SPECIAL SUPERNOVA SIGNATURE FROM BINARY BLACK HOLE PROGENITOR SYSTEMS

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ABSTRACT

The gravitational wave detection by LIGO-Virgo scientific collaboration show that the binary black hole (BBH) systems with BH mass of tens of solar masses widely exist in the universe. Two main types of scenarios have been invoked for the formation of BBH systems, including isolated binary evolution in galactic fields and dynamical interactions in dense environments. Here we propose that if the BBH systems are formed from isolated binary evolution, the supernova signal associated with the second core collapse would show some identifiable features, due to the accretion feedback from the companion BH. Depending on the binary properties, we show that the supernova lightcurve could present a sharp peak around \(\sim 10\) days, with luminosity even at the level of the super luminous supernovae (e.g. \(\sim 10^{44}\) erg s\(^{-1}\)) or present a plateau feature lasting for several tens of days with regular luminosity of core collapse supernovae. Comparing the event rate density of these special supernova signals with the event rate density of LIGO-Virgo detected BBH systems could help to distinguish the BBH formation channel.

Keywords: stars: binary—star: evolution—neutron star—fast radio burst: DM

1. INTRODUCTION

With the first detection of binary black hole (BBH) coalescence signal, GW150914 (Abbott et al. 2016), the LIGO-Virgo scientific collaboration (LVC) opened up the field of gravitational-wave astrophysics. In the first two observing runs (O1 and O2), LVC discovered another nine BBH merger events, providing an estimates of the BBH merger rate density \(R = 53.2^{+55.8}_{-28.2}\) Gpc\(^{-3}\) yr\(^{-1}\) (Abbott et al. 2019). During the third observing run (O3), more BBH merger events are continued to be discovered with some interesting special cases, such as coalescence with asymmetric masses [e.g. GW190412 (Abbott et al. 2020a) and GW190814 (Abbott et al. 2020b)].

The formation channel of BBH systems is still under debated. Two main types of scenarios have been invoked for the formation of BBH systems, including isolated binary evolution in galactic fields (Tutukov & Yungelson 1973; Lipunov et al. 1997; Belczynski et al. 2016) and dynamical interactions in dense environments (Sigurdsson & Hernquist 1993; Portegies Zwart & McMillan 2000; Rodriguez et al. 2015). In the binary evolution scenario, the faster evolving star first produced a BH through core collapse, forming a BH + massive star binary. After a certain time delay, the second core-collapse event would lead to a BBH system formation. Two core collapses are likely to be accompanied by two supernova (SN) explosions.

In this letter, we propose that the second SN explosion will be special because it has a very close black hole as its companion star. When the SN material expands and approaches to the companion BH, a violent accretion process could trigger strong feedback to the SN explosion. Here we show that once the feedback is energetic enough, the second SN would present some identifiable signatures. Comparing the event rate density of these special supernova signals with the event rate density of LIGO-Virgo detected BBH systems could help to distinguish the BBH formation channel.

2. MODEL DESCRIPTION

Consider a binary system with a massive star and a companion BH (with a mass \(M_{\text{BH}}\)), where the orbital separation is \(d\). When the massive star explodes as a SN, a total mass of \(M_{\text{ej}}\) could be ejected with an explosion energy \(E_{\text{sn}}\). Based on numerical simulations of SN explosions, the density profile of SN ejecta could be described by a broken power-law (Matzner & McKee 1999)

\[
\rho_{\text{ej}}(v, t) = \begin{cases} 
\zeta_p \frac{M_{\text{ej}}}{v_{\text{ej},d}^3} \left( \frac{r}{v_{\text{tr}} t} \right)^{-\delta}, & v_{\text{ej,min}} \leq v < v_{\text{tr}} \\
\zeta_p \frac{M_{\text{ej}}}{v_{\text{ej},d}^3} \left( \frac{r}{v_{\text{tr}} t} \right)^{-n}, & v_{\text{tr}} \leq v \leq v_{\text{ej,max}}
\end{cases}
\]
where the transition velocity $v_{tr}$ could be obtained from the density continuity condition

$$v_{tr} = \zeta_0 \left( \frac{E_{sn}}{M_{ej}} \right)^{1/2} \simeq 1.2 \times 10^4 \text{ km s}^{-1} \left( \frac{E_{sn}}{10^{51} \text{ erg}} \right)^{1/2} \left( \frac{M_{ej}}{M_\odot} \right)^{-1/2}.$$  

The numerical coefficients depend on the density power-indices as (Kasen et al. 2016)

$$\zeta_\rho = \frac{(n-3)(3-\delta)}{4\pi(n-\delta)}, \quad \zeta_\nu = \left[ \frac{2(5-\delta)(n-5)}{(n-3)(3-\delta)} \right]^{1/2}.$$  

For core-collapse SNe, the typical values of the density power-indices are $\delta = 1, n = 10$ (Chevalier & Soker 1989).

