IMPLICATIONS OF INTERMEDIATE-MASS BLACK HOLES FOR GRAVITATIONAL RADIATION

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Black holes have historically been thought to come in two flavors: between a few and tens of solar masses, formed in supernovae; and millions to billions of solar masses, grown in the centers of galaxies. However, several recent lines of evidence point to intermediate-mass black holes that exist in a number of dense stellar clusters. These black holes are expected to be found in binaries. As a result, three and four body interactions are common, in a realm including both Newtonian effects and general relativistic effects such as precession of the pericenter and orbital evolution due to gravitational radiation. These objects may therefore be a new source of gravitational waves with unique properties. We discuss the possibility of detecting this gravitational radiation with future instruments such as LISA and Advanced LIGO.

1. Introduction

The initial mathematical foundation of black holes was established by Schwarzschild in 1916, but observational evidence has been slower to accumulate because black holes can only be observed indirectly, through their influence on nearby gas or stars. Nonetheless, over the last three decades the evidence for stellar-mass (a few to tens of solar masses; see, e.g., Orosz[1]) and supermassive (millions to billions of solar masses; e.g., Eckart and Genzel[2]) black holes has become incontrovertible. Strangely, it has been more difficult to establish the existence of intermediate-mass

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black holes (IMBHs), at hundreds to thousands of solar masses, even though most formation scenarios for supermassive black holes involve a stage of this mass. However, observations of numerous galaxies and possibly some globular clusters are beginning to build a case for the existence of these objects as well (see Miller and Colbert[3] for a recent review).

Many candidates for IMBHs are associated with dense stellar clusters (see Miller and Colbert[3]). At the stellar number densities of $\sim 10^{5-6}$ pc^{-3} inferred for either massive young clusters or the high-mass end of globular clusters, this implies that over billions of years there will be many dynamical interactions of an IMBH with either stars or stellar remnants. Encounters with neutron stars or stellar-mass black holes are promising for the generation of gravitational radiation, because IMBHs tend to sink to the center of clusters and exchange into binaries, which have a high cross section of interaction. These binaries may have properties that can allow for strong tests of the predictions of general relativity.

We now review briefly the interactions of binaries in a dense stellar cluster and discuss the implications of these interactions for the detection of gravitational radiation by ground-based and space-based instruments.

2. Cluster Dynamics and Gravitational Radiation

In the last 15-20 years, it has been appreciated that binary stars play an important role in the dynamics of globular clusters. These globulars, with $N \sim 10^{5-6}$ stars, have half-mass relaxation times

$$t_{\rm rel} = (N/8\ln N)t_{\rm dyn} \tag{1}$$

that are $\sim 10^{8-9}$ yr, where $t_{\rm dyn} \sim 10^{4-5}$ yr is the dynamical time, i.e., comparable to the time for a star to cross the cluster (e.g., Binney and Tremaine[4]). Because a relaxation time is defined as a typical time for stellar orbital parameters to change by of order themselves, this is a characteristic time for "significant" evolution of the cluster as a whole. For example, on this timescale the cluster core increases its number density while the outer parts expand. However, this is such a short time compared to the $\sim 10^{10}$ yr age of globulars that if there are no binary or multiple star systems, many clusters would have undergone core collapse (Binney and Tremaine[4]). Binary stars alleviate this problem because interactions with single stars can tighten binaries, leading to recoil that acts like a heat source and allows the cluster to reach a quasi steady state (Binney and Tremaine[4]).

In clusters, heavy objects of mass $M > \langle m\rangle$, where $\langle m\rangle$ is the average mass, sink to the center on a typical timescale $(\langle m\rangle/M)t_{\rm rel}$. Therefore, binaries tend to interact in the cores of clusters, as would intermediate-mass black holes. Unlike single stars, whose cross section is close to their physical size, binaries have an effective cross section equal to the area of their orbit. In particular, consider a binary-single interaction that has negative total energy. In Newtonian point-mass interactions this must ultimately be resolved as a binary and a single star, with it being typical that the two most massive of the three objects end up in the final binary. Thus, IMBHs will rapidly exchange into binaries. In addition, because stellar-mass black holes, with $M \sim 5 - 20\,M_\odot$, are significantly more massive than $\langle m \rangle$ in a globular, if there are such black holes in the cluster they tend to end up as partners with IMBHs. Further interactions with single stars tend to harden the binary (Heggie[5]). If the IMBH and stellar-mass black hole get close enough, gravitational radiation will shrink the orbit and cause coalescence. This allows the binary to be a gravitational wave source for space-based detectors such as LISA, and possibly for ground-based detectors such as Advanced LIGO, VIRGO, TAMA, or GEO-600. Recently, Gültekin et al.[6] examined the interactions of IMBHs in globular clusters and found that if the initial mass of the IMBH is more than $\sim 100 - 150\,M_\odot$ (possibly because of a core collapse in a young cluster producing a massive star; see Ebisuzaki et al.[7], Gürkan et al.[8]), then tens of stellar-mass black holes can merge with a given IMBH before the cluster runs out of black holes.

The rate for detected mergers could be as high as a few per year to tens per year for Advanced LIGO, depending on the mass distribution of IMBHs, and there could be several active sources detectable with LISA in nearby galaxy clusters such as Virgo and Fornax (see Miller[9]). In the $\sim 10^{-3}$ Hz range (the optimal sensitivity for LISA), Gültekin et al.[6] show that the eccentricity of IMBH binaries can occupy a wide range, much of which is $e \sim 0.1 - 0.2$. At those eccentricities circular binary templates may suffice for detection, but effects such as pericenter precession, orbital decay, and possibly even Lense-Thirring precession will be detectable, leading to breaking of degeneracies and possibly direct determination of the distance to galaxy clusters (see Miller[9]). In addition, if many merger events are detected with ground-based instruments, the mass ratios seen will provide valuable information about the amount of gravitational radiation recoil in a merger, which is currently highly uncertain (Favata et al.[10]). This is because the low escape speeds from globular clusters, only ~ 50 km s^{-1}, will act as a filter; recoil faster than this prevents further mergers, so there will be a strong mapping between mass ratio and kick speed.

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