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Tidal disruption as a probe for supermassive black hole binaries

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Abstract. Supermassive black hole binaries (SMBHBs) are the products of frequent galaxy mergers. It is very hard to be detected in quiescent galaxy. By using one million particle direct N-body simulations on special many-core hardware (GPU cluster), we study the dynamical co-evolution of SMBHB and its surrounding stars, specially focusing on the evolution of stellar tidal disruption event (TDE) rates before and after the coalescence of the SMBHB. We find a boosted TDE rate during the merger of the galaxies. After the coalescence of two supermassive black holes (SMBHs), the post-merger SMBH can get a kick velocity due to the anisotropic GW radiations. Our results about the recoiling SMBH, which oscillates around galactic center, show that most of TDEs are contributed by unbound stars when the SMBH passing through galactic center. In addition, the TDE light curve in SMBHB system is significantly different from the curve for single SMBH, which can be used to identify the SMBHB.

Keywords. galaxies: evolution, galaxies: kinematics and dynamics, methods: numerical

1. Introduction

It is believed that massive galaxies are assembled by smaller galaxies through multiple mergers (e.g. Springel *et al.* 2005). And observations indicate the existence of a supermassive black hole (SMBH) in the galactic center for almost all of the massive galaxies. Besides, people find that the merger of two galaxies may drive plenty of gas infuse to the galactic center, prompt the star burst, feed the central SMBH and thus invoke the active galactic nuclei (AGNs). As a result, the feedback from accreting SMBH will limit the growth of the itself and affect the evolution of the host galaxy, which induce a close connection between the SMBH and its host galaxy (e.g. Croton *et al.* 2006). For this reason, the evolution of two SMBHs is very important.

In a merging system with two galaxies, their SMBHs will firstly approach each other to form a SMBHB through dynamic friction, and then continually dissipate their orbit energy mainly through gas dynamics or gravitational three body interactions with surrounding stars (e.g. Begelman *et al.* 1980). After they get close enough, the gravitational waves (GWs) will be very efficient to coalesce the SMBHB, accompanied with a strong GW burst and a recoiling velocity to the remnant SMBH (e.g. Campanelli *et al.* 2007). In the past decade, there are some indirectly observational evidences, though all of them are in gaseous environment, to confirm this scenario. However, in quiescent galaxies, the observational evidence for SMBHBs is missing. Whether the SMBHB can keep as a binary system or finally coalescence is still under debate.

Fortunately, there is a good probe can be used. A SMBH can tidally disrupt star accompanied with very strong emission flare lasting for several months or even years, which can temporally light up the quiescent SMBH (e.g. Rees 1988; Komossa & Bade 1999). Studies about the tidal disruption event (TDE) from SMBHB, both for statistic research on event rate and specific research on light curve, can help us to get a better understanding of SMBHB. Besides, the recoiling remnant SMBH after the coalescence can also produce TDE or other special signatures (e.g. Gualandris & Merritt 2008; Komossa & Merritt 2008). For this reason, we have finished series investigations focusing on the TDEs in SMBHB, which includes the TDE rate evolution of merging SMBHB and recoiling SMBH, and the variation of TDE flare light curve in closely bound SMBHB system.

2. Methods

We use direct N-body simulation with simplified tidal disruption scheme to investigate the dynamical co-evolution between SMBHB and its host galaxy. For simplicity, two merging galaxies with SMBHs are identical. We trace the evolution of TDE rate from two separated SMBHs to bound binary and finally the recoiling remnant. The integrations have been done by a GPU accelerated parallel direct N-body code (φ-GRAPE and φ-GPU) (e.g. Harfst *et al.* 2007), on the *laohu* GPU cluster in National Astronomical Observatories of China (NAOC) (more details can be found in Li *et al.* 2012).

To specifically investigate the flare light curve of TDE in closely bound SMBHB, we have done series of scattering experiments. According to analytical and SPH simulation results (e.g. Evans & Kochanek 1989), the fluid elements of disrupted star have approximate test particle orbits, which enables us to simulate the debris through scattering experiments. Finally, we can convert the evolution of mass falling rate of debris into the variation of light curve (more details can be found in Liu *et al.* 2009).

