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Gravitational waves from compact binaries

Marc van der Sluys[1,2]

[1]*Radboud University Nijmegen, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands, sluys@astro.ru.nl*

[2]*Foundation for Fundamental Research on Matter, The Netherlands*

Abstract. In this review, I give a summary of the history of our understanding of gravitational waves and how compact binaries were used to transform their status from *mathematical artefact* to *physical reality*. I also describe the types of compact (stellar) binaries that LISA will observe as soon as it is switched on. Finally, the status and near future of LIGO, Virgo and GEO are discussed, as well as the expected detection rates for the *Advanced* detectors, and the accuracies with which binary parameters can be determined when BH/NS inspirals are detected.

1. Introduction

These are exiting times for gravitational-wave astronomy, both in a negative, but especially in a positive sense. On the one hand, the funding and the future of the LISA mission have become uncertain, and in the best scenario the space mission may be launched with a very different design. On the other hand, the existing ground-based gravitational-wave detectors LIGO and Virgo may not yet have detected any cosmological sources, but the instruments are being upgraded to their *Advanced* status, and may start taking data, possibly detecting gravitational waves for the first time, as soon as 2015. Meanwhile, the LCGT in Japan has its funding approved, and a third LIGO station may be built in Australia. In the next three sections, I will look at the history of our understanding of gravitational waves and the role compact binaries played there, discuss the stellar binaries that LISA will detect as soon as it starts observing, and show the present and future status of the ground-based detectors, the expected detection rates and the accuracies with which parameters can be determined from binary coalescences.

2. A history of compact-binary and gravitational-wave research

2.1. The physical reality of gravitational waves

A natural consequence of Einstein's theory of General Relativity (GR, Einstein 1916a, 1918a) are gravitational waves (GWs, Einstein 1916b, 1918b). These *ripples in space-time* should be generated by accelerated masses in an asymmetric distribution; for example *close binaries* have a quadrupole moment and should be GW sources. However, for a long time there was no consensus on the question whether these waves were mathematical artefacts in the theory, or actual physical phenomena. Sir Arthur Eddington, who was one of the first people to provide evidence for GR from a total solar eclipse in 1919 (Dyson et al. 1920) calculated the radiation reaction of a system of two masses on themselves (Eddington 1922). However, his method was not valid for gravitationally bound systems, and hence the results did not apply to binaries. Attempts to compute the energy released by a binary system suffered from the fact that a coordinate transformation could always be found, such that the energy flux vanishes. Even in the fifties and sixties of the twentieth century predictions were published which claimed that in a close binary, GWs carried away energy (Landau & Lifshitz 1951), transported energy into the system (Havas & Goldberg 1962), carried no energy (Infeld & Plebanski 1960), or any of the above, depending on the coordinate system used (Infeld & Plebanski 1960).

According to Landau & Lifshitz (1951), a circular binary with masses M_1, M_2, orbital separation a and angular velocity ω loses energy at a rate that is given by

$$\frac{dE}{dt} = -\frac{32}{5}\frac{G}{c^5}\left(\frac{M_1 M_2}{M_1 + M_2}\right)^2 a^4 \omega^6. \tag{1}$$

Paczyński (1967) was one of the first authors to realise that one could observe binary systems which undergo mass transfer to prove or disprove the existence of gravitational waves: *"As soon as an adequate theory of evolution of those binaries will be available, an indirect observational check of the existence of gravitational radiation will be possible."* He proposes to measure the change in orbital period of a binary with known parameters and uses Eq.1 to show that this change should amount to

$$\frac{dP}{dt} = -3.68 \times 10^{-6} \frac{M_1 M_2}{(M_1 + M_2)^{1/3}} P_{\rm orb}^{-5/3}, \tag{2}$$

where M_1 and M_2 are expressed in solar masses ($M_\odot$) and the orbital period P in seconds. This means that for a typical binary the cumulative effect from the change in orbital period over one year is more than a few seconds for $P_{\rm orb} < 10^3$ s, and hence could be measured. Earlier that year, Smak (1967) had found that the magnitude of the star HZ 29, which we now call AM CVn, was variable by ~ 0.02 magnitudes over a period of ~ 18 minutes. He hypothesised that the measured periodicity might indicate that it is in fact a binary system. If true, this would mean that $P \equiv P_{\rm orb} \approx 18$ min $\sim 10^3$ s, and it would be interesting to observe this object and look for a systematic change in period.

Paczyński also shows that the merger time for a binary due to GW emission is

$$T_0 = 3.2 \times 10^{-3}\,{\rm yr} \cdot \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} P_{\rm orb}^{8/3} \tag{3}$$

(using the same units as before), that this is equal to the Hubble time for binaries with $P_{\rm orb} \approx 14$ h, and that binaries whose evolution may be affected by angular-momentum loss (AM) due to GWs include W UMa-type binaries (contact binaries), novae and U Gem-type binaries (which we now call *dwarf novae*). The last category contains WZ Sge, with relatively well-measured orbital parameters and mass-transfer (MT) rate. Paczyński concludes that the observed MT rate cannot be explained when constant mass and AM are assumed, and remarks: *"Suppose that the gravitational radiation is physically real [...] the agreement is reasonable."*

Vila (1971) takes the next step and constructs grids of models for the late evolutionary phases of compact binaries that evolve under the influence of AM loss due to gravitational waves. He considers white-dwarf (WD) accretors with a range of masses, and low-mass donors with different compositions, all for $P_{\rm orb} \lesssim 1\,$h. He tabulates the orbital separation, MT rate and age of the systems as a function of donor mass and orbital period, so that they can be used with newly discovered systems. He also applies his models to four observed systems with orbital periods shorter than 1 hr. WZ Sge is still the system with the most-complete observational data, and he shows that the observed MT rate nicely matches his models. He concludes that *"[...] in all cases considered, gravitational radiation was a* sina qua non *for mass transfer."*

2.2. Our understanding of AM CVn, cataclysmic variables and compact X-ray binaries

As we have seen, HZ 29 was known to be a variable star at that time (hence the name change to AM CVn) and suspected to be a binary. The star was already recorded by Malmquist (1936) and noted in Humason & Zwicky (1947, its initial name came from the 29th place the object took in their list) as a *faint and decidedly blue* star. Greenstein & Matthews (1957) obtained spectra for this object, and showed that it has few features, is hydrogen-poor and helium-rich. They concluded that this may be a very faint hot subdwarf, or a white dwarf. Ostriker & Hesser (1968) reanalyse the earlier data, add their own observations, and confirm the periodicity, at $P \approx 17.5$ minutes. However, changing radial velocities, indicative of a binary system, were not found.

