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Prospects for the Discovery of Black Hole Binaries without Mass Accretion with Gaia

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Abstract. We study the prospect for Gaia to detect black hole binary systems without the mass transfer from their companion stars. Gaia will be able to discover Galactic black holes without mass accretion by detecting the proper motion of their companion stars. We evaluate the number of such black hole binaries which have the orbital period short enough to be detected by Gaia during its operation, taking into account the binary evolution model.

Keywords. black hole physics, astrometry, binaries: general, stars: evolution

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From the star formation rate ($\sim 3.5 M_\odot$ yr^{-1}) and the initial mass function (IMF), one can estimate the number of stellar-mass black holes in our Galaxy as $\gtrsim 10^{8-9}$ (Brown & Bethe 1994; Timmes *et al.* 1996). Those whose existence is confirmed from the observations form X-ray binaries, the systems of a black hole and a companion star with mass accretion. However, only a few dozens of such black holes have been detected (Remillard & McClintock 2006), and so we can expect that in our Galaxy there are much more black holes without mass accretion from their companions. Then, how can we discover such black holes? One of the ways is to detect the motion of companion stars by astrometric observations, such as *Gaia*, *JASMINE*, etc. *Gaia* was launched at the end of 2013, and it can perform absolute astrometric measurements with a great precision on objects with $V \lesssim 20$ (Barstow *et al.* 2014). In this work we estimate the number of non-accreting black hole binaries using *Gaia* during its operation (~ 5 years).

The necessary conditions for a black hole binary without mass accretion to be detected by *Gaia* are the followings:

(i) The binary should contain a black hole and a main sequence star/giant star/white dwarf. In other words, the binary should be older than the lifetime of a primary star (i.e., the progenitor of a black hole) and younger than the lifetime of a secondary star.

(ii) The radius of a secondary star should be smaller than the Roche lobe radius of the binary so as to avoid the mass transfer.

(iii) The orbital period of the binary should be short enough to be detected by Gaia within its operation time (e.g. $\lesssim 2$ years).

We assume the initial mass function (IMF) as

$$\Psi(\bar{M}_1)d\bar{M}_1 \propto \begin{cases} \bar{M}_1^{-1.3}d\bar{M}_1, & 0.08M_\odot \leqslant \bar{M}_1 < 0.5M_\odot, \\ \bar{M}_1^{-2.2}d\bar{M}_1, & 0.5M_\odot \leqslant \bar{M}_1 < 1.0M_\odot, \\ \bar{M}_1^{-\alpha_{\rm IMF}}d\bar{M}_1, & 1.0M_\odot \leqslant \bar{M}_1 < 150M_\odot, \end{cases} \tag{0.1}$$

a flat mass ratio distribution ($\Phi(q) = 1$), and a log-flat orbital separation distribution ($\Gamma\left(\bar{A}\right) \propto 1/\bar{A}$). As for the stellar evolution processes, we take into account the common envelope phase that would be important when the mass ratio is less than ~ 0.5. During this phase, the orbital separation becomes larger because the orbital energy is used to expel the envelope of a primary star. We can estimate the number of black hole binaries without mass accretion that are detectable by Gaia, N, from the following equation:

$$N = \frac{f_{\rm bin}}{1+f_{\rm bin}} \int_{M_{\rm min,BH}}^{M_{\rm max}} d\bar{M}_1 \Psi\left(\bar{M}_1\right) \int_{q_{\rm min}}^{q_{\rm max}} dq\, \Phi(q) \times \int_0^1 d\bar{e}\, \Xi\left(\bar{e}\right) \int_{t_{\rm L,1}}^{t_{\rm L,2}} dt \int_{\bar{A}_{\rm RL}}^{\bar{A}_{\rm 2yr}} d\bar{A}\, \Gamma\left(\bar{A}\right), \quad (0.2)$$

where $f_{\rm bin} = 0.5$ is the binary fraction, $M_{\rm min,BH} = 20M_\odot$ is the minimum ZAMS mass for a star to become a black hole after its death, $t_{{\rm L},i}$ is the lifetime of a primary ($i = 1$) and a secondary ($i = 2$) star. Here, the lower limit of the orbital separation integral, $\bar{A}_{\rm RL}$, is determined from the condition (ii), and the upper limit, $\bar{A}_{\rm 2yr}$ is determined from the condition (iii).

According to our calculations, we found that the number of black hole binaries without mass accretion in our Galaxy is $\sim 1.5 \times 10^5$, i.e. Gaia may detect $\lesssim 0.1\%$ of Galactic stellar mass black holes ($\sim 10^{8-9}$) by astrometry. If we can discover a large number of Galactic black holes in this way, we will be able to construct their mass function with better statistics, which is important to understand the stellar evolution processes and the binary evolution processes.

References

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