Here we assume that the SN ejecta undergoes a homologous expansion i.e., $r = vt$, where the inner boundary of the ejecta could be defined by the slowest ejecta,

$$R_{\text{min}}(t) = R_{\text{min},0} + v_{ej,\text{min}} t,$$

where $v_{ej,\text{min}}$ is the minimum velocity of the ejecta and $R_{\text{min},0}$ is the initial radius of the innermost radius when the explosion enters the homologous phase. Similarly, the outermost layer of the SN ejecta should be

$$R_{\text{max}} = R_{\text{max},0} + v_{ej,\text{max}} t,$$

where $v_{ej,\text{max}}$ is the maximum velocity of the ejecta and $R_{\text{max},0}$ is the initial radius of the outermost radius in the homologous phase.

With the expansion, a good fraction of the SN material would enter and be trapped by the gravitational potential of the companion BH. If one takes spherical coordinate with origin at the center of the BH, the gravitational binding energy for an SN ejecta element with mass $m$ would be $E_{\text{gra}} = GM_{BH}m/r$. If this gravitational binding energy larger than the kinetic energy of this element $\frac{1}{2}mv^2$, it will be trapped and accreted by the central BH. We thus define an accretion radius of the BH as

$$R_{\text{acc}} = \frac{2GM_{BH}}{v^2} \simeq 5.3 \times 10^9 \text{ cm} \left( \frac{M_{BH}}{20 M_\odot} \right) \left( \frac{v}{10^4 \text{ km s}^{-1}} \right)^{-2}.$$  

When the outermost radius of SN ejecta reach $d - R_{\text{acc}}$, the outer part SN ejecta with $\rho_{ej} \propto r^{-3}$ begins to fall into the BH. The time for the falling process is set as

$$t_{\text{start}} = \frac{d - R_{\text{acc}}}{v_{ej,\text{max}}} \simeq 10^4 \text{ s} \left( \frac{d}{10^{15} \text{ cm}} \right) \left( \frac{v_{ej,\text{max}}}{10^4 \text{ km s}^{-1}} \right)^{-1}.$$  

In this phase, the material falling rate is

$$\dot{M} = 2\pi R_{\text{acc}}^2 v_{ej}$$

$$= \frac{8\pi G^2 M_{BH}}{d^3} \zeta \frac{M_{ej}}{v_{tr}} \left( \frac{d}{v_{tr} t} \right)^{-n}, \quad t_{\text{start}} \leq t < t_{tr},$$

where $t_{tr} \sim d/v_{tr}$ is the characteristic time when the falling region reaches down to the inner part ejecta, namely when the velocity of falling ejecta element $v$ becomes the transition velocity $v_{tr}$. The falling rate at the characteristic time is

$$\dot{M}_{tr} \simeq 4.1 \times 10^{-9} M_\odot \text{ s}^{-1} \left( \frac{M_{ej}}{10 M_\odot} \right)^{5/2} \left( \frac{M_{BH}}{20 M_\odot} \right)^2 \times \left( \frac{d}{10^{15} \text{ cm}} \right)^{-3} \left( \frac{E_{sn}}{10^{51} \text{ erg}} \right)^{-3/2}.$$  

When $t > t_{tr}$, the density structure of the SN ejecta falling into the BH starts to follow $\rho_{ej} \propto r^{-\delta}$, so that the falling rate becomes

$$\dot{M} = \dot{M}_{tr} \left( \frac{t}{t_{tr}} \right)^{\delta}, \quad t_{tr} \leq t \leq t_{\text{end}},$$

where $t_{\text{end}} \sim d/v_{ ej,\text{min}}$ is taken as the terminal timescale of the falling process. The accretion timescale could be estimated as $t_{acc} \sim t_{acc}/\alpha$, where $\alpha \sim 0.1-0.01$ is the standard dimensionless viscosity parameter (Shakura & Sunyaev 1973) and $t_{acc}$ is the timescale for material freely falling from $R_{\text{acc}}$ to the BH, which is

$$t_{\text{acc}} = \frac{3\pi}{32G} \left( \frac{R_{\text{acc}}}{M_{BH}} \right)^{1/2} = 0.68 \text{ s} \left( \frac{R_{\text{acc}}}{10^9 \text{ cm}} \right)^{3/2} \left( \frac{M_{BH}}{20 M_\odot} \right)^{-1/2}.$$  