The suspected binary nature of AM CVn was confirmed by Warner & Robinson (1972), who performed high-speed photometry and showed that this is an eclipsing system. They propose that AM CVn is a cataclysmic-variable (CV) star in a late stage of its evolution, where all hydrogen has been stripped from the system. The rapid flickering that is observed is then explained by variations in luminosity of the hot spot, caused by changes in the mass-transfer rate. Faulkner et al. (1972) show that combining a prescription for the Roche-lobe radius and Kepler's equation gives

$$P_{\rm orb} \approx 3.83 \times 10^4\,{\rm s} \cdot \left(\frac{\bar{\rho}_{\rm donor}}{\rm g\,cm^{-3}}\right)^{-1/2}. \qquad (4)$$

For AM CVn, this results in $\bar{\rho}_{\rm donor} \approx 1.3 \times 10^3\,{\rm g\,cm^{-3}}$, which indicates that the donor cannot contain hydrogen, in agreement with the lack of H-lines in the spectrum. A helium-main-sequence star would probably dominate the spectrum and give rise to large, measurable orbital velocities, and hence they conclude that the donor of AM CVn must be a low-mass ($\sim 0.04\,M_\odot$), degenerate helium WD. They propose the evolutionary scenario where this is a "dwarf-nova"-type binary, where MT occurs through an accretion disc. The binary was originally detached, but angular-momentum loss due to gravitational-wave emission had shrunk the orbit until MT started. The donor survived the onset of the MT and currently the mass transfer is driven by GWs. Note that gravitational waves play a dominant role in the formation and evolution of this binary, and that, in its essence, this picture still stands today.

Tutukov & Yungelson (1979) constructed analytic evolution models for low-mass close binaries with main-sequence (MS) and degenerate donor stars. They show that some CVs may evolve under the influence of GW emission, but that an additional mechanism for AM loss is needed to explain most CVs (magnetic braking, as we now know), in particular those for which the orbital-evolution timescale $\tau_{\rm orb} \sim P_{\rm orb}/\dot{P}_{\rm orb} \lesssim 10^8\,$yr. In addition, they find that if more than $\sim 10^{-5}$ of all binaries with $P_{\rm orb} \lesssim 10\,$h have two degenerate members, the double-degenerate binaries, rather than the W UMa-systems, will dominate the detectable GW spectrum.

Finally, an important piece of our understanding about a different class of potential gravitational-wave sources, that of the *ultracompact X-ray binaries* (UCXBs), was published by Pringle & Webbink (1975). They devised a model to explain the variable X-ray source Ariel 1118–61, which was discovered a few months earlier with the Ariel V satellite (Ives et al. 1975). Pringle & Webbink assumed that the periodicity of 6.75 minutes was due to an orbital motion and proposed a model in which a white dwarf transfers mass to a neutron star (NS). Using this model, they estimate that the mass of the WD donor would be $\sim 0.12\,M_\odot$, and that the MT rate is on the order of $10^{-7}\,M_\odot$/yr. The authors admit that the orbital origin of the periodicity is uncertain and that rotation or pulsation may also be responsible. Indeed, it is now thought that the system is a high-mass X-ray binary (Chevalier & Ilovaisky 1975; Janot-Pacheco et al. 1981), where the 6.75-minute periodicity is due to the slow rotation of the NS (*e.g.* Maraschi et al. 1976). However, even though the assumption by Pringle & Webbink (1975) of an orbital cause for the periodicity does not apply to this particular source, their scenario is currently the canonical model to explain the formation and evolution of ultracompact X-ray binaries.

3. Observing galactic binaries with LISA

The *Laser Interferometer Space Antenna* (LISA) is a proposed space mission to detect low-frequency gravitational waves. The mission should consist of three spacecraft in a triangular configuration, with arm lengths of $\sim 5 \times 10^6$ km. The constellation would be in an orbit around the Sun, trailing the Earth by about 20°. Laser beams between the spacecraft should measure minute changes in their separations, and thus detect GWs. In its current design, LISA should be sensitive to frequencies between roughly 0.1 mHz and 0.1 Hz, corresponding to binary orbital periods between 20 s and 5 hours. There are a number of classes of galactic binaries that LISA could (and should!) observe. These include *detached binaries* — double white dwarfs, WD-NS binaries, and double NSs, as well as *interacting binaries* — CVs, AM CVn stars, UCXBs, each of which will be discussed in more detail below. These so-called *LISA verification binaries* should be detected as soon as LISA observations begin, and should help us to understand the instrument (Stroeer & Vecchio 2006). Basic observed properties for the main types of verification binaries are listed in Table 1 and the expected GW frequency and amplitude of the binaries with relatively well-known parameters are shown in Fig. 1.

Table 1. Observed properties of LISA verification binaries (Nelemans 2011).

Type	Number	P (min)	$M_1 (M_\odot)$	$M_2 (M_\odot)$	d (pc)
AM CVn	25	5.4 – 65.1	0.55 – 1.2	0.006 – 0.27	100 – 3000
CVs	6	59 – 85	$\gtrsim 0.7$	0.10 – 0.15	43 – 200
DWDs	5	60 – 200	0.2 – 0.6		100 – 1100
UCXBs	5	11 – 20	~ 1.4?	0.03 – 0.06	5000 – 12000

