Mem. S.A.It. Vol. 81, 302
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Memorie della

Observational evidence for stellar mass binary black holes and their coalescence rate

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Abstract. We review the formation scenarios for binary black holes, and show that their coalescence rate depends very strongly on the outcome of the second mass transfer. However, the observations of IC10 X-1, an binary with a massive black hole accreting from a Wolf-Rayet star proves that this mass transfer can be stable. We analyze the future evolution of IC10 X-1 and show that it is very likely to form a binary black hole system merging in a few Gyrs. We estimate the coalescence rate density of such systems to be $0.06\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$, and the detection rate for the current LIGO/VIRGO of $0.69\,\mathrm{yr}^{-1}$, a much higher value than the expected double neutron star rate. Thus the first detection of a gravitational wave source is likely to be a coalescence of a binary black hole.

Key words. Stars: binaries

1. Introduction

Detecting binary black holes (BBH) is extremely difficult. They do not emit significant electromagnetic radiation, like the black holes (BH) in accreting systems. They can only be discovered via their gravitational influence: either through microlensing or through observation of burst of gravitational waves when they coalesce. Microlensing caused by a BBH is an extremely rare event, we know only a few candidates for microlensing through single BHs (Bennett et al. 2002; Mao et al. 2002; Poindexter et al. 2005), and the the microlensing by BBH must be much less frequent. The development of gravitational wave observatories on the other hand is very promising and may lead to detection of a BBH coalescence. The current sensitivity of LIGO and VIRGO interferometers permits to detect a coalescence of a system of two $10\,\mathrm{M}_\odot$ BHs at a distance exceeding 100Mpc (Abbott et al. 2009). The sensitivity of the instruments is being improved which brings us closer to a possibility of detection.

In this paper we investigate discuss the possibility of existence of BBHs. In section 2 we outline the challenge of formation of a BBH from the point of view of binary evolution. In section 3 we summarize the observations of IC10 X-1, and discuss its future evolution. We estimate the merger and detection rate of BBHs based on IC10 X-1 in section 4, and in section 5 we summarize and discuss these results.

2. Challenges in formation of binary black holes

The formation scenario of BBHs has been discussed in the literature by many authors, see e.g. Lipunov et al. (1997a,b); Belczyński et al. (2000); Grishchuk et al. (2001); Belczynski et al. (2007). Here we provide an outline based on the StarTrack binary population synthesis code (Belczynski et al. 2002, 2008).

In order to form a tight BBH with a merger time shorter than the Hubble time we need to start with binary consisting of two massive stars, with the mass above $20\,M_\odot$. They will evolve very quickly and soon one of them, the initially more massive will enter the giant phase. This will lead to a mass transfer that will initially be meta stable but once the mass ration becomes close to unity it will stabilize. After this initial mass transfer the system will consist of a He star - the core of the initially more massive one, and the rejuvenated companion, that has gained a significant amount of mass from the companion. The Helium star evolves further and soon a first BH is formed. Now the system consist of a BH and the companion that will soon become a giant an start transferring mass onto the BH. This ensuing mass transfer is the bottleneck of the BBH formation. The BH has a mass that is typically much smaller than the rejuvenated donor. Therefore the mass transfer is not stable and the system enters a common envelope (CE) phase. The system may survive it yet if the donor has developed a well defined structure of a core and envelope (Taam & Sandquist 2000). The simulations, however, show that the donors do not have that structure and the CE phase leads to a merger rather than formation of a tight binary. However, if a binary manages to survive this mass transfer episode than its further evolution is simple. The donor is stripped of its envelope and it becomes a He star. This star evolves also quickly and explodes forming a second BH. Thus if a system avoids a merger during the second mass transfer than a merging BBH can be formed.

These considerations have been presented by Belczynski et al. (2007). That paper concludes that although BBH are very bright and detectable by gravitational wave interferometers up to very large distances the effective merger rate will be quite low since the formation rate of BBH is extremely small if the system do not survive the CE episode. However, our knowledge of the physics involved in CE evolution is poor and this leads to huge uncertainty in the calculations of formation and merger rates od BBHs. This conclusion was based on the analysis of binary evolution of stars with the solar metallicity. The evolution of metal free star has been considered by Belczynski et al. (2004).