Obviously, the accretion timescale is much smaller than the dynamical timescale. We thus take the fast accretion approximation and assume the BH accretion rate $\dot{M}_{acc}$ roughly equals to the falling rate $\dot{M}$. According to Eq. 8, the accretion process is super-Eddington. In this case, the accretion process could have strong feedback to the SN explosion. Here we consider three feedback mechanisms: 1) accretion disk radiation; 2) Blandford-Znajek jet (Blandford & Znajek 1977); and 3) Blandford-Payne outflow (Blandford & Payne 1982).

We treat the disk evolution as multi-color blackbody, then the effective temperature of the disk is (Strubbe & Quataert 2009)

$$\sigma T_{eff}^4 = \frac{3GM_{BH}Mf}{8\pi R^3} \times \left[ \frac{1}{2} + \left\{ \frac{1}{4} + \frac{3}{4}f \left( \frac{10M}{M_{Edd}} \right)^2 \left( \frac{R}{R_S} \right)^{-2} \right\}^{1/2} \right]^{1/2} - 1$$

where $f = 1 - (R_{ms}/R)^{1/2}$, $R_S = 2R_S$, and $R_S = GM_{BH}/c^2$. $R_{ms}$ is the marginally stable orbit radius in
unit of $r_g$, and is expressed as (Bardeen et al. 1972; Page & Thorne 1974)

$$R_{ms} = 3 + Z_2 - [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2},$$

where $Z_1 = 1 + (1 - a^2)^{1/3}(1 + a)^{1/3} + (1 - a)^{1/3}$, $Z_2 = (3a^2 + Z_1^2)^{1/2}$. Here, $a = J_{BZ}/(GM_H^2)$ is the BH spin parameter. The disk luminosity is thus given by

$$L_{disk} = 2\int_{R_{ms}}^{R_{out}} 2\pi R\sigma T_{eff}^4 dR.$$  \hspace{0.5cm} (13)

In our case (super-Eddington accretion), we find that $L_{disk} \sim 0.2 L_{Edd} \sim 10^{38} \text{erg s}^{-1} (M_{BH}/20 M_\odot)$.

The BZ jet power could be estimated as (Lee et al. 2000; Li 2000; Wang et al. 2002; McKinney 2005; Lei & Zhang 2011; Lei et al. 2013; Liu et al. 2017)

$$L_{BZ} = 1.7 \times 10^{50} a^2 \left(\frac{M_{BH}}{M_\odot}\right)^2 B_{H,15}^2 F(a) \text{ erg s}^{-1},$$

where $F(a) = [(1 + q^2)/q^2][(q + 1)/q] \arctan q - 1$ with $q = a/(1 + \sqrt{1 - a^2}$). $B_{H}$ is the magnetic field strength threading the BH horizon, which could be estimated by equating the magnetic pressure on the horizon to the ram pressure of the accretion flow at its inner edge (e.g. Moderski et al. 1997),

$$B_{H}^2 = \frac{8\pi}{\rho c^2} \approx \frac{M_{acc} \kappa}{4\pi r_H},$$

where $r_H = (1 + \sqrt{1 - a^2})r_g$ is the radius of the BH horizon. In our case, the BZ jet luminosity could be written as

$$L_{BZ}(t) = \eta_{BZ} \dot{M}_{tr} c^2 \left\{ \left(\frac{t}{t_{tr}}\right)^{10}, \quad t_{start} \leq t < t_{tr} \right\}
\left\{ \left(\frac{t}{t_{tr}}\right)^{10}, \quad t_{tr} \leq t \leq t_{end} \right\}$$

where $\eta_{BZ} = 0.52a^2 F(a)/(1 + \sqrt{1 - a^2})^2$, we have $\eta_{BZ} = 0.0008$ for $a = 0.1$ and $\eta_{BZ} = 0.17$ for $a = 0.9$. When the SN expands to a radius of $R_{SN}$, it will roughly take $t_B \sim 3000 \times L_{BZ,45}^{-1/3} \Omega_{10}^{4/3} R_{13}^{2/3} M_{10}^{1/3} \text{ for the BZ jet to breakout the SN material (Bromberg et al. 2011)}$. Since the breakout timescale is smaller than the termination timescale of the accretion process, the BZ jet very likely penetrates through the SN envelope. In this case, most of the BZ jet power would dissipate outside of the SN instead of injecting energy into the SN material. Therefore, the feedback effect from BZ power could be neglected here.