3. Results

TDE in merging galaxies. The evolution of TDE rate during galaxy merger can be divided into three phases. In phase I, $r_{\rm bh}$, the separation of two SMBHs, is far more larger than their gravitational radii, which means that their TDE rates are similar to single SMBH in normal galaxy. As $r_{\rm bh}$ reduce to $r_{\rm inf}$, the influence radius of the SMBH, the bound SMBHB is forming, which corresponding to phase II. Finally, the SMBHB will sink into galactic center and the binary evolved to phase III. The left panel of Fig. 1 shows the evolution of TDE rate and $r_{\rm bh}$.

Our statistical research about $r_{\rm apo}$, the last apocenter prior to the disruption, for all of disrupted stars indicates that the distribution of $r_{\rm apo}$ has a significant peak, corresponding to where the most of disrupted stars come from. Based on our simulation results, the most of disrupted stars come from the region around $r_{\rm inf}$ in phase I. That is consistent with the prediction of classical loss cone theory. As $r_{\rm bh}$ decreasing, the primary $r_{\rm apo}$ peak is moving inward. Then the TDEs are dominated by stars inside SMBHB orbit, in another word, those bound stars perturbed by one of the SMBH. As shown in the left panel of Fig. 1, that leads to a very efficient loss cone refilling rate and a significantly enlarged TDE rate compare to PI. In phase III, as $r_{\rm bh}$ continually shrinking, the most of stars inside SMBHB orbit have been consumed through three-boy scattering and tidal disruption. Thus, due to the triaxial stellar distribution in merged galactic core, the contribution from those unbound stars outside $r_{\rm inf}$ become dominating. The TDE rate in this stage is between PI and PII. Our extrapolation results show that, for a galaxy similar to M32, the TDE rate in phase I is $\sim 3 \times 10^{-5} {\rm M}_{\odot}\ {\rm yr}^{-1}$, and there is an order of

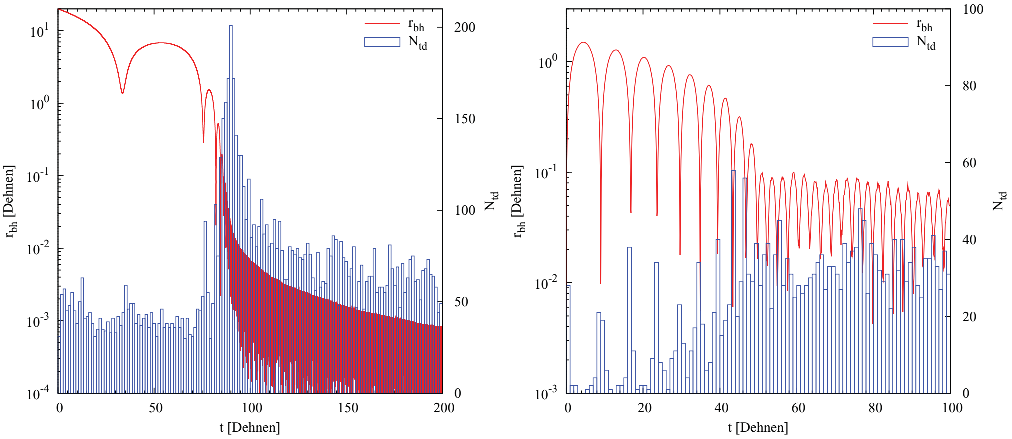

Figure 1. *Left panel*: evolution of TDE rate for merging galaxies. Red solid line represents $r_{\rm bh}$ and blue box denotes $N_{\rm td}$, number count of TDEs in every time bin. *Right panel*: similar to the left panel, here is the evolution of TDE rate for a recoiling SMBH. (See the electronic edition with color.)