3. IC10 X-1

IC10 has been discovered 120 years ago (Swift 1889). It is an irregular dwarf galaxy at distance approximately 660kpc (Saha et al. 1996; Sakai et al. 1999; Borissova et al. 2000) It has a rather low metallicity of $0.15Z_\odot$ (Lequeux et al. 1979), and it is the only starburst galaxy in the Local Group, with the star formation rate of $0.04 - 0.08\,M_\odot yr^{-1}$ (Hunter & Gallagher 1986). IC10 hosts a very large number of WR stars (Richer et al. 2001; Massey & Holmes 2002), with the surface density of WR star being four times larger than anywhere else in the Local Group even for the regions of highest star formation (Massey & Johnson 1998; Royer et al. 2001; Crowther et al. 2003). The ROSAT X-ray observations (Brandt et al. 1997) revealed several sources, with IC10 X-1 being the brightest.

3.1. Observations and the present state

IC10 X-1 has already been reported to show some X-ray variability in the discovery paper (Brandt et al. 1997). The optical companion has been identified as a WR star MAC92 (Clark & Crowther 2004), with the use of WR star catalogues obtained previously (Massey et al. 1992; Crowther et al. 2003). This preliminary optical identification has been confirmed by a detailed study with the Chandra and Hubble observations (Bauer & Brandt 2004). Further Chandra observations (Wang et al. 2005) have confirmed

the X-ray variability of IC10 X-1: the X-ray flux has been monitored over a period of half a day and it varied systematically by a factor of four. This suggested that IC10 X-1 may be eclipsing accretion powered binary. An analysis of a long time X-ray flux using Chandra data together if the X-ray monitor on board of Swift satellite revealed the orbital period of 32 hours (Prestwich et al. 2007). In this paper the authors analyzed the spectroscopic observations of IC10 X-1 at two different epochs and obtained a lower limit on the radial velocity amplitude. This lead to a preliminary estimate of the mass of the BH in the system. The mass of the WR star was estimated to be at least $17\,M_\odot$. For the inclination of 90 degrees this implied a BH mass of $23\,M_\odot$. For smaller inclinations and higher masses of the WR star the estimate mass of the black hole was larger. Thus, IC10 X-1 hosts one of the most massive stellar BHs known. A few months later a detailed spectroscopic study of this binary lead to measurement of a detailed radial velocity curve (Silverman & Filippenko 2008), and the the analysis in this paper confirms the mass estimate of Prestwich et al. (2007).

Thus IC10 X-1 is a binary consisting of a BH with the mass of at least $23\,M_\odot$ accreting from a WR star with mass of $17\,M_\odot$ or more. If the mass of the WR is larger than the BH is also more massive. For the upper limit on the WR star mass of $35\,M_\odot$ and the smallest possible inclination still allowing for eclipses the estimate of the mass of the BH is $\approx 34\,M_\odot$.

3.2. Future evolution

What will be the future evolution of IC10 X-1 and what are its implications? The WR donor star in the binary is losing mass at through its strong wind. The mass loss rates from WR stars are highly uncertain. They have been estimated with various observation techniques (Nieuwenhuijzen & de Jager 1990; Hamann & Koesterke 2000; Nugis & Lamers 2000). We have estimated the expected mass loss rates from stars in low metallicity environment like the one in IC10 and calculated the final remnant mass as a function of the initial star mass, for details see Belczynski et al. (2009). One clue to the mass loss rates comes from the existence of the BH with the mass of at least $23\,M_\odot$. In order to form such a massive BH the initial star must have been very massive and the winds strength must not have been strong. In fact only the models where the winds a scaled down by at least 50% from the fiducial values REF lead to formation of BHs with the mass exceeding $23\,M_\odot$.

Assuming that the current mass loss rate is not stronger than the one offered for the progenitor of the BH in the system we find that the WR star will lose a few solar masses before it collapses and forms a BH. The mass of the BH formed in this collapse will not differ much from the mass of the collapsing star and will likely be $\approx 13\,M_\odot$, assuming the present mass of $17\,M_\odot$. If the mass of the WR star is larger than the BH will be more massive.

