論文の内容の要旨

Gravitational hierarchical three-body systems with an invisible inner binary: application to binary black-hole search and their dynamical stability

(不可視連星を含む階層的重力三体系：

連星ブラックホール探査への応用とその力学的安定性)

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In 2015, LIGO detected the gravitational waves (GWs) from a binary black-hole merger (BBH) for the first time. The discovery gave a huge impact on astronomy, and since then the origin and evolution of BBHs have been widely studied in various contexts. Current continual detection of BBH mergers suggests an abundant population of progenitor BBHs before coalescence with relatively wide separations. The presence of progenitor wide-separation BBHs are also supported by the current formation scenarios, regardless of the details. Nevertheless, they have not yet been discovered because they generally do not emit any detectable signals in both electromagnetic(EM) and gravitational waves. Therefore, such progenitor BBHs needs to be searched for with different methods.

According to current observations, hierarchical triples, which consist of an inner binary and a well-separated tertiary, are known to be ubiquitous in the universe. Although they are mostly stellar triples, the fact implies a fraction of progenitor BBHs may form triple systems with visible tertiaries. In addition, some previous studies suggested such triples can be formed through dynamical capture process in dense clusters. We assume the presence of such triples, and propose novel methods to search for progenitor BBHs through the detection of anomalous motions of tertiary. The motion of the tertiary should be modulated by the gravitational perturbations induced by the invisible inner BBH, and therefore it should include the signature of the inner hidden BBH.

In this thesis, we assume our fiducial triple consisting of inner massive binary of $\mathcal{O}(10)\ M_\odot$ and a visible tertiary of $\mathcal{O}(1)\ M_\odot$, with week-scale and month-scale inner and outer orbital periods, respectively. We consider three different probes to search for inner BBHs. The first probe is the short-term radial velocity (RV) variations of a tertiary star, which have a timescale around half the inner orbital period. The second one is the long-term tertiary RV variations, which have the timescale much longer than the orbital periods of two orbits in a triple system. The third one is the arrival time variations of a tertiary pulsar if the tertiary is a pulsar rather than a star. Although tertiary pulsars are likely to be even rarer than tertiary stars, great precision of pulsar timing observations can search for more distant systems beyond kpc scale. This is complementary to the former two methods using RV observations, which is usually applicable up to $\mathcal{O}(100)$ pc scale.

We show that the short-term RV variations can be used as a probe of inner hidden BBH, when a tertiary star is near-by ($\ll$ kpc) and bright enough ($\lesssim$ 15 mag) through mock observations. The variations indeed reach $\mathcal{O}(100)$ m/s amplitude with week-scale periods, which will be detected with intensive high precision RV follow-ups. We conclude that the short-term RV variations provide a suitable method to identify inner BBHs especially for coplanar triples. On the other hand, we find that the long-term RV variations change the Kepler motion amplitude for inclined triples, as a result of orbital plane evolution with respect to the line of sight. The amplitude, therefore, becomes comparable to the huge Kepler motion amplitude itself. For instance, our fiducial triple has $\mathcal{O}(100)$ km/s variations, which should be detected even without high precision RV observations. We show numerically that the variations have long timescale, but still can be detected within decades depending on orbital parameters. For instance, the variations should be detected within a few decades for our fiducial triples. Therefore, we conclude that the long-term RV variations are very promising probe of the inner BBHs in inclined triples.

As for the pulsar arrival time variations, we show that it is possible to identify an inner BBH and its orbital parameters unambiguously. Moreover, we found that very precise pulsar timing with μsec scale uncertainty can identify an inner BBH down to hour-scale orbital period, given a day-scale outer orbital period. Since closer BBHs can be searched with future space-based low-frequency GW detectors, we can effectively cover a large parameter space of inner BBHs combining two methods in the future.

Finally, we consider the dynamical stability of triple systems. This is worth studying in order to examine the stable triples to which we can apply our methods. Even apart from the point, the dynamical stability is on its own important in the three-body problem. It has been widely studied previously, and many stability/instability criteria and the disruption time estimation model based on a Random Walk have been proposed. We performed a series of numerical simulations for different configurations of hierarchical triples. We found that the previous models are applicable only to a limited range of orbital configurations. In particular, we found that retrograde triples tend to remain stable for longer timescales. The result indicates the importance of extending the models, based on the disruption processes depending on orbital configurations in the future.

In summary, we propose methods to detect progenitor BBHs with relatively wide separations, in different ways from GW observations. We show that such BBHs can be detected with RV and pulsar timing observations of visible tertiaries, if the BBHs are inside triples. We expect that (star - BBH) triples will be searched for from candidate (star - unseen companion) binaries in the future. If such triples are successfully detected, the discovery will become remarkable as the first detection of not only progenitor BBHs, but also triples including BBHs.