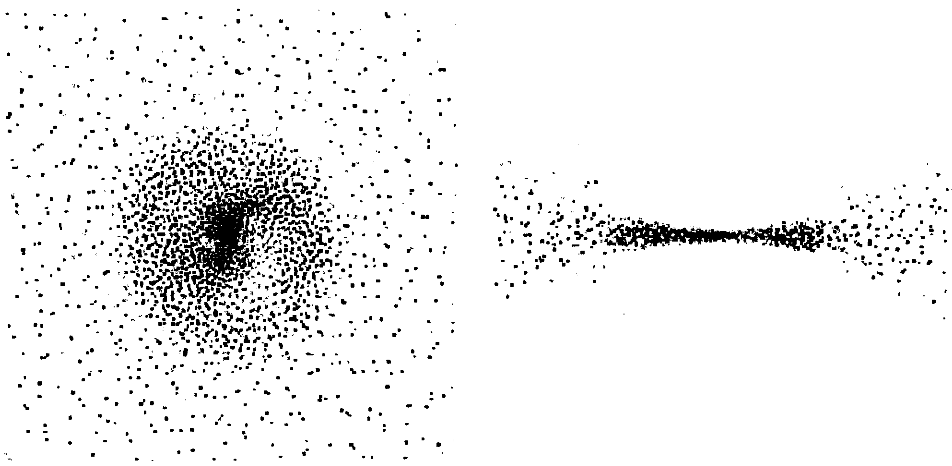

Figure 3. Example of disk and dynamic spiral arm formation around the primordial protostellar core.

5. Protoplanetary Disk Around the First Proto-star

Although fragmentation is not expected to take place during the runaway collapse stage for $\alpha_0 > 0.3$, the possibility of the fragmentation of massive circum stellar disk after the formation of the central protostellar core is not still excluded by this investigation. These possibilities should be investigated including the feedback effect from the radiation from the central core.

According to the runaway collapsing self-similar flow, the mass included in the collapsing core decreases with increasing central density until effective γ exceeds 3/4. According to the spherically symmetric calculation by Omukai & Nishi (1998), the mass included in the core when the collapse is halted is about $0.005M_\odot$. After the formation of this adiabatic stable core, the massive envelope accretes onto the core or around the core depending on the angular momentum. If the core is formed by the above infinitely collapsing self-similar flow, central core can not be a massive star at the beginning of the accretion stage. Therefore, the early evolution of this disk may be significantly important to determine the mass of the first stars. We calculated the accretion flow with $\gamma = 1.1$ simultaneously with the stable core with $\gamma = 5/3$ until the disk radius becomes large enough. As a result, the disk becomes unstable to the spiral mode. If the viscosity or nonaxisymmetric waves transfer angular momentum faster than the disk accumulation, the core may grow to be massive (Tsuribe 1999). On the other hand, if accretion from the massive envelope is fast enough to make the disk very unstable, disk fragmentation may take place to form a multiple system (Miyama 1992). So far, calculation that can predict the result of this accretion stage correctly does not exist. This may be a crucial problem in determining the mass of the first stars.

6. Summary

In this contribution, the criterion for fragmentation of a collapsing rotating primordial protostellar core is investigated. According to the cosmological formation of dense core, quasi-spherical knots collapse first leaving the outer filaments behind. The thermal evolution of the central core can be approximated well by a simple polytropic relation $p \propto \rho^{1.1}$ over a wide range of the density in the three-dimensional rotating core collapse started from quasi-spherical initial conditions. Both systematic numerical hydrodynamical calculations and a simple spheroid model yield a fragmentation criterion for above collapsing cloud core, predicting that fragmentation does not occur if the core has moderately warm initial condition, i.e., $\alpha_0 > 0.3$. Although centrifugal force halts temporarily the collapse of the central core, nonaxisymmetric waves enable the central region to continue to collapse until the equation of state become stiffer than $\gamma = 4/3$. The collapsing core with $\gamma = 1.1$ is stable against elongation and binary fragmentation. This implies single stable protostellar core formation at the final stage of the runaway collapse. The massive envelope will fall onto the small stable core after the stable central core formation. The possibility of fragmentation during this accretion stage is still an open question and will be resolved in future work.

Acknowledgments. The author thanks S. Inutsuka, K. Omukai, R. Nishi, and H. Susa for discussions and Richard Larson for reading and comments on the manuscript. The author is also grateful to H. Sato and M. Umemura for continuous encouragement and useful discussions. This work was partly supported by JSPS Research Fellowships for Young Scientists. Numerical calculations are carried out at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan, and at the Data Processing Center at Kyoto University.

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