On the other hand, the BP outflow luminosity could be estimated as (Armitage & Natarajan 1999)

$$L_{BP} = \frac{(B^{P_{ms}}_{ms})^2 \dot{M}_{ms} \Omega_{ms}^2}{32c},$$

where $r_{ms} = R_{ms} r_g$ is the marginally stable orbit radius. $\Omega_{ms}$ is the Keplerian angular velocity at the marginally stable orbit radius, which could be calculated as

$$\Omega_{ms} = \frac{c^3}{GM_BH (R_{ms}^2 + a)}.$$  \hspace{0.5cm} (18)

The poloidal disk magnetic field $B^{P_{ms}}_{ms}$ has a relationship with the magnetic field strength threading the BH horizon $B_H$ as (Blandford & Payne 1982)

$$B^{P_{ms}}_{ms} = B_H \left(\frac{r_{ms}}{r_H}\right)^{-5/4}.$$  \hspace{0.5cm} (19)

In our case, we can derive the BP outflow luminosity as

$$L_{BP}(t) = \eta_{BP} \dot{M}_{tr} c^2 \left\{ \left(\frac{t}{t_{tr}}\right)^{10}, \quad t_{start} \leq t < t_{tr} \right\}
\left\{ \left(\frac{t}{t_{tr}}\right)^{10}, \quad t_{tr} \leq t \leq t_{end} \right\}$$

where $\eta_{BP}$ is efficiency which depends on the BH spin parameter

$$\eta_{BP} = \frac{1}{16} \left(1 + \frac{1}{\alpha^2}\right)^{1/2} \frac{R_{ms}^{3/2}}{(P_{ms}^a + a)^2}.$$  \hspace{0.5cm} (21)

We have $\eta_{BP} = 0.006$ for $a = 0.1$ and $\eta_{BP} = 0.013$ for $a = 0.9$. Comparing with the BZ jet, BP outflow is less collimated, therefore most of the BP power could be injected into the SN envelope. In this scenario, the SN bolometric luminosity can be expressed by (Arnett 1982)

$$L_{SN}(t) = e^{-2(\frac{\tau^2}{\tau_m^2})} \int_{0}^{t} 2 \frac{t}{\tau_m} L_{heat}(t') e^{-2(\frac{\tau^2}{\tau_m^2})} dt'.$$

where $\tau_m$ is the effective diffusion timescale,

$$\tau_m = \left(\frac{2\tau_{m_0}}{\beta \nu c}\right)^{1/2}.$$  \hspace{0.5cm} (23)

where $\kappa$ is the opacity of the SN ejecta, $\beta = 13.8$ is a constant for the density distribution of the ejecta. Here we take

$$L_{heat}(t) = L_{disk}(t) + L_{BP}(t) + L_{Ni}(t),$$

where $L_{Ni}$ is the heating power from the radioactive decay of $^{56}\text{Ni}$.

3. RESULTS

Depending on the orbital separation of the binary system $d$ and the supernova properties, such as the ejecta mass $M_{ej}$ and the explosion energy $E_{sn}$, the accretion feedback power $L_{disk} + L_{BP}$ could be larger, comparable or smaller than the radioactive decay heating power. For the last case, the SN lightcurve would behave as a normal core collapse SN. It is very difficult to justify the existence of a companion BH. But for the first two cases, the SN lightcurve could be significantly altered.

1 For cases we are interested, $L_{BP}$ is always larger than $L_{disk}$.
For instance, when the accretion feedback power is much larger than the radioactive heating power, we find that the SN lightcurve would show a sharp peak, whose luminosity could reach the order of $10^{44}$ erg s$^{-1}$, as luminous as the super luminous supernovae (Gal-Yam 2019, for a review). Here we show an example in Figure 1, where $d = 10^{13}$ cm, $M_{ej} = 5M_{\odot}$, $E_{sn} = 10^{51}$ erg, $v_{\text{min}} = 50$ km s$^{-1}$, $M_{BH} = 20M_{\odot}$, $a = 0.5$ and $M_{Ni} = 0.5M_{\odot}$ are adopted. In the literature, a newly formed magnetar is commonly proposed to be the energy source of SLSNe (Kasen & Bildsten 2010; Woosley 2010).