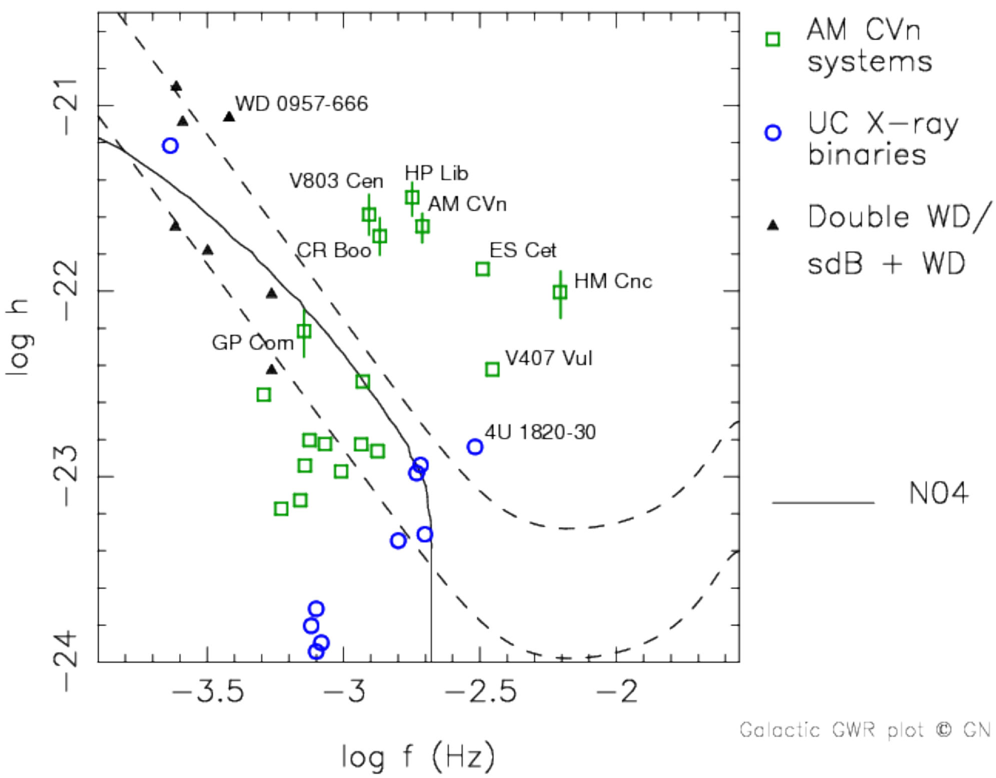

Figure 1. GW frequencies f and strain amplitudes h for the LISA verification binaries. This is an updated version of Fig. 2 from Nelemans (2009) (Nelemans, private communication). Data are collected in Nelemans (2011). Only the systems for which errors are reliably known have error bars in h. The dashed lines show the LISA instrumental noise for an SNR of 1 and 5, the solid line is the Galactic foreground noise from Nelemans et al. (2004).

Observations with LISA will improve our astrophysical understanding of compact-binary evolution and binary interaction, including the still poorly understood common-envelope (CE) or envelope-ejection phase (Webbink 1984; Taam & Sandquist 2000; Nelemans et al. 2000; van der Sluys et al. 2006) which allows the dramatic shrinkage of a binary orbit that seems necessary to produce compact binaries. LISA will shed light on the evolution of the progenitors of type-Ia supernovae, and on the evolution of the massive binaries that are the progenitors of BH/NS binaries.

3.1. Double white dwarfs

Double white dwarfs (DWDs) are the most abundant sources for LISA. Since WDs are the most common end points for the evolution of single stars, DWDs play that role for binaries. Yu & Jeffery (2010) find that LISA can detect $\sim 3\times10^8$ DWDs, of which only $\sim 3\times10^4$ can be resolved, with orbital periods between ~ 7 and 24 min. Hence, most of these systems act as a source of *foreground noise*, the solid line in Fig. 1 (Nelemans et al. 2004). Of all these predicted binaries, several tens have been observed (*e.g.* Saffer et al. 1988; Marsh 1995; Kilic et al. 2011), but so far only a few systems have been found that emit gravitational waves in the LISA frequency band (Nelemans 2011).

According to Yu & Jeffery (2010), about 60% of the DWD systems that LISA can resolve are helium-helium DWDs, followed by nearly 40% CO-He DWDs. Their models suggest that while two thirds of all systems in the Galaxy must have formed through two episodes of a common envelope, no less than 97% of the DWD binaries that LISA observes should have been formed through this channel. Liu et al. (2010) find over 10^4 resolvable DWDs, 67% of which are He-He DWDs and most of the rest CO-He DWDs. All resolvable DWDs are produced through the double-CE channel in their study. Observing resolvable double white dwarfs with LISA will therefore prove a severe test for our understanding of the outcome of CEs for these systems, for which there are still many uncertainties (*e.g.* Nelemans et al. 2000; van der Sluys et al. 2006; Webbink 2008).

3.2. Cataclysmic variables

Cataclysmic variables (see Warner (1995), and the proceedings by Knigge elsewhere in this volume) are low-mass semidetached binaries with a white-dwarf accretor. In a typical CV, the donor star has a mass that is lower than that of the WD, is unevolved (typically main sequence) and has a convective envelope. Common envelopes generally play an important role in the formation of CVs, and their evolution during the CV stage is dominated by angular-momentum loss, either through *magnetic braking* (MB) for systems with $P_{\rm orb} \gtrsim 3$ h, or through a combination of gravitational-wave emission and reduced MB for systems with $P_{\rm orb} \lesssim 3$ h when donors have become fully convective.

CVs are expected to reach a minimum orbital period at $\sim 65-70$ min, after which the orbit starts expanding again. Because of this reversal in orbital evolution, one would expect to find an accumulation of CVs around this period (Barker & Kolb 2003). Indeed, such a peak in the distribution has now been found, albeit at a period of $\sim 80-86$ min (Gänsicke et al. 2009). A small number of known CVs may be observable by LISA (Meliani et al. 2000; Nelemans 2011) at the low-frequency end of the spectrum. However, the poorly constrained masses and distances make it difficult to compute GW amplitudes. A few CVs are included as triangles (together with the double WDs) in Fig. 1.

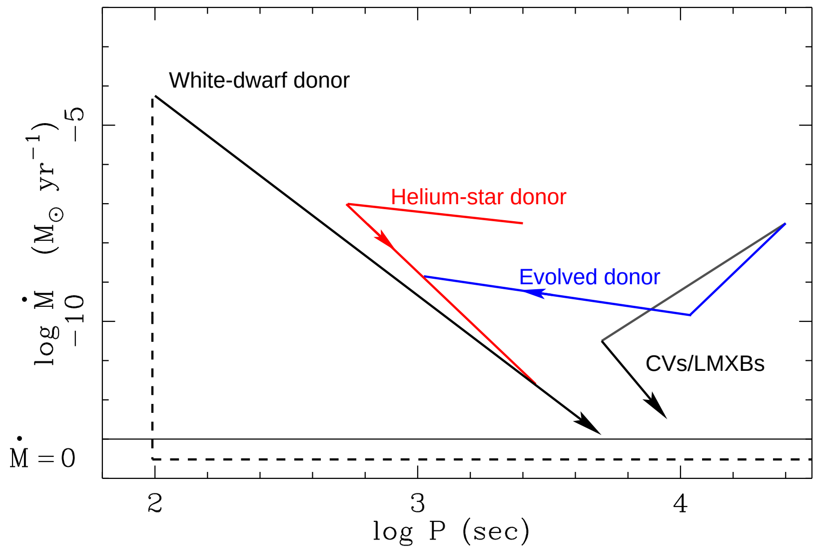

Figure 2. Formation scenarios for AM CVn stars and UCXBs in the $\log P_{\rm orb}$ – $\log \dot{M}$ plane: systems with WD donors have expanding orbits and decreasing MT rates from the moment MT starts and evolve from the upper-left to the lower-right of the diagram. Helium-star donors and evolved MS donors reach different minimum periods and can be observed with negative or positive $\dot{P}_{\rm orb}$. All three scenarios overlap at long $P_{\rm orb}$, the He-star and evolved MS donors evolve in an identical way for most of the expanding phase. CVs and 'normal' LMXBs never reach ultrashort periods. For more details, see Fig. 1 in Nelemans et al. (2010).

