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Cataclysmic variables as multimessenger sources: the gravitational wave emission

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The direct detection of gravitational waves has triggered the interest in gravitational wave sources. Cataclysmic variables are binary sources whose expected emission is in the sensitivity band of the forthcoming space based interferometer LISA, scheduled for launch after 2030. I present an estimation of the gravitational wave emission of about one thousand cataclysmic variables, using the distances estimated with the Gaia DR2 parallaxes. The most promising gravitational sources are AM CVn and WZ Sge systems.

The Golden Age of Cataclysmic Variables and Related Objects V (GOLDEN2019)
2-7 September 2019
Palermo, Italy

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PoS(GOLDEN2019)054

1. Introduction

The direct detection of gravitational waves from the binary black hole mergers GW150914 [1], GW151226 [2], GW170104 [3], GW170608 [4], GW170814 [5], the additional events in the recently GWTC-1 catalog [7] and the first coalescence of a binary neutron star system [6] by Advanced LIGO, Advanced Virgo have opened a new observational window in astronomy. The spectrum of gravitational waves extends from 10^{-10} to 10^{4} Hz encompassing a large variety of astronomical sources (Fig. 1) and demanding different detection techniques [46].

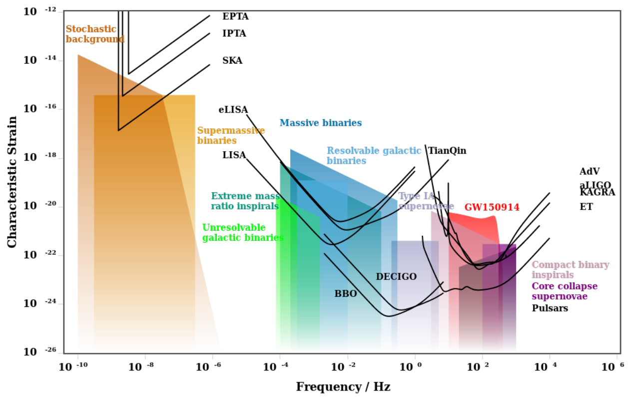

Figure 1: The spectrum of gravitational waves, based on the tool at http://rhcole.com/apps/GWplotter/

The Very Low Frequency region, below 10^{-5} Hz, includes the stochastic background and the radiation of supermassive binaries and is investigated using pulsar timing techniques [47]. The Low Frequency region between 10^{-5} and 0.1 Hz, the domain of space based interferometers, includes the coalescence of supermassive black holes and of extreme mass ratio systems and the emission of resolvable and unresolvable galactic binaries. The High Frequency region, above some Hz, is the domain of ground based interferometers and includes the mergers of stellar mass black holes, of neutron stars, of neutron star/black hole mergers, core collapse supernovae, pulsars, stochastic background of unresolved black hole and neutron star binaries.

The space based laser interferometer LISA aims to detect gravitational waves in the frequency range from 10^{-5} Hz to 10^{-1} Hz, where the sensitivity of ground based instruments is limited by seismic noise. Cataclysmic variables, binary systems where a white dwarf is accreting material from another star [69], are among the potential sources, with the advantage that electromagnetic observations are available, providing information about the sky position and the orbital period of the system. To date, more than one thousand cataclysmic variables are known [57], [58], with an estimated total number of the order of 10^{6} in the Galaxy [37]. Their orbital periods range from minutes to hours, thus their gravitational emission, occurring at twice the orbital period, lies in the LISA frequency range. An astrophysical background from binary systems is expected, mainly from galactic unresolved contact binaries, pairs of white dwarfs or neutron stars and cataclysmic binaries [37], [20].

The gravitational wave emission of binary systems has been investigated in detail [64], [45], [31], [40], [30], [37], [20], [70] and requires the knowledge of the orbital period, the distance and the masses of the components. In the following, the estimation of the gravitational wave emission of about one thousand cataclysmic variables is presented. The distances have been estimated using the Gaia DR2 parallaxes [32], [33].

The paper firstly summarizes the properties of cataclysmic variables relevant for the gravitational wave emission. Then the distances to cataclysmic systems are discussed. The properties and the sensitivity of the LISA interferometer are presented later. Finally, the gravitational wave emission is estimated for about one thousand systems, a sample larger than in previous estimations reported in literature [19], [44] (about 160 systems each) and [53] (about 500 systems).

