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The Observed Rate of Binary Black Hole Mergers can be Entirely Explained by Globular Clusters

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Abstract

Since the first signal in 2015, the gravitational-wave detections of merging binary black holes (BBHs) by the LIGO and Virgo collaborations (LVC) have completely transformed our understanding of the lives and deaths of compact object binaries, and have motivated an enormous amount of theoretical work on the astrophysical origin of these objects. We show that the phenomenological fit to the redshift-dependent merger rate of BBHs from Abbott et al. is consistent with a purely dynamical origin for these objects, and that the current merger rate of BBHs from the LVC could be explained entirely with globular clusters alone. While this does not prove that globular clusters are the dominant formation channel, we emphasize that many formation scenarios could contribute a significant fraction of the current LVC rate, and that any analysis that assumes a single (or dominant) mechanism for producing BBH mergers is implicitly using a specious astrophysical prior.

Over the past 5 yr, the observed rate of binary black hole (BBH) mergers in the local universe has been significantly constrained. After the detections of GW150914, GW151012, and GW151226 in the first observing run, initial estimates put the volumetric merger rate between 9 and 240 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ at 90% confidence at $z = 0$ (Abbott et al. 2016). Merger rates $\gtrsim$100 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ were largely understood to be explicable by isolated binary evolution (e.g., Belczynski et al. 2016), with dynamical assembly (e.g., Rodriguez et al. 2016) only contributing a small fraction of the population. But as more BBH mergers have been detected, the measured local merger rate has decreased by an order of magnitude, while sufficient numbers of higher-redshift mergers allow the slope of the rate to be observed. By fitting the observed detections to a phenomenological model of the form $R(z) = R_0(1 + z)^{\kappa}$, an analysis of the latest GW transient catalog (GWTC-2, Abbott et al. 2020) suggests an increasing merger rate with a local value of $19^{+16}_{-9}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ at $z = 0$.

There have been many theoretical models of the merger rate of BBHs from GCs, both before and after the first detection of GWs (e.g., Portegies Zwart & Mcmillan 2000; Rodriguez et al. 2015) with the majority predicting a volumetric merger rate at $z = 0$ of ~ 10 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. Using the Cluster Monte Carlo code (CMC), several groups have studied the BBH merger rate from GCs and the unique properties of their sources. The analysis of the BBH merger rate from GCs initially predicted a merger rate anywhere from 2 to 20 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ at $z = 0$, based on the luminosity function and comoving spatial density of observed GCs in the local universe (Rodriguez et al. 2016). Of course, this initial analysis ignored the contributions of GCs that were disrupted before the present day, which can significantly increase the contribution to the BBH merger rate (e.g., Fragione & Kocsis 2018). In Rodriguez et al. (2018), we combined a cosmological model for GC formation (El-Badry et al. 2019) with star-by-star CMC models of GCs to estimate the BBH merger rate as a function of cosmological redshift.

In the left panel of Figure 1, we show the predictions from Rodriguez et al. (2018) and updated predictions using the same cosmological model and fitting procedure[7] with newer GC models (covering a wider range of parameters) from Kremer et al. (2020). When compared to the allowed range and cosmological evolution of the BBH merger rate from GWTC-2 (Abbott et al. 2020), it is obvious that *the entire phenomenological BBH merger rate can potentially be explained by GCs alone*. At $z = 0$ the original fits predict a merger rate of 15 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, while the newer fits from Kremer et al. (2020) predict a merger rate of 17 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. In both cases, the merger rate increases as a function of redshift. Comparing the ratio of the rate at $z = 1$ to $z = 0$, we find that $R(1)/R(0) = 3.1$ for the original fits from Rodriguez et al. (2018), and $R(1)/R(0) = 3.2$ for the Kremer et al. (2020) models. Both ratios are consistent with the phenomenological value of $R(1)/R(0) = 2.5^{+7.8}_{-1.9}$ from Abbott et al. (2020).

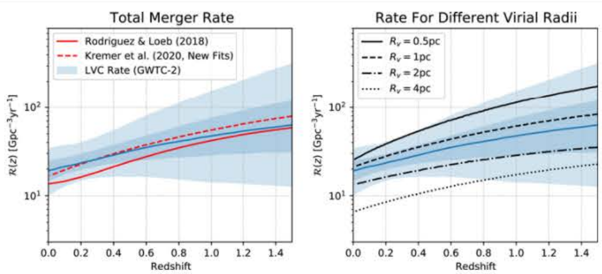

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Figure 1. The merger rate of BBHs from GCs compared to the latest LVC results. The left panel shows the predictions from Rodriguez & Loeb (2018) and updated predictions from Kremer et al. (2020) using the same cosmological model. The right panel shows the fits to the models from Kremer et al. (2020) broken down according to cluster virial radius, assuming that all clusters are born with initial radii of 0.5, 1, 2, or 4 pc. The total prediction on the left is the average of these four values. In blue, we show the median, 50%, and 90% intervals of the phenomenological merger rate fit from GWTC-2 (Abbott et al. 2020).

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The primary improvement in the models of Kremer et al. (2020) is the extent of the grid, with the newer grid containing clusters with higher initial masses, more compact initial virial radii (as small as 0.5 pc), and a wider range of metallicities. All together, they capture nearly the complete spectrum of present-day dense star clusters in the Milky Way. We have assumed in the left panel of Figure 1 that clusters of different initial radii contribute equally to the total rate. To make this more explicit, we show what the merger rate would look like from GCs assuming all cluster were born with virial radii of 0.5, 1, 2, or 4 pc in the right panel of Figure 1. The four values clearly span the 90% region of allowed merger rates from Abbott et al. (2020). As pointed out in Kremer et al. (2020), initial concentrations of clusters directly control the slope of the merger rate, with the contributions from clusters with 0.5, 1, 2, and 4 pc having ratios of $R(1)/R(0) = 4.2$, 2.8, 2.1, and 2.6, respectively. Given that many young clusters in the local universe are observed to have initial effective radii between 1 and 2 pc (e.g., Scheepmaker et al. 2007), this suggests remarkably good agreement with current LIGO and Virgo collaborations (LVC) findings.

Of course, there are many such dynamical scenarios for forming merging BBHs , many of which are consistent with the 90% uncertainties from the LVC's phenomenological model. But while the measured merger rates can now be explained by a single formation channel alone, there is no reason to believe that is the case. Several studies of the current LVC BBH catalog have suggested that multiple formation scenarios likely operate in producing BBH mergers (e.g., Wong et al. 2020; Zevin et al. 2020) with the latter suggesting that no single channel likely contributes more than 70% to the total population. This note is meant to emphasize this point: given that GCs alone can naturally explain the most up-to-date BBH merger rate from the LVC, it is no longer reasonable to assume that dynamical processes constitute a subdominant fraction of the full merger rate.

Footnotes

7 For the updated model we have added an additional correction accounting for the formation of central-massive BHs in GCs, from Antonini et al. (2019); see Kremer et al. (2019) for details. This

central massive BHs in GCs, from Antonini et al. ([illegible]); see Kremer et al. ([illegible]) for details. This decreases the BBH merger rate from the densest GCs by ~10%.

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