arXiv:0912.4925v1 [astro-ph.CO] 24 Dec 2009

DETECTING COALESCENCES OF INTERMEDIATE-MASS BLACK HOLES IN GLOBULAR CLUSTERS WITH THE EINSTEIN TELESCOPE

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We discuss the capability of a third-generation ground-based detector such as the Einstein Telescope (ET) to detect mergers of intermediate-mass black holes (IMBHs) that may have formed through runaway stellar collisions in globular clusters. We find that detection rates of ~ 2000 events per year are plausible.[1]

Keywords: Gravitational Waves; Intermediate-Mass Black Holes; the Einstein Telescope.

The Einstein Telescope (ET), a proposed third-generation ground-based gravitational-wave (GW) detector, will be able to probe GWs in a frequency range reaching down to ~ 1 Hz.[2] This bandwidth will allow the ET to probe sources with masses of hundreds or a few thousand $M_\odot$ which are out of reach of LISA or the current ground-based detectors LIGO, Virgo, and GEO-600.

Globular clusters may host intermediate-mass black holes (IMBHs) with masses in the $\sim 100 - 1000\ M_\odot$ range (see Ref. 3 and references therein). If the stellar binary fraction in a globular cluster is sufficiently high, two or more IMBHs can form.[4] These IMBHs then sink to the center in a few million years, where they form a binary and merge via three-body interactions with cluster stars followed by gravitational radiation reaction (see[4,5] for more details). Therefore, the rate of IMBH binary mergers is just the rate at which pairs of IMBHs form in clusters. The rate of detectable coalescences is

$$R \equiv \frac{dN_{\rm event}}{dt_o} = \int_{M_{\rm tot,min}}^{M_{\rm tot,max}} dM_{\rm tot} \int_0^1 dq \int_0^{z_{\rm max}(M_{\rm tot},q)} dz \frac{d^4 N_{\rm event}}{dM_{\rm tot} dq dt_e dV_c} \frac{dt_e}{dt_o} \frac{dV_c}{dz}. \quad (1)$$

Here $M_{\rm tot}$ is the total mass of the coalescing IMBH-IMBH binary and $q \leq 1$ is the mass ratio between the IMBHs; $z_{\rm max}(M_{\rm tot}, q)$ is the maximum redshift to which the ET could detect a merger between two IMBHs of total mass $M_{\rm tot}$ and mass ratio q; $dt_e/dt_o = (1+z)^{-1}$ is the relation between local time and our observed time, and

dV_c/dz is the change of comoving volume with redshift, given by

$$\frac{dV_c}{dz} = 4\pi D_H^3 \left[\Omega_M(1+z)^3 + \Omega_\Lambda\right]^{-1/2} \left\{ \int_0^z \frac{dz'}{\left[\Omega_M(1+z')^3 + \Omega_\Lambda\right]^{1/2}} \right\}^2 . \quad (2)$$

We assume a flat universe ($\Omega_k = 0$), and use $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, $H_0 = 72$ km s^{-1} Mpc^{-1}, and $D_H = c/H_0 \approx 4170$ Mpc, so that the luminosity distance can be written as a function of redshift as:[6]

$$D_L(z) = D_H(1+z) \left\{ \int_0^z \frac{dz'}{\left[\Omega_M(1+z')^3 + \Omega_\Lambda\right]^{1/2}} \right\} . \quad (3)$$

We make the following assumptions. **1.** IMBH pairs form in a fraction g of all globular clusters. **2.** We neglect the delay between cluster formation and IMBH coalescence. **3.** When an IMBH pair forms in a cluster, its total mass is a fixed fraction of the cluster mass, $M_{\rm tot} = 2 \times 10^{-3}\ M_{\rm cl}$, consistent with simulations.[7] The mass ratio is uniform in $[0, 1]$. We restrict our attention to systems with a total mass between $M_{\rm tot,min} = 100 M_\odot$ and $M_{\rm tot,max} = 20000 M_\odot$. Thus,

$$\frac{d^4 N_{\rm event}}{dM_{\rm tot}\, dq\, dt_e\, dV_c} = g \frac{d^3 N_{\rm cl}}{dM_{\rm cl}\, dt_e\, dV_c} \frac{1}{2 \times 10^{-3}} . \quad (4)$$

