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研究課題名（英文） Understanding formation and properties of gravitational waves events from galactic nuclei

研究代表者
Trani Alessandro（Trani, Alessandro）

東京大学・大学院理学系研究科（理学部）・客員共同研究員

研究者番号：２０８８１５４３

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研究成果の概要（和文）：このプロジェクトは、銀河核における重力波源の形成と進化の予測に大きな進展をもたらした。まず、三重系の安定性に関する一連の研究を発表した。これによって、三重系と星団内のコンパクト天体との重力波合体の予測も可能になった。関連研究として、革新的なモンテカルロ/N 体スキームを用いて、銀河核におけるコンパクト天体の繰り返し合体を調べました。また、超大質量ブラックホール周辺での3天体の遭遇の影響を調べ、LIGO-Virgo-KAGRAの設計感度バンド内でそのような天体が持つ可能性のある離心率を明らかにした。

研究成果の学術的意義や社会的意義
This project made advances on the formation of gravitational wave sources, which were detected in 2015 and whose origin is still unknown. Through the use of numerical and analytical models, we put constraints on the properties and merger rates of gravitational wave mergers from black hole binaries.

研究成果の概要（英文）：This project made great progress at predicting the formation and evolution of gravitational wave sources in galactic nuclei. We first published a series of studies on the stability of triple systems. This also allowed us to produce predictions of gravitational wave mergers from triple systems with compact objects in stellar clusters. Related research included investigating the repeated mergers of compact object in galactic nuclei, using an innovative Monte-Carlo/N-body scheme. We then investigated the impact of three-body encounters around supermassive black holes, revealing the eccentricity that such sources may have within the LIGO-Virgo-KAGRA band at design sensitivity. Additionally we developed and published the first 1-dimensional active galactic nuclei modeling package, which enabled the modeling of active galactic nuclei properties, essential for understanding the impact on the embedded black hole population.

研究分野： Astrophysics

キーワード： Gravitational waves　Gravity　Dynamics　Active galactic nuclei

１．研究開始当初の背景

The first gravitational wave event observed by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 2015 has opened a new observable window on the universe. Already ~15 gravitational wave (GW) events from binary black holes (BHs) have been confirmed to date, and the number is expected to quadruplicate by the end of the year. The Japanese KAGRA observatory has recently joined the third observing run, improving source localization on the sky and signal-to-noise ratio. More ground-based and space-borne detectors are currently being designed and build (e.g. Einstein Telescope, LISA, DECIGO). The direct detection of gravitational waves raised an important unresolved question: how such massive BH-BH binary form and merge? Currently, the sky localization and distance measure of GW events are still coarse and limited. Therefore, our only way to gain insights on their origin is to compare the merger properties inferred from observations with theoretical models. However, existing theoretical models of the astrophysical origin of GW events are currently either incomplete or in tension with data [e1]. It is thus crucial to improve our theoretical models, in order to interpret the vast amount of data expected in the forthcoming years. Understanding the astrophysical origin of the forthcoming GW detections is a critical step towards solving the greatest challenges of modern astrophysics and cosmology.

２．研究の目的

This project aims at making predictions on the formation and evolution of GW sources in galactic nuclei. This will be achieved through an innovative hybrid Monte-Carlo/N-body approach, able to model the relevant physical processes that are unattainable via traditional N-body models. Accomplishing this goal will thus define a new pathway for the formation of stellar-mass GW events. The comparison between GW source properties from the theoretical model and the observed ones will enable us to understand whether the observed (and forthcoming) events originate from galactic nuclei or other pathways. Discriminating between such pathways is a fundamental step to understand the origin of GW and their associated physics, especially in view of the next GW interferometers and multi-messenger observations.

３．研究の方法

We employed various numerical and analytical methods and techniques, including TSUNAMI N-body code, which I have developed during my JSPS Fellowship at the University of Tokyo. TSUNAMI integrates the Newtonian equations of motion derived from a time-transformed Hamiltonian. Thanks to this implementation, TSUNAMI is uniquely suited to study the dynamical evolution of few-body systems in which strong gravitational encounters are frequent and the mass ratio between the interacting objects is large. The current implementation in C++ already includes post-Newtonian corrections 1PN, 2PN, and 2.5PN, necessary to model GW-induced spiral-in.