3.3. AM CVn systems

AM CVn systems are binaries with white-dwarf accretors, like CVs, but with shorter ($P_{\rm orb} \lesssim 65$ min) orbital periods and hydrogen-poor, helium-rich spectra (Warner 1995; Solheim 2010). The absence of hydrogen in the donor envelopes allows for smaller donor stars, hence shorter orbital periods. AM CVn stars are the most important guaranteed LISA sources (see Fig. 1).

There are three possible donor types for AM CVn stars, hence three different formation channels (see Fig. 2), each of which involves at least one common envelope. The *white-dwarf channel* involves two WDs which were brought into a short orbit through a CE, after which angular-momentum losses shrank the orbit sufficiently for mass transfer to start (Paczyński 1967). Mass transfer starts at orbital periods of a few minutes, and from that moment on the orbits expand while the MT rates decrease (see Fig. 2). In the *helium-star channel* (Savonije et al. 1986; Tutukov & Fedorova 1989), the donor is a non-degenerate remnant after the CE, and MT starts at longer orbital periods. For these systems, the orbit shrinks and the MT rate increases in the first part of the evolution as an AM CVn star until a minimum period is reached, after which the period becomes longer while the MT rate decreases. The *evolved main-sequence channel* may be a third formation channel, where an evolved donor fills its Roche lobe at a finely tuned moment, forming a CV for which a combination of MB and gravitational-wave AM loss leads to ultrashort periods (Tutukov et al. 1985; Podsiadlowski et al. 2003). The donor star may or may not have (a detectable amount of) hydrogen left in the ultracompact stage (Nelemans et al. 2010).

In the last half decade or so, the systematic search for hydrogen-poor spectra with strong helium lines, or for peculiar colours, has yielded more than ten new ultracompact systems (Anderson et al. 2005, 2008; Roelofs et al. 2005, 2009; Rau et al. 2010). Currently about 25 AM CVn systems are known (Solheim 2010). The binary with the shortest orbital period currently known is HM Cnc, with $P_{\rm orb} \approx 5.4$ min (Burwitz & Reinsch 1999; Ramsay et al. 2002; Roelofs et al. 2010). At very short orbital periods ($P_{\rm orb} \lesssim 10$ min) there is no room in the binary for an accretion disc, and the mass-accretion stream impacts directly onto the WD surface, thereby producing X-rays. If the mass-transfer rate remains high, helium novae are expected to occur (Kato et al. 1989). Indeed, such a nova was found for V445 Puppis (Kato & Hachisu 2003; Woudt et al. 2009). Bildsten et al. (2007) predict that for AM CVns with a CO WD donor undergoing helium novae, the flashes become stronger as the orbital period increases and the MT rate decreases, until the last flash has a sufficiently high helium-shell mass that a faint thermonuclear supernova can occur. Since these events look like type-Ia supernovae, but only have $\sim 10\%$ of their luminosity, they were dubbed "type-.Ia supernovae". The supernova SN 2002bj may be the first observed member of this class (Poznanski et al. 2010).

3.4. Ultracompact X-ray binaries

Ultracompact X-ray binaries are to low-mass X-ray binaries (LMXBs, see the review by Charles elsewhere in this volume) what AM CVn stars are to CVs: their ultrashort-period and hydrogen-poor cousins. In a typical UCXB, a neutron star accretes from a white-dwarf donor, in a binary with an orbital period of less than an hour or so. In Sect.2.2 we saw that this canonical formation scenario was developed by Tutukov & Yungelson (1979) and is very similar to that of AM CVn stars with WD donors. Apart from the *white-dwarf donor* channel for UCXBs, an *evolved main-sequence donor* channel was proposed by Podsiadlowski et al. (2002), where the donor fills its Roche lobe near the end of the MS, and the system evolves to ultrashort periods under the influence of angular-momentum loss due to strong magnetic braking and gravitational-wave emission. This model was put forward in particular to explain the observed negative $\dot{P}_{\rm orb}$ of the 11-minute system 4U 1820–30 in the globular cluster NGC 6624 (van der Klis et al. 1993). However, van der Sluys et al. (2005a,b) showed that this scenario depends on very strong MB, and requires extremely fine-tuned initial conditions, so that it is unlikely to happen in nature. Since this binary is in a globular cluster, a dynamical formation scenario is more likely, and seems to explain the overabundance of UCXBs in globular clusters (Ivanova et al. 2005; Lombardi et al. 2006; Voss & Gilfanov 2007). Meanwhile, the negative period derivative of 4U 1820–30 is not yet explained, even with sophisticated models including a triple system, tidal dissipation and resonant trapping (see Prodan, elsewhere in these proceedings).

While (especially accretor) masses are somewhat higher in UCXBs than in AM CVn systems, the former are less common and hence one would expect a smaller contribution from UCXBs to the LISA sources.

3.5. Neutron-star and black-hole binaries

Compact binaries where each member is a neutron star or black hole are the main targets for LIGO/Virgo (see Sect. 4.2), but they may be detected earlier in their evolution — when still at longer orbital periods — with LISA as well. These objects are much rarer than the white-dwarf binaries, and their formation rates, as well as their merger rates, are very uncertain, especially for systems containing BHs (see Sect. 4.2.2 below, Abadie et al. 2010c, and references therein). In this class of binaries, only eight double NSs are currently known, and only one of those (PSR J0737–3039, see below) has a frequency that lies in the LISA band (the low-frequency, high-amplitude circle in Fig. 1). In total, several tens of these systems may be observable with LISA (*e.g.* Nelemans et al. 2001), and our understanding of the evolution of massive binaries can improve appreciably by combining these observations with those of LIGO and Virgo at the merger state.