2. Cataclysmic Variables

The catalog of cataclysmic variables by Ritter and Kolb [57], [58], available online [1], version 7.23, contains the main properties of more than 1400 systems. The sample of cataclysmic variables is steadily increasing, thanks to the new high cadence optical surveys: SDSS, OGLE, CRTS, ASASSN, MASTER... The present compilation discusses systems in the Ritter and Kolb catalog with the addition of some new discovered systems. The orbital period is known for the majority of cataclysmic variables. The period distribution is shown in Fig. 2, that clearly shows the period gap. Two classes of systems are of interest for gravitational wave emission, the WZ Sge systems, about one hundred systems with periods in 60-90 minutes range [38], and AM CVn systems, about fifty systems with periods in the 5-65 minutes range [55].

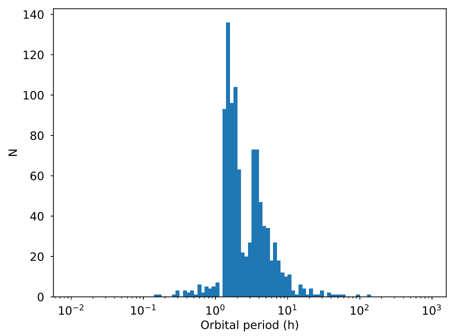

Figure 2: Distribution of the orbital periods of cataclysmic variables

The masses of the primary and secondary stars are known only for a small fraction of all known cataclysmic variables, about 10%. The distribution of the masses of the primary (about 150 systems) and of secondary stars (about 140 systems) are reported in Fig. 3, left and right.

I have estimated the masses of the primary and secondary stars with missing values following the approach by [44]. The mass of the primary is estimated using the unweighted average of the systems below the period gap, in the period gap and above the period gap:

$$M_1 = 0.76 M_\odot \text{ below period gap} \tag{2.1}$$

$$M_1 = 0.76 M_\odot \text{ in period gap} \tag{2.2}$$

$$M_1 = 0.86 M_\odot \text{ above period gap} \tag{2.3}$$

[1] http://wwwmpa.mpa-garching.mpg.de/RKcat/

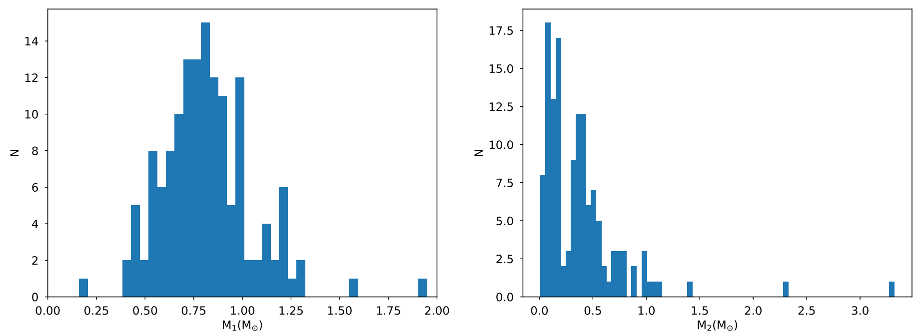

Figure 3: Distribution of the mass of the primary (left) and secondary (right)

The mass of the secondary star has been estimated with a mass-period relation, following the approach by [63]. I have fitted the mass versus orbital period for the systems with periods smaller than ten hours:

$$M_2(M_\odot) = 0.014 + 0.090P(hr) \tag{2.4}$$

3. Distances

The Ritter and Kolb catalog does not report the distances of cataclysmic variables. Historical compilations of distances of a few tens systems have been presented by [22], [51], [52]. Before Gaia, distances based on parallax measurements using ground and space based telescopes were available for about fifty systems. Ground based parallax measurements have been obtained by [65] and [66] for 26 cataclysmic variables. Space based parallax measurements have been performed with HST [34], [42], [43], [23], [24], [35], [36], [59] and Hipparcos [29].

Limits to the distance of cataclysmic variables have been set using the infrared K magnitude of the secondary star [17]. The K surface brightness is related to the $V-K$ colour index via a linear relation or a combination of linear relations [17] and to the angular diameter of the star [18]. The energy distribution of cataclysmic variables has been discussed by [67] to discriminate the contributions of the secondary star and of the accretion disk. Since near infrared photometry cannot disentangle the two contributions, only limits to distance can be set [21]. The method of K surface brightness [17] has been updated by [22], [56], [25]. An approach to distance estimation using theoretical models for the secondary star, assuming that is filling the Roche lobe, has been proposed by [39]. A calibration of absolute magnitude of cataclysmic variable based on 2MASS infrared data has been proposed by [8], [9], who estimated the distances of more than four hundreds cataclysmic variables.