４．研究成果

While there have been many studies examining the stability of hierarchical triple systems, the meaning of "stability" is somewhat vague and has been interpreted differently in previous literatures. In this work we focused on "Lagrange stability," which roughly refers to the stability against the escape of a body from the system, or "disruption" of the triple system, in contrast to "Lyapunov-like stability," which is related to the chaotic nature of the system dynamics. We compute the evolution of triple systems using direct N-body simulations up to 10^7 P out, which is significantly longer than previous studies (with P out being the initial orbital period of the outer body). We obtain the resulting disruption timescale T_d as a function of the triple orbital parameters with particular attention to the dependence on the mutual inclination between the inner and outer orbits, i_{mut}. By doing so, we have clarified explicitly the difference between Lagrange and Lyapunov stabilities in astronomical triples. Furthermore, we find that the von Zeipel-Kozai-Lidov oscillations significantly destabilize inclined triples (roughly with $60° < i_{mut} < 150°$) relative to those with $i_{mut} = 0°$. On the other hand, retrograde triples with $i_{mut} > 160°$ become strongly stabilized with much longer disruption timescales. We show the sensitivity of the normalized disruption timescale T_d/P out to the orbital parameters of triple system. The resulting T_d/P out distribution is practically more useful in a broad range of astronomical applications than the stability criterion based on the Lyapunov divergence. In the cores of dense stellar clusters, close gravitational encounters between binary and single stars can frequently occur. Using the TSUNAMI code, we computed the outcome of a large number of binary-single interactions involving two black holes (BHs) and a star to check how the inclusion of orbital energy losses due to tidal dissipation can change the outcome of these chaotic interactions. Each interaction was first simulated without any dissipative processes and then we systematically added orbital energy losses due to gravitational wave emission [using post-Newtonian (PN) corrections] and dynamical tides and recomputed the interactions. We find that the inclusion of tides increases the number of BH-star mergers by up to 75 per cent; however, it does not affect the number of BH-BH mergers. These results highlight the importance of including orbital energy dissipation due to dynamical tides during few-body encounters and evolution of close binary systems within stellar cluster simulations. BH-star mergers are largely unaffected by the inclusion of these terms. The dynamical stability of hierarchical triple systems is a long-standing question in celestial mechanics and dynamical astronomy. Assessing the long-term stability of triples is challenging because it requires computationally expensive simulations. We proposed a convolutional neural network model to predict the stability of equal-mass hierarchical triples by looking at their evolution during the first 5×10^5 inner binary orbits. We employed the regularized few-body code TSUNAMI to simulate 5×10^6 hierarchical triples, from which we generate a large training and test data set. We developed 12 different network configurations that use different combinations of the triples' orbital elements and compare their performances. Our best model uses six time series, namely, the semimajor axes ratio, the inner and outer eccentricities, the mutual inclination, and the arguments of pericenter. This model achieves excellent performance, with an area under the ROC curve score of over 95% and informs of the relevant parameters to study triple systems stability. All trained models are made publicly available, which allows predicting the stability of hierarchical triple systems 200 times faster than pure N-body methods. We examine the stability of hierarchical triple systems using direct N-body simulations without adopting a secular perturbation assumption. We estimate their disruption timescales in addition to the mere stable/unstable criterion, with particular attention to the mutual inclination between the inner and outer orbits. First, we improve the fit to the dynamical stability criterion by Mardling & Aarseth widely adopted in the previous literature. Especially, we find that that the stability boundary is very sensitive to the mutual inclination; coplanar retrograde triples and orthogonal triples are much more stable and unstable, respectively, than coplanar prograde triples. Next, we estimate the disruption timescales of triples satisfying the stability condition up to 10^9 times the inner orbital period. We also show that the disruption timescales of triples are highly sensitive to tiny changes of the initial parameters, reflecting the genuine chaotic nature of the dynamics of those systems. A binary star orbited by an outer companion constitutes a hierarchical triple system. The outer body may excite the eccentricity of the inner binary through the von Zeipel-Lidov-Kozai (ZLK) mechanism, triggering the gravitational wave (GW) coalescence of the inner binary when its members are compact objects. Here, we study a sample of hierarchical triples with an inner black hole (BH) - BH binary, BH - neutron star (NS) binary, and BH - white dwarf (WD) binary, formed via dynamical interactions in low-mass young star clusters. We find that the inner binaries in our triples cannot merge via GW radiation alone, and the ZLK mechanism is essential to trigger their coalescence. Contrary to binaries assembled dynamically in young star clusters, binary BHs merging in triples have preferentially low-mass ratios ($q \simeq 0.3$) and higher primary masses ($m_p \gtrsim 40 M_\odot$). We derive a local merger rate density of 0.60, 0.11, and $0.5 \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$ for BH-BH, BH-NS, and BH-WD binaries, respectively. Additionally, we find that merging binaries have high eccentricities across the GW spectrum, including the LIGO-Virgo-KAGRA (LVK), LISA, and DECIGO frequencies. About 7 per cent of BH-BH and 60 per cent of BH-NS binaries will have detectable eccentricities in the LVK band. Our results indicate that the eccentricity and the mass spectrum of merging binaries are the strongest features for the identification of GW mergers from triples. Most population-synthesis codes are based on the same stellar evolution model, limiting our ability to explore the main uncertainties. Here, we present the new version of the code SEVN, which overcomes this issue by interpolating the main stellar properties from a set of pre-computed evolutionary tracks. We describe the new interpolation and adaptive time-step algorithms of SEVN, and the main upgrades on single and binary evolution. With SEVN, we evolved 1.2×10^9 binaries in the metallicity range $0.0001 \leq Z \leq 0.03$, exploring a number of models for electron-capture, core-collapse and pair-instability supernovae, different assumptions for common envelope, stability of mass transfer, quasi-homogeneous evolution, and stellar tides. We find that stellar evolution has a dramatic impact on the formation of single and BCOs. Just by slightly changing the overshooting parameter ($\lambda_{\rm ov} = 0.4, 0.5$) and the pair-instability model, the maximum mass of a black hole can vary from ≈ 60 to ≈ 100 $M_\odot$. Furthermore, the formation channels of BCOs and the merger efficiency we obtain with SEVN show significant differences with respect to the results of other population-synthesis codes, even when the same binary-evolution parameters are used. For example, the main traditional formation channel of BCOs is strongly suppressed in our models: at high metallicity ($Z \gtrsim 0.01$) only <20 per cent of the merging binary black holes and binary neutron stars form via this channel, while other authors found fractions >70 per cent. We presented a novel, few-body computational framework designed to shed light on the likelihood of forming intermediate-mass (IM) and supermassive (SM) black holes (BHs) in nuclear star clusters (NSCs) through successive BH mergers, initiated with a single BH seed. Using observationally motivated NSC profiles, we find that the probability of an ~ 100 $M_\odot$ BH to grow beyond ~ 1000 $M_\odot$ through successive mergers ranges from ~ 0.1 per cent in low-density, low-mass clusters to nearly 90 per cent in high-mass, high-density clusters. However, in the most massive NSCs, the growth time-scale can be very long ($\gtrsim 1$ Gyr); vice versa, while growth is least likely in less massive NSCs, it is faster there, requiring as little as ~ 0.1 Gyr. The increased gravitational focusing in systems with lower velocity dispersions is the primary contributor to this behaviour. We find that there is a simple '7-strikes-and-you're-in' rule governing the growth of BHs: Our results suggest that if the seed survives 7-10 successive mergers without being ejected (primarily through gravitational wave recoil kicks), the growing BH will most likely remain in the cluster and will then undergo runaway, continuous growth all the way to the formation of an SMBH (under the simplifying assumption adopted here of a fixed background NSC). Furthermore, we find that rapid mergers enforce a dynamically mediated 'mass gap' between about 50-300 $M_\odot$ in an NSC. Models of accretion discs surrounding active galactic nuclei (AGNs) find vast applications in high-energy astrophysics. The broad strategy is to parametrize some of the key disc properties such as gas density and temperature as a function of the radial coordinate from a given set of assumptions on the underlying physics. Two of the most popular approaches in this context were presented by Sirko & Goodman and Thompson et al. We present a critical reanalysis of these widely used models, detailing their assumptions and clarifying some steps in their derivation that were previously left unsaid. Our findings are implemented in the pAGN module for the PYTHON programming language, which is the first public implementation of these accretion-disc models. We further apply pAGN to the evolution of stellar-mass black holes embedded in AGN discs.