Of special interest as tests of general relativity are the double-NS binaries containing a pulsar. The first of these binaries discovered is the well-known *Hulse-Taylor pulsar* PSR B1913+16 (Hulse & Taylor 1975). The presence of the pulsar in this system allows its masses and orbital parameters to be determined to great accuracy. In particular, the orbital decay that has been measured over the last three decades agrees extremely well with that predicted by GR (*e.g.* Weisberg et al. 2010). In 2003, the millisecond pulsar PSR J0737–3039 was discovered and it was found to be in a 2.4-hour orbit with another NS, indicating that the merger time was only 85 Myr (Burgay et al. 2003). The discovery that the secondary star in this system is also a pulsar (Lyne et al. 2004) confirmed that the companion is indeed a NS and opened the way to even more stringent tests of GR. Kramer et al. (2006) and Breton et al. (2008) report accurate measurements of the mass ratio, Shapiro delay, periastron advance, orbital decay, gravitational redshift and spin precession. Each of these quantities predicts an allowed region in the $M_1 - M_2$ plane, and *all* these regions overlap in a very narrow location in that plane. Hence, these systems are consistent with GR to very high precision, and indicate that we understand the production of gravitational waves, at least in the weak GR regime.

4. Detecting binary inspirals with LIGO, Virgo and GEO

4.1. Status of the detectors

4.1.1. Current status

LIGO (Laser Interferometer Gravitational-wave Observatory, Sigg & the LIGO Scientific Collaboration 2008), Virgo (Acernese et al. 2008) and GEO (Willke et al. 2004) are ground-based, (sub)kilometre-scale laser interferometers designed to detect high-frequency (10s to 1000s of Hz) GWs. LIGO consists of three Michelson interferometers, two colocated detectors with 4-km and 2-km arms sharing a vacuum enclosure in Hanford, Washington, U.S.A., and a 4-km interferometer in Livingston, Louisiana, U.S.A. In Europe, Virgo has 3-km arms and is located near Pisa, Italy, GEO-600, near Hannover, Germany, has arms with a length of 600 m. The detectors have performed several science runs, and the LIGO and Virgo collaborations have been sharing their data since 2007, creating a detector network with independent detectors in four different locations. Because a single interferometer has no direction sensitivity, a network of (non-colocated) detectors is needed to derive the source position from the difference in arrival time between the detectors.

Because of the higher frequencies they are sensitive to, LIGO and Virgo are searching for different sources than LISA. Currently, four working groups monitor *the stochastic GW background* (remnants from the Big Bang; Abbott et al. 2009e,a), *continuous waves* ("pulsars with hills"; Abbott et al. 2008; The LIGO Scientific Collaboration et al. 2011), "unmodelled" *bursts* (core-collapse supernovae, perhaps gamma-ray bursts; Abbott et al. 2009b, 2010) and *compact binary coalescences* (BH/NS-binary inspirals and mergers; Abadie et al. 2010a, 2011). The last category of events is the most relevant one for this binary conference, and I will focus on the binary inspirals in Sect. 4.2.

4.1.2. Near-future detectors

Since the existing observatories in Europe and the U.S.A. are only very limited in their coverage of the globe, plans to build a detector in the southern hemisphere have existed for some time. This year (2011), a decision will be made whether a third LIGO station (LIGO South) will be built in Australia. Western Australia is indeed one of the best locations on Earth to build a detector that is complementary to the existing network, improving the accuracy of the sky localisation with a factor of ~ 4 and that of the distance and inclination more moderately (Aylott et al. 2011). In addition, in late 2010 funding was approved to build the Large-scale Cryogenic Gravitational-wave Telescope (LCGT) in Japan (Kuroda & the LCGT Collaboration 2010). This detector will be built underground, have 3-km arms, use cryogenic suspension and could take its first data in 2016. Where LIGO South can improve direction sensitivity in the north-south direction, LCGT will do the same in the east-west direction.

Meanwhile, the *initial* LIGO and Virgo detectors are being upgraded to *Advanced* LIGO/Virgo (*e.g.* Smith & the LIGO Scientific Collaboration 2009; Harry & the LIGO Scientific Collaboration 2010). The detectors will become about ten times more sensitive, resulting in a $\sim 1000\times$ higher detection rate (see Sect. 4.2.2). At the same time, the seismic isolation will be improved, decreasing the lower limit of the sensitivity band from 40 Hz to 10 Hz. This will allow a much longer monitoring time of the inspiral phase (10–15 min instead of 25 s for a NS-NS system, 35 s rather than 1 s for a $10 + 10\,M_\odot$ BH-BH system), and the detection of many more GW cycles, especially for high-mass systems, before the binary merges, resulting in a more accurate parameter estimation. The instruments are currently under construction, and the first science data is expected to be taken in 2015, although it may take more time to reach designed sensitivity. The first direct detection of GWs may also take place around that time, although predicted detection rates have large uncertainties (see Sect. 4.2.2 and Table 2). While LIGO and Virgo are being upgraded, GEO will be used as a testbed for the new technology that is being developed, and will meanwhile keep taking data when possible.

4.2. Compact-binary coalescences

LIGO and Virgo are sensitive to the last seconds to minutes of the *inspiral*, and to the *merger* of compact binaries consisting of neutron stars and/or black holes, as well as to the *ringdown* (Abbott et al. 2009c) of the resulting BHs.

4.2.1. Detections so far

Despite the promising title of this section, searches for compact binary coalescences (CBCs) in the first LIGO/Virgo science runs have *not* resulted in the detection of gravitational waves (Abbott et al. 2009d; Abadie et al. 2010b, 2011). The low-mass (binary masses of $2 - 35\,M_\odot$) CBC search in the combined LIGO Science Run 5/Virgo Science Run 1 (S5/VSR1) took place from May to September 2007. The horizon distances for NS-NS ($1.35 + 1.35\,M_\odot$), BH-NS ($5.0 + 1.35\,M_\odot$) and BH-BH ($5.0 + 5.0\,M_\odot$) coalescences were about 30, 50 and 90 Mpc, respectively, during this run. From the fact that no detection was made, upper limits for the event rates were derived for the three types of binaries of $\sim 9 \times 10^{-3}\,\mathrm{yr}^{-1}$, $\sim 2 \times 10^{-3}\,\mathrm{yr}^{-1}$ and $\sim 5 \times 10^{-4}\,\mathrm{yr}^{-1}$ per Milky-Way-equivalent galaxy. This means that the observations have started to constrain the most optimistic models by about an order of magnitude (Abadie et al. 2010b).