For comparison, we also plot the SN lightcurve when the heating power is dominated by a magnetar with spin period $P = 5$ ms, and dipole magnetic field $B = 10^{14}$ G. The lightcurve of our model and the magnetar model are clearly different. For our model, the accretion feedback would terminate when the inner boundary of the ejecta passes over the BH, so that the SN lightcurve would undergo a rapid decay after the peak, and then change to the normal decay as powered by the radioactive decay. But for the magnetar model, the energy injection always continues, so that the SN lightcurve is always dominated by magnetar power, which would undergo a relatively slow decay after the peak. Such different lightcurve behaviors could help us distinguish whether the SLSN is powered by our model or the magnetar model.

On the other hand, when the accretion feedback power is comparable to the radioactive heating power, we find that the SN lightcurve would show a plateau feature. Here we also show an example for this case in Figure 1, where $d = 3 \times 10^{13}$ cm, $M_{ej} = 5M_{\odot}$, $E_{sn} = 10^{51}$ erg, $v_{\text{min}} = 50$ km s$^{-1}$, $M_{BH} = 20M_{\odot}$, $a = 0.5$ and $M_{Ni} = 0.5M_{\odot}$ are adopted. For comparison, we also plot the SN lightcurve when the heating power is dominated by a magnetar with spin period $P = 6.5$ ms, and dipole magnetic field $B = 7 \times 10^{13}$ G. In this case, the SN lightcurve of our model would also undergo a rapid decay after the plateau feature, which is clearly distinct from the magnetar model.

4. CONCLUSION AND DISCUSSION

In this letter, we propose that if the BBH systems detected by LVC are formed from isolated binary evolution, the supernova signal associated with the second core collapse would show some identifiable features, due to the accretion feedback from the companion BH. When the feedback power is much greater than the radioactive decay power, the supernova lightcurve could show a sharp peak as luminous as the SLSNe (e.g. $\sim 10^{44}$ erg s$^{-1}$). When the feedback power is comparable to the radioactive decay power, the supernova lightcurve could contain a plateau feature. Finally, if the feedback power is much smaller than the radioactive decay, no new features could show up.

In addition, the accretion of the companion BH is likely to produce a jet via the BZ mechanism. The jet would pass through the supernova envelope and produce X-ray radiation through internal dissipation and multi-band afterglow radiation through external dissipation. These signals will be the direct evidence to identify whether a supernova signal is related to the BBH system. However, due to the beaming effect of the jet, the radiation can only be seen within the jet opening angle. In the future, with the development of X-ray and optical sky survey project, the probability of jointly detecting jet related signal together with the supernova signal will be greatly increased.

In principle, each binary evolution formed BBH system would be associated with such a supernova signal that we propose here, but only a small fraction could be identified, depending on the modification degree of the light curve, and essentially depending on the properties of the binary system, such as the orbital separation $d$. Assuming the Ni mass produced in the supernova explosion is $0.5M_{\odot}$, the orbital separation $d$ needs to be smaller than $3.5 \times 10^{13}$ cm $^2$, in order to make the companion

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Figure 1. Examples of SNe lightcurves the accretion feedback power from the companion BH is larger (upper panel) or comparable to (lower panel) the radioactive heating power.
BH feedback larger than the radioactive decay power. From the observation perspective, LVC gives a rough estimation for the event rate density of BBH mergers, e.g. $R = 53.2^{+55.8}_{-28.2}$ Gpc$^{-3}$ yr$^{-1}$ (Abbott et al. 2019). LVC detected BBH systems normally have two black holes with several tens of solar masses. According to the simplest estimation, the initial orbital separation for these systems should be smaller than $1.14 \times 10^{13}$ cm, otherwise the merger delay time would be larger than the Hubble time. Based on this, we can roughly estimate that the event rate density for our proposed special supernova signals would be larger than $53.2^{+55.8}_{-28.2}$ Gpc$^{-3}$ yr$^{-1}$. In future works, systematically searching for these signals from the supernovae archive data to provide their event rate, would be helpful to justify whether the LVC detected BBH systems is indeed originated from binary evolution channel.

We thank Bing Zhang for helpful discussion. This work is supported by the grants No. 11722324, 11690024, 11703001 and 11773010 from the National Natural Science Foundation of China, the Strategic Priority Research Program of the Chinese Academy of Sciences, Grant No. XDB23040100 and the Fundamental Research Funds for the Central Universities. LDL is supported by the National Postdoctoral Program for Innovative Talents (Grant No. BX20190044), China Postdoctoral Science Foundation (Grant No. 2019M660515) and “LiYun” postdoctoral fellow of Beijing Normal University.

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Figure 1. For less massive ejecta, a smaller value of the orbital separation is needed to produce a notable signature.