The typical lifetime of a $17\,M_\odot$ WR star is several hundred thousand years, certainly not exceeding 10^6yr. What is remarkable about this binary that it is a system that defies the "bottleneck" problem outlined in section 2. The current mass of the first formed BH is large enough to make the mass transfer from the companion stable. Thus the apparent problem in formation of BBHs outlined above is automatically solved. The system is in a stable mass transfer state after the formation of the first black hole and its companion is likely to form another BH within the next few hundred thousand years.

Also the binary should not be disrupted in the formation of the second BH. First the system is not going to loose a lot of mass when the BH is formed. Second, the kick velocity may be imparted on the newly formed BH. However, numerical estimates of such kicks show that they are smaller than in the case of neutron stars, and may reach at most $150\mathrm{km\,s^{-1}}$. The relative orbital velocity of the components of the binary has been measured to be $\approx 800\mathrm{km\,s^{-1}}$. The kick velocity would have to be larger than that in oder to disrupt the system. Thus the system is not going to be disrupted by the formation of the second BH.

Therefore in a few hundred thousand years IC10 X-1 will evolve into BBH system with the masses of at least $23\,M_\odot$ and $13\,M_\odot$. The orbit

will most likely be similar to the current one, however it may be altered by the natal kick. If the orbit remains the same then the merger time of the BBH binary will be ≈ 3Gyrs. A detailed simulation with the kick velocity drawn from Maxwellian distribution with the width of 150km s^{-1}, has shown that only in 3% of cases the merger time of the BBH exceeds the Hubble time.

4. The binary black hole population

4.1. Estimate of the BBH merger rate density

The estimate of the cosmic merger rate density based on a single object may seem like futile task yet in the field of gravitational wave astronomy this has already been done. The observational estimate of the BNS merger rate depends crucially on the observations of a single object, namely the binary pulsar J0737-3039 (Burgay et al. 2003).

In order to estimate the rate density we need to evaluate the volume in which IC10 X-1 could have been found, as well as the time in which it is observable. In order to estimate the volume we need to analyze critically the crucial observations that led us to the identification of the nature of IC10 X-1, and find the most constraining one. IC10 X-1 was identified as a variable X-ray source, and X-ray observations allowed to determine its orbital period. The second crucial observation was the spectroscopic measurement of the the radial velocity curve. This is the most constraining one: the spectroscopy of star is possible down to the apparent magnitude of $m_V \approx 21$. For a WR with the absolute magnitude of $M \approx -5$ this corresponds to the distance modulus of 25, i.e. the distance of $R_{obs} = 2$Mpc. Thus the volume in which IC10 X-1 is observable is $V_{obs} = 4\pi R_{obs}^3/3 \approx 33.5\,\mathrm{Mpc}^3$. In the following we will assume conservatively that the entire sky has been surveyed for IC10 X-1 like objects. Since IC10 X-1 has been discovered and identified in X-rays, the duration of the X-ray bright phase defined the time it is observable. For IC10 X-1 we assume conservatively that the observability time is equal to the lifetime of the WR star, namely $t_{obs} = 0.5$Myr. Therefore the local formation rate of IC10 X-1 like objects is

$$\mathcal{R} = (V t_{obs})^{-1} = 0.06\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}\,. \quad (1)$$

Since nearly all of the systems that form will merge within the Hubble time this is also the estimate of the merger rate density.

4.2. The expected BBH merger rate

The gravitational wave signal from a coalescing binary in the inspiral phase depends on a single parameter, the chirp mass $\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$, where m_i are the masses of the components of the binary. For a given signal to noise ratio the range up to which a binary can be detected is $D \propto \mathcal{M}^{5/6}$, and thus the volume where binaries can be detected scales as $V_{det} \propto \mathcal{M}^{5/2}$. The chirp mass for the BBH that will form from IC10 X-1 is $\approx 14\,\mathrm{M}_\odot$, while the chirp mass for the double neutron star (DNS) binary consisting of two $1.4\,\mathrm{M}_\odot$ star is $\approx 1.2\,\mathrm{M}_\odot$. Thus the the BBH that forms out of IC10 X-1 from a distance 7.8 times larger than the fiducial DNS binary. For the already finished S5 run of the LIGO detector the detectability range for DNS system was ≈ 18 Mpc, so the detectability distance for a BBH with the chirp mass of $\approx 14\,\mathrm{M}_\odot$ was $D_{BBH} \approx 140$ Mpc. We can now estimate the expected BBH coalescences rate, as the volume observed was $V_{BBH} \approx 11.5 \times 10^6\,\mathrm{Mpc}^3$. Thus the expected detection rate is