4.2.2. Predicted horizon distances and detection rates

The horizon distances and predicted detection rates for NS-NS, BH-NS and BH-BH coalescences for Initial and Advanced LIGO/Virgo, obtained by collecting a number of population-synthesis models, are compared and discussed in detail in Abadie et al. (2010c). A very brief summary of the results in that study, taken from their Table V, is shown in Table 2. While horizon distances are fairly firm (they are based on the assumption that the design sensitivity will be met), the predicted detection rates range over about three orders of magnitude between the different population-synthesis studies. The reason for this "poor performance" is the fact that there are large uncertainties about the formation of NSs and BHs, in part because only a small number of NS-NS, and no BH-NS and BH-BH binaries have been observed (see Sect. 3.5). Hence, apart from the range of values found in the literature, a most likely rate is quoted as well. The table shows that for the *Initial detectors*, a single detection would have been allowed for the most optimistic estimate, whereas the most likely value suggests about one detection in 30 years, for all types of binaries combined. For the *Advanced detectors*, the sensitivity will be about ten times higher, so that the detection volume is increased by a factor of ~ 1000 (the detected amplitude falls off as d^{-1}), as is the detection rate. For the Advanced detectors, the predictions range between one detection per year and five detections per day, with a most likely rate of one per five days, for all binary types and once the designed sensitivity has been reached. This is a very promising picture indeed!

Table 2. Horizon distances and predicted detection rates for Initial and Advanced LIGO/Virgo, assuming $M_{\mathrm{NS}} = 1.4\,M_\odot$ and $M_{\mathrm{BH}} = 10.0\,M_\odot$. Source: Abadie et al. (2010c), Table V.

Horizon distances (Mpc)	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo	33	70	161
Advanced LIGO/Virgo	445	927	2187

Detection rates (yr^{-1})	NS-NS	BH-NS	BH-BH
Initial LIGO/Virgo: range	2×10^{-4} – 0.2	7×10^{-5} – 0.1	2×10^{-4} – 0.5
Initial LIGO/Virgo: most likely	0.02	0.004	0.007
Advanced L/V: range	0.4 – 400	0.2 – 300	0.4 – 1000
Advanced L/V: most likely	40	10	20

4.2.3. Parameter estimation

After a detection has been made, one would like to extract the binary parameters from the signal. Because of the high dimensionality of the parameter space, Bayesian methods are used for *model selection* (*i.e.*, which model describes the signal best; Veitch &

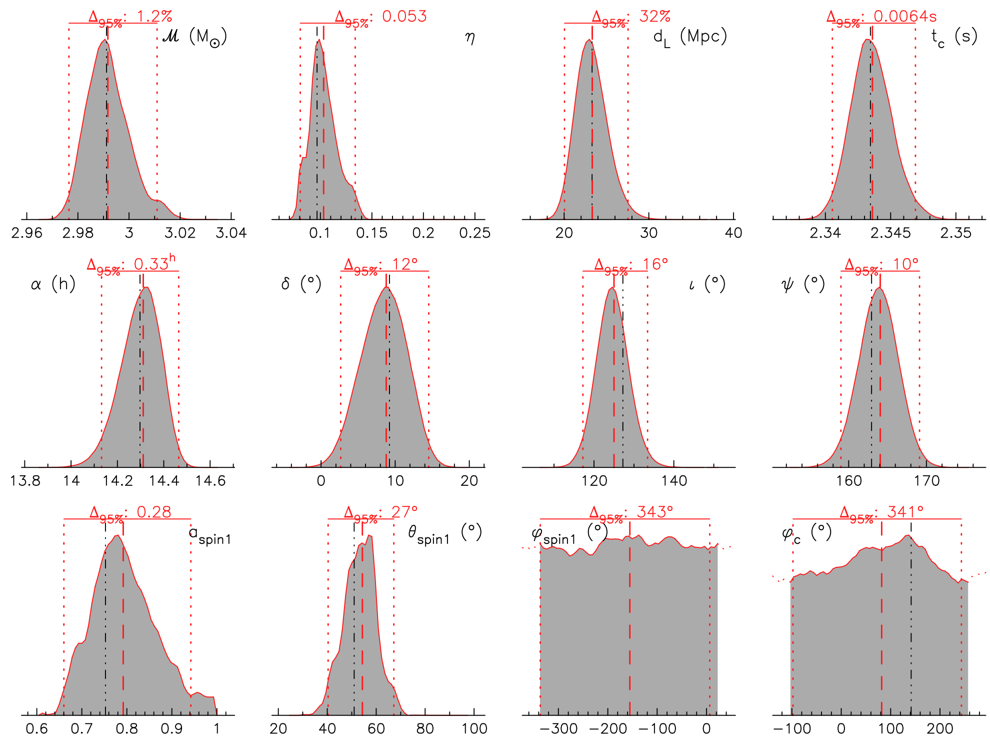

Figure 3. Posterior PDFs for parameter estimation on a simulated signal from a BH-NS ($10.0 + 1.4\,M_\odot$) inspiral at a distance of 22.4 Mpc, using the two 4-km LIGO detectors and Virgo, and Gaussian noise. The BH has 80% of its critical spin, and the network SNR is 17.0. The 12 parameters are chirp mass ($\mathcal{M}$), symmetric mass ratio (η), distance (d_L), time of coalescence (t_c), sky position (α, δ), inclination (ι), polarisation angle (ψ), BH spin magnitude, tilt and phase ($a_{spin1}, \theta_{spin1}, \varphi_{spin1}$) and orbital phase ($\varphi_c$). Dash-dotted lines are the true parameter values, dashed lines are median values and the dotted lines marked with $\Delta_{95\%}$ indicate the 95% ("2σ") probability ranges. Numbers at the top show the accuracy for each parameter. The figure is adapted from van der Sluys et al. (2008).