５．主な発表論文等

〔雑誌論文〕　計19件（うち査読付論文　9件／うち国際共著　9件／うちオープンアクセス　0件）

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２．論文標題 Sparse Identification of Variable Star Dynamics	５．発行年 2022年
３．雑誌名 ApJ	６．最初と最後の頁 161
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ac5624	査読の有無 有
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１．著者名 T.Ryu , A.A.Trani, N.W.C.Leigh	４．巻 515
２．論文標題 Tidal Disruption Events by Compact Supermassive Black Hole Binaries	５．発行年 2022年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stac1987	査読の有無 有
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１．著者名 A.A.Trani, S.Rieder, A.Tanikawa, G.Iorio, R.Martini, G.Karelin, H.Glanz, S.Portegies Zwart	４．巻 106
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３．雑誌名 PRD	６．最初と最後の頁 43014
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1．著者名 T.Hayashi，A.A.Trani，Y.Suto	4．巻 939
2．論文標題 Dynamical disruption timescales and chaotic behavior of hierarchical triple systems	5．発行年 2022年
3．雑誌名 ApJ	6．最初と最後の頁 81
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３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 1362~1372
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３．雑誌名 Celestial Mechanics and Dynamical Astronomy	６．最初と最後の頁 10
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s10569-023-10174-z	査読の有無 無
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２．論文標題 Spin misalignment of black hole binaries from young star clusters: implications for the origin of gravitational waves events	５．発行年 2021年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 910～919
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１．著者名 Hayashi 林 Toshinori 利憲、Suto 須藤 Yasushi 靖、Trani 三努郎 Alessandro A. 虎似	４．巻 958
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３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 26～26
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2．論文標題 Three-body encounters in black hole discs around a supermassive black hole	5．発行年 2024年
3．雑誌名 Astronomy & Astrophysics	6．最初と最後の頁 A135～A135
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3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 4227～4250
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1．著者名 Di Cintio Pierfrancesco、Pasquato Mario、Barbieri Luca、Trani Alessandro A.、di Carlo Ugo N.	4．巻 673
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3．雑誌名 Astronomy & Astrophysics	6．最初と最後の頁 A8～A8
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〔学会発表〕　計8件（うち招待講演　7件／うち国際学会　3件）

1．発表者名 A.A.Trani
2．発表標題 A new model of common envelope evolution
3．学会等名 Niels Bohr Institute, Workshop on Gravitational wave formation pathways（招待講演）（国際学会）
4．発表年 2022年

１．発表者名
A.A.Trani

２．発表標題
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A.A.Trani

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （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