$$\mathcal{N} = 0.69 \tilde{D}_{DNS}^3 \tilde{\mathcal{M}}_{BBH}^{5/6} \tilde{R}_{obs}^{-3} \tilde{t}_{obs}^{-1}\,\mathrm{yr}^{-1} \quad (2)$$

where $\tilde{D}_{DNS} = D_{DNS}/18\,\mathrm{Mpc}$, $\tilde{\mathcal{M}}_{BBH} = \mathcal{M}_{BBH}/14.3\,\mathrm{M}_\odot$, $\tilde{R}_{obs} = R_{obs}/2\,\mathrm{Mpc}$, and $\tilde{t}_{obs} = t_{obs}/0.5\,\mathrm{Myr}$. One has to remember that this estimate is based on a single object so in order to be fair we have presented explicitly the scalings. However we will argue below that this estimate of the detection rate should be considered as a conservative lower limit. For a more detailed discussion see Bulik et al. (2008).

5. Conclusions

The detection rate obtained above has to be treated with some caution as it was obtained

with the use of just a single object. However, we must stress that the assumptions made in calculating it are rather conservative. The lifetime of the WR star has been assumed to 0.5 Myr, yet for the higher masses of the star this time is even smaller, which makes the rate density go up. Also we have been quite conservative in determining the detectability distance for IC10 X-1 like binaries. The spectroscopy is difficult even for a WR star at the distance of to IC10, but with the best telescopes available it might be possible up to 2 Mpc. If this distance is actually smaller than the value we have assumed than the estimate of the rate density will also go up. We have also made an assumption that the entire sky has been surveyed for IC10 X-1 like objects. This is also conservative because if the actual volume surveyed was smaller than the rate density has to go up again. We have also neglected the upward correction on the rate due to the fact that IC10 X-1 is an eclipsing binary.

In the calculation of the detection rate we made a crucial assumption that the rate density estimates locally can be extrapolated to the distance of hundreds of Mpc. This is an assumption that is also made in case of estimates of the DNS coalescence detection rate. On the scales of hundreds of Mpc the mean galaxy density may be a little lower than in the Local Group within the distance of 2Mpc, yet the effect cannot be very significant. It may decrease the detection rate by a factor of a few at most. The expected detection rate depends strongly on the estimated chirp mass of the future BBH binary. This in turn depends on the strength of the winds and the amount of wind mass loss from the WR before it forms a BH. However, we have an estimate of the wind from the existence of the massive BH in the system, and also form observations. These two estimates imply that the mass of the compact object to be formed from the WR star should not be small. It should be stressed at this point that the uncertainty in the mass of the BH and the ensuing uncertainty in the chirp mass of the BBH is the most significant source of uncertainty in the estimate of the BBH coalescence rate.

The astrophysical significance of this rate is quite interesting. First, it is much higher than the double neutron star coalescence rate. The rate is so large that the probability of detection in the LIGO S5 and VIRGO VSR1 data is significant. If the data analysis of these observations does not lead to a detection then the upper limits will certainly be very intriguing. The LIGO and VIRGO detectors are operating now with the enhanced sesitivity. Thus, it is likely that the current observational runs of LIGO and VIRGO will finally be awarded with a detection and the first source of gravitational waves will be a coalescing BBH.

6. DISCUSSION

ANDRZEJ ZDZIARSKI: How does the existence of other high mass binaries like. e.g. Cyg X-1, affect this estimate?

TOMASZ BULIK: There are other binaries which may potentially fall in the same category, like Cyg X-1, or NGC300 X-1. Their existence and analysis of their future evolution may only increase the expected BBH rate density. however, before we do that we need unambiguous determination of the present state of these binaries in order to be able to analyze their future evolution.

Acknowledgements. This research has been supported by the MNISW grants 1P03D00530 and N N203 302835. TB is grateful to the hospitality of Observatoire de Paris in Meudon where this paper was written.

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