Vecchio 2008; Aylott et al. 2009) and *parameter estimation* (Röver et al. 2006, 2007; van der Sluys et al. 2008; Raymond et al. 2010; Aylott et al. 2011). For parameter estimation a *Markov-chain Monte-Carlo* method is used, which results in a multidimensional (9D for non-spinning binary members, 12D when allowing one spinning member, and 15D when both objects may be spinning) posterior probability-density function (PDF), from which *best values* for the parameters can be derived, as well as the *accuracies* of those values and *correlations* between the parameters. An example result of parameter estimation on a BH-NS signal as would be detected by LIGO/Virgo is shown in Fig. 3. Although the recovered sky position is far from accurate for electromagnetic (EM) standards, the masses of the two objects and the spin of the BH can be determined fairly well. In addition, the distance and orientation (ι, ψ) can be determined directly, which is often difficult or impossible in the case of an EM detection. The poor sky localisation of the source means that it may be difficult to provide accurate sky positions for rapid EM follow-up. However, combined with the accurate timing it may not be difficult to identify a GW event with *e.g.* the EM detection of a gamma-ray burst.

5. Conclusions

Gravitational waves are a physical reality (since ~ the 1960's/70's), can bring detached binaries to Roche-lobe overflow and can influence or drive mass transfer in compact binaries. LISA should fly and will see CVs, AM CVn stars, UCXBs, BH/NS binaries and *many* DWDs. LIGO and Virgo have been up, running and observing for a few years, have not found any (cosmological) sources yet, but will detect between one source per year and a few sources per day once the Advanced detectors are working.

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References

Abadie, J., Abbott, B. P., Abbott, R., & al. 2010a, ApJ, 715, 1453
— 2010b, Phys.Rev.D, 82, 102001
— 2010c, CQG, 27, 173001
— 2011, Phys.Rev.D, 83, 122005
Abbott, B., Abbott, R., Adhikari, R., Ajith, P., Allen, B., & al. 2008, ApJL, 683, L45
— 2009a, Phys.Rev.D, 80, 062002
— 2009b, Phys.Rev.D, 80, 102001
— 2009c, Phys.Rev.D, 80, 062001
— 2009d, Phys.Rev.D, 79, 122001
Abbott, B. P., Abbott, R., Acernese, F., Adhikari, R., Ajith, P., Allen, B., Allen, G., Alshourbagy, M., Amin, R. S., Anderson, S. B., & et al. 2009e, Nat, 460, 990
— 2010, ApJ, 715, 1438
Acernese, F., Alshourbagy, M., & al. 2008, CQG, 25, 184001
Anderson, S. F., Becker, A. C., Haggard, D., Prieto, J. L., & al. 2008, AJ, 135, 2108
Anderson, S. F., Haggard, D., Homer, L., Joshi, N. R., Margon, B., & al. 2005, AJ, 130, 2230
Aylott, B., Farr, B., Kalogera, V., Mandel, I., Raymond, V., Rodriguez, C., van der Sluys, M., Vecchio, A., & Veitch, J. 2011, Physical Review D, submitted. arXiv:1106.2547
Aylott, B., Veitch, J., & Vecchio, A. 2009, CQG, 26, 114011
Barker, J., & Kolb, U. 2003, MNRAS, 340, 623
Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJL, 662, L95
Breton, R. P., Kaspi, V. M., Kramer, M., McLaughlin, M. A., Lyutikov, M., Ransom, S. M., Stairs, I. H., Ferdman, R. D., Camilo, F., & Possenti, A. 2008, Science, 321, 104
Burgay, M., D'Amico, N., Possenti, A., Manchester, R. N., Lyne, A. G., Joshi, B. C., McLaughlin, M. A., Kramer, M., Sarkissian, J. M., Camilo, F., Kalogera, V., Kim, C., & Lorimer, D. R. 2003, Nat, 426, 531
Burwitz, V., & Reinsch, K. 1999, in Astronomische Gesellschaft Abstract Series, edited by R. E. Schielicke, vol. 15 of Astronomische Gesellschaft Abstract Series, 27
Chevalier, C., & Ilovaisky, S. A. 1975, IAUC, 2778, 1
Dyson, F. W., Eddington, A. S., & Davidson, C. 1920, Royal Society of London Philosophical Transactions Series A, 220, 291
Eddington, A. S. 1922, Royal Society of London Proceedings Series A, 102, 268
Einstein, A. 1916a, Annalen der Physik, 354, 769
— 1916b, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), Seite 688-696., 688
— 1918a, Annalen der Physik, 360, 241