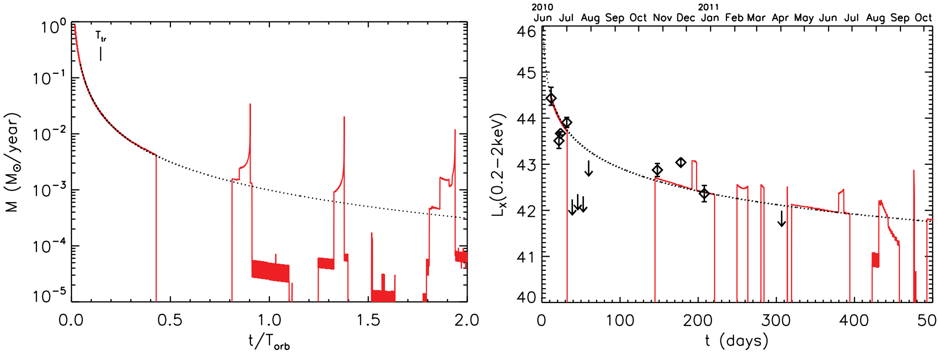

Figure 2. *Left panel*: Accretion rates of debris *vs.* time for a TDE in SMBHB, by Liu *et al.* 2009. Red Solid line is simulation result and doted line denotes the theoretical rate $\propto t^{-5/3}$ for single BH. $T_{\rm tr}$ marks the interruption time. *Right panel*: A rebuild X-ray light curve with red solid line for the SMBHB TDE in SDSS J120136.02+300305.5 (by Liu *et al.* 2014). Diamonds mark the observational data from XMM-Newton and Swift, and arrows represent the non-detection upper limit (see more details in Saxton *et al.* 2012). (See the electronic edition with color.)

magnitude boosted rate $\sim 5\times10^{-4}{\rm M}_\odot\ {\rm yr}^{-1}$ in phase II. The detailed treatment will be presented by Li *et al.* 2015, in preparation.

TDE for recoiling remnant SMBH. After SMBHB coalescence, the remnant SMBH may get a recoil velocity. For most of the cases, it is not strong enough to make the SMBH escape away from its host galaxy. Thus the recoiling SMBH will oscillate around galactic center and damp its energy through dynamic friction. Similar to Gualandris & Merritt 2008, we have divided the trajectory evolution of the recoiling SMBH into three phases, the phase I with fast damping oscillation outside core, the phase II for SMBH oscillating inside the core region with very slow damping, and then phase III the equilibrium status. Our simulation with tidal disruption has shown strongly boosted TDE rate every time when the recoiling SMBH passing through the galactic center (as shown in the right panel of Fig. 1). That indicates the captured stars dominate the TDE when SMBH return back to the center region (see more detail in Li *et al.* 2012).

Tidal flare light curve of SMBHB. According to the results above, it is possible to statistically investigate the evolution of SMBHB in gas poor environment. In addition, by analyzing the tidal flare light curve, we can even identify a specific SMBHB system. For a TDE in closely bound SMBHB, due to gravitational perturbation from another black hole (BH), some of the debris from disrupted star can not return and accreted by the primary SMBH which caused the disruption. As a result, the periodic perturbation from secondary BH will excite the truncations and recurrences for the flare light curve, as our simulation result shown in the left panel of Fig. 2. According to this figure, the light curve represented by red solid line in SMBHB system is significantly different from the case in single BH represented by dotted black line (more details in Liu *et al.* 2009).

This prediction has been confirmed by observation recently. Saxton *et al.* 2012 have caught a TDE in galaxy SDSS J120136.02+300305.5. It has special light curve represented by diamonds and arrows in the right panel of Fig. 2. That can be well explained by our SMBHB model in 2009. After a series simulations, we have got sets of parameters which can perfectly fit to the observation, as shown in the right panel of Fig. 2 for example (more details in Liu *et al.* 2014).

4. Conclusion

As we have shown in this letter, TDE can be a very powerful probe for investigating SMBHB in quiescent galaxy. As the two BHs evolving in merging galaxy, their TDE rates are also evolving. There is a boosted TDE rate during the formation of the SMBHB. And the TDE rate for recoiling remnant SMBH can be also enhanced when the SMBH passing through galactic center. With more TDEs which may be observed by LSST in the near future, we can statistically investigate the evolution of SMBHB through our results here. Besides, by using our flare light curve evolution model, we can specifically find out some SMBHB candidates, as we have already done for SDSS J120136.02+300305.5.

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