4. The distribution of cluster masses scales as $(dN_{\rm cl}/dM_{\rm cl}) \propto M_{\rm cl}^{-2}$ independently of redshift. We confine our attention to clusters with masses ranging from $M_{\rm cl,min} = 5 \times 10^4 M_\odot$ to $M_{\rm cl,max} = 10^7 M_\odot$. The total mass formed in all clusters in this mass range at a given redshift is a redshift-independent fraction $g_{\rm cl}$ of the total star formation rate per comoving volume:

$$\frac{d^3 N_{\rm cl}}{dM_{\rm cl}\, dt_e\, dV_c} = \frac{g_{\rm cl}}{\ln(M_{\rm cl,max}/M_{\rm cl,min})} \frac{d^2 M_{\rm SF}}{dV_c\, dt_e} \frac{1}{M_{\rm cl}^2} . \quad (5)$$

5. The star formation rate as a function of redshift z rises rapidly with increasing z to $z \sim 2$, after which it remains roughly constant:[8]

$$\frac{d^2 M_{\rm SF}}{dV_c\, dt_e} = 0.17 \frac{e^{3.4z}}{e^{3.4z} + 22} \frac{\left[\Omega_M(1+z)^3 + \Omega_\Lambda\right]^{1/2}}{(1+z)^{3/2}}\ M_\odot\ {\rm yr}^{-1}\ {\rm Mpc}^{-3} . \quad (6)$$

Rather than computing $z_{\rm max}(M_{\rm tot}, q)$ [Eq. 1] for all values of $M_{\rm tot}$ and q, we rely on the following fitting formula for the luminosity-distance range $D_{\rm L,max}$ as a function of the redshifted total mass $M_z = M_{\rm tot}(1+z)$, obtained by using the effective-one-body, numerical relativity (EOBNR) gravitational waveforms[9] to model the inspiral, merger, and ringdown phases of coalescence:

$$D_{\rm L,max}(M_z) = (1.25\ {\rm Gpc}) A \begin{cases} M_z^{3/5} & \text{if } M_z < M_0 \\ M_z^{11/10} M_z^{-1/2} & \text{if } M_z > M_0 \end{cases} , \quad (7)$$

where $A = 4$, $M_0 = 600 M_\odot$ for $q = 1$ and $A = 2.25$, $M_0 = 450 M_\odot$ for $q = 0.25$. We use $\rho = 8$ as the SNR threshold for a "single ET" configuration. We determine the sky-location and orientation averaged range by dividing the horizon distance by 2.26,[10] ignoring redshift corrections to this factor.

We can compute $z(D_L)$ by inverting Eq. (3). For a given choice of $M_{\rm tot}$ and q, the maximum detectable redshift $z_{\rm max}(M_{\rm tot}, q)$ is then obtained by finding a self-consistent solution of $z\Big(D_{\rm L,max}\big(M_{\rm tot}(1+z_{\rm max})\big)\Big) = z_{\rm max}$.

We substitute these expressions into Eq. (1) to obtain the rate of detectable coalescences. We carry out the integrals of $M_{\rm tot}$ and z in Eq. (1) for two specific values of q. For $q = 1$, we find the total rate to be $R = 2.5 \times 10^5\ g\ g_{\rm cl}\ {\rm yr}^{-1}$; for $q = 0.25$, it is $R = 2 \times 10^5\ g\ g_{\rm cl}\ {\rm yr}^{-1}$. The range varies smoothly with q; therefore, we estimate that the full rate, including the integral over q is

$$R = \frac{2\times 10^{-3}\ g\ g_{\rm cl}\ {\rm yr}^{-1}}{\ln(M_{\rm tot,max}/M_{\rm tot,min})} \int_{M_{\rm tot,min}}^{M_{\rm tot,max}} \frac{M_\odot dM_{\rm tot}}{M_{\rm tot}^2} \int_0^1 dq \int_0^{z_{\rm max}(M_{\rm tot},q)} dz\ 0.17 \frac{e^{3.4z}}{e^{3.4z}+22} \frac{4\pi (D_H/{\rm Mpc})^3}{(1+z)^{5/2}} \times \left\{ \int_0^z \frac{dz'}{[\Omega_M (1+z')^3 + \Omega_\Lambda]^{1/2}} \right\}^2 \approx 2000 \left(\frac{g}{0.1}\right) \left(\frac{g_{\rm cl}}{0.1}\right) {\rm yr}^{-1}, \tag{8}$$

where we arbitrarily chose $g = 0.1$ and $g_{\rm cl} = 0.1$ as the default scalings.

Mergers between pairs of globular clusters containing IMBHs can increase this rate by up to a factor of ~ 2.[11] Ref. 1 contains additional details on coalescences involving intermediate-mass black holes as gravitational-wave sources for the ET.

Acknowledgments

IM is supported by the NSF Astronomy and Astrophysics Postdoctoral Fellowship under award AST-0901985 and was partially supported from NASA ATP Grant NNX07AH22G. JG's work is supported by a Royal Society University Research Fellowship. MCM acknowledges NASA ATP grant NNX08AH29G.

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