— 1918b, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), Seite 154-167., 154
Faulkner, J., Flannery, B. P., & Warner, B. 1972, ApJL, 175, L79+
Gänsicke, B. T., Dillon, M., Southworth, J., Thorstensen, J. R., Rodríguez-Gil, P., Aungwerojwit, A., Marsh, T. R., Szkody, P., Barros, S. C. C., Casares, J., de Martino, D., Groot, P. J., Hakala, P., Kolb, U., Littlefair, S. P., Martínez-Pais, I. G., Nelemans, G., & Schreiber, M. R. 2009, MNRAS, 397, 2170
Greenstein, J. L., & Matthews, M. S. 1957, ApJ, 126, 14
Harry, G. M., & the LIGO Scientific Collaboration 2010, CQG, 27, 084006
Havas, P., & Goldberg, J. N. 1962, Physical Review, 128, 398
Hulse, R. A., & Taylor, J. H. 1975, ApJL, 195, L51
Humason, M. L., & Zwicky, F. 1947, ApJ, 105, 85
Infeld, L., & Plebanski, J. 1960, Motion and relativity (Pan. Wyd. Naukowe)
Ivanova, N., Rasio, F. A., Lombardi, J. C., Jr., Dooley, K. L., & Proulx, Z. F. 2005, ApJL, 621, L109
Ives, J. C., Sanford, P. W., & Bell Burnell, S. J. 1975, Nat, 254, 578
Janot-Pacheco, E., Ilovaisky, S. A., & Chevalier, C. 1981, A&A, 99, 274
Kato, M., & Hachisu, I. 2003, ApJL, 598, L107
Kato, M., Saio, H., & Hachisu, I. 1989, ApJ, 340, 509
Kilic, M., Brown, W. R., Allende Prieto, C., Agüeros, M. A., Heinke, C., & Kenyon, S. J. 2011, ApJ, 727, 3
Kramer, M., Stairs, I. H., Manchester, R. N., McLaughlin, M. A., Lyne, A. G., Ferdman, R. D., Burgay, M., Lorimer, D. R., Possenti, A., D'Amico, N., Sarkissian, J. M., Hobbs, G. B., Reynolds, J. E., Freire, P. C. C., & Camilo, F. 2006, Science, 314, 97
Kuroda, K., & the LCGT Collaboration 2010, CQG, 27, 084004
Landau, L., & Lifshitz, E. 1951, The Classical Theory of Fields (Addison-Wesley, Cambridge, Mass)
Liu, J., Han, Z., Zhang, F., & Zhang, Y. 2010, ApJ, 719, 1546
Lombardi, J. C., Jr., Proulx, Z. F., Dooley, K. L., Theriault, E. M., Ivanova, N., & Rasio, F. A. 2006, ApJ, 640, 441
Lyne, A. G., Burgay, M., Kramer, M., Possenti, A., Manchester, R. N., Camilo, F., McLaughlin, M. A., Lorimer, D. R., D'Amico, N., Joshi, B. C., Reynolds, J., & Freire, P. C. C. 2004, Science, 303, 1153
Malmquist, K. G. 1936, Stockholms Observatoriums Annaler, 12, 7
Maraschi, L., Treves, A., & van den Heuvel, E. P. J. 1976, Nat, 259, 292
Marsh, T. R. 1995, MNRAS, 275, L1
Meliani, M. T., de Araujo, J. C. N., & Aguiar, O. D. 2000, A&A, 358, 417
Nelemans, G. 2009, CQG, 26, 094030
— 2011. URL http://www.astro.ru.nl/~nelemans/dokuwiki/doku.php?id=verification_binaries:intro
Nelemans, G., Verbunt, F., Yungelson, L. R., & Portegies Zwart, S. F. 2000, A&A, 360, 1011
Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. 2001, A&A, 375, 890
— 2004, MNRAS, 349, 181
Nelemans, G., Yungelson, L. R., van der Sluys, M. V., & Tout, C. A. 2010, MNRAS, 401, 1347
Ostriker, J. P., & Hesser, J. E. 1968, ApJL, 153, L151+
Paczyński, B. 1967, AcA, 17, 287
Podsiadlowski, P., Han, Z., & Rappaport, S. 2003, MNRAS, 340, 1214
Podsiadlowski, P., Rappaport, S., & Pfahl, E. D. 2002, ApJ, 565, 1107
Poznanski, D., Chornock, R., Nugent, P. E., Bloom, J. S., Filippenko, A. V., Ganeshalingam, M., Leonard, D. C., Li, W., & Thomas, R. C. 2010, Science, 327, 58
Pringle, J. E., & Webbink, R. F. 1975, MNRAS, 172, 493
Ramsay, G., Hakala, P., & Cropper, M. 2002, MNRAS, 332, L7
Rau, A., Roelofs, G. H. A., Groot, P. J., Marsh, T. R., Nelemans, G., Steeghs, D., Salvato, M., & Kasliwal, M. M. 2010, ApJ, 708, 456

Raymond, V., van der Sluys, M. V., Mandel, I., Kalogera, V., Röver, C., & Christensen, N. 2010, CQG, 27, 114009
Roelofs, G. H. A., Groot, P. J., Marsh, T. R., Steeghs, D., Barros, S. C. C., & Nelemans, G. 2005, MNRAS, 361, 487
Roelofs, G. H. A., Groot, P. J., Steeghs, D., Rau, A., de Groot, E., Marsh, T. R., Nelemans, G., Liebert, J., & Woudt, P. 2009, MNRAS, 394, 367
Roelofs, G. H. A., Rau, A., Marsh, T. R., Steeghs, D., Groot, P. J., & Nelemans, G. 2010, ApJL, 711, L138
Röver, C., Meyer, R., & Christensen, N. 2006, CQG, 23, 4895
— 2007, Phys.Rev.D, 75, 062004
Saffer, R. A., Liebert, J., & Olszewski, E. W. 1988, ApJ, 334, 947
Savonije, G. J., de Kool, M., & van den Heuvel, E. P. J. 1986, A&A, 155, 51
Sigg, D., & the LIGO Scientific Collaboration 2008, Classical and Quantum Gravity, 25, 114041
Smak, J. 1967, AcA, 17, 255
Smith, J. R., & the LIGO Scientific Collaboration 2009, CQG, 26, 114013
Solheim, J.-E. 2010, PASP, 122, 1133
Stroeer, A., & Vecchio, A. 2006, CQG, 23, 809
Taam, R. E., & Sandquist, E. L. 2000, ARAA, 38, 113
The LIGO Scientific Collaboration, the Virgo Collaboration: J. Abadie, Abbott, B. P., Abbott, R., Abernathy, M., Accadia, T., Acernese, F., & al. 2011, ArXiv e-prints. 1104.2712
Tutukov, A. V., & Fedorova, A. V. 1989, Soviet Ast., 33, 606
Tutukov, A. V., Fedorova, A. V., Ergma, E. V., & Yungelson, L. R. 1985, Soviet Astronomy Letters, 11, 52
Tutukov, A. V., & Yungelson, L. R. 1979, AcA, 29, 665
van der Klis, M., Hasinger, G., Verbunt, F., van Paradijs, J., Belloni, T., & Lewin, W. H. G. 1993, A&A, 279, L21
van der Sluys, M. V., Röver, C., Stroeer, A., Raymond, V., Mandel, I., Christensen, N., Kalogera, V., Meyer, R., & Vecchio, A. 2008, ApJL, 688, L61
van der Sluys, M. V., Verbunt, F., & Pols, O. R. 2005a, A&A, 431, 647
— 2005b, A&A, 440, 973
— 2006, A&A, 460, 209
Veitch, J., & Vecchio, A. 2008, CQG, 25, 184010
Vila, S. C. 1971, ApJ, 168, 217
Voss, R., & Gilfanov, M. 2007, MNRAS, 380, 1685
Warner, B. 1995, Cambridge Astrophysics Series, 28
Warner, B., & Robinson, E. L. 1972, MNRAS, 159, 101
Webbink, R. F. 1984, ApJ, 277, 355
— 2008, in Astrophysics and Space Science Library, edited by E. F. Milone, D. A. Leahy, & D. W. Hobill, vol. 352 of Astrophysics and Space Science Library, 233
Weisberg, J. M., Nice, D. J., & Taylor, J. H. 2010, ApJ, 722, 1030
Willke, B., Aufmuth, P., & al. 2004, CQG 21, 417
Woudt, P. A., Steeghs, D., Karovska, M., Warner, B., Groot, P. J., Nelemans, G., Roelofs, G. H. A., Marsh, T. R., Nagayama, T., Smits, D. P., & O'Brien, T. 2009, ApJ, 706, 738
Yu, S., & Jeffery, C. S. 2010, A&A, 521, A85+