The distance of novae can be measured using the expansion parallax [27], [62] of shells around novae years or decades after the outburst, combining the angular expansion rate with the measurement of radial velocity [27], [62], but accounting for the system inclination and for non isotropic mass ejection [27], [68]. An approach based on the position of red clump giants on colour-magnitude diagrams and reddening-distance relations towards galactic novae discussed by [49] has provided the distance to 73 novae [49].

The advent of Gaia [32], [33] has reshaped the domain of distances in astronomy. The Data Release DR2 has provided the position, proper motion, photometry in different bands, radial velocities and parallaxes for nearly 1.7 billion stars [26]. While data release DR1 has provided parallaxes for 16 cataclysmic variables [54], data release DR2 includes parallaxes for more than one thousand cataclysmics and has been used for several investigations. The work by [28] has tested the Disk Instability Model (DIM) using a sample of about 130 cataclysmic variables with DR2 parallaxes. The Gaia distance of 18 novae has been used by [61] to derive a new maximum magnitude versus rate of decline (MMRD) relation and the inclination-corrected 1100-6000 Å disk luminosity. The work by [60] has compared the Gaia parallaxes of 41 novae with the previous distance estimates. The first volume-limited sample of cataclysmic variables, 42 systems within 150 pc, has been built by [50]. The sample, 77 per cent complete, has been used to estimate the space density of cataclysmic variables.$4.8^{+0.6}_{-0.8} \times 10^{-6}$ pc^{-3}.

4. LISA interferometer

The frequencies of gravitational emission of cataclysmic variables are in the sensitivity band of space based interferometers. The initial LISA design was a constellation of three spacecraft in heliocentric orbit lagging the Earth by 20 degrees, with an arm length of 5 million km [41], later changed in eLISA, with a shorter arm length [12], [11]. After the ESA call for missions for L3, a new LISA design was proposed, with three arms and six laser links between three identical spacecrafts in a triangular formation, separated by 2.5 million km and scheduled for launching in 2034. The constellation of the three spacecrafts will orbit the Sun in a triangular configuration centered in the ecliptic plane and trailing the Earth by about 20 degrees, while the triangle plane will be inclined by 60 degrees with respect to the ecliptic. The interferometer will monitor the whole sky, measuring the two polarizations of gravitational waves at the same time, in the frequency band from about 10^{-5} Hz to about 10^{-1} Hz [10]. The three spececrafts will contain free falling test masses and will be controlled to be constantly centered on the masses, that act as the end side for the optical length and as a geodesic reference. Each test mass will be a 46 mm cube made of Au-Pt alloy, surrounded by the Gravitational Reference Sensor (GRS) with capacitive sensing. Each spacecraft will contain two units with a Gravitational Reference Sensor and an embedded free-falling test mass. The standard Michelson interferometer configuration cannot be used in LISA, due to the large distance between spacecrafts. The lasers will be used in a transponder mode, sending a beam from one spacecraft to the other one, where the laser is phase locked to the incident beam and a replicated beam is sent back. The operation will be used in all three arms of LISA, with two transponders in each arm. The technique of Time-Delay Interferometry (TDI) will build a virtual interferometer during post-processing. The LISA Pathfinder (LPF) [13] has demonstrated the LISA concept and tested the key technologies, placing two test masses in free fall, unperturbed by other stray forces at a level more than five times better than the original specifications [14], [15].

5. Gravitational Wave Emission

The gravitational wave emission of cataclysmic variables has been addressed by [19] and by [44], who investigated a sample of about 160 objects each. A sample of about 500 cataclysmic variables has been investigated by [53], who used the distances based on the parallax, the nova expansion parallax, the Period-Luminosity-Colour relation [8], [9]. The investigation described in the present paper has used the Gaia DR2 distances of about one thousand cataclysmic variables in the Ritter and Kolb catalog and some new systems detected by all sky surveys, to estimate their gravitational emission.

Cataclysmic variables, as other binary systems, emit gravitational waves at twice the orbital frequency and harmonics. The contribution of the harmonics is generally negligible, since the orbits are progressively circularized during the evolution. The gravitational wave characteristic amplitude produced by a binary system is [64]:

$$h = 8.7 \times 10^{-21} \left(\frac{\mu}{M_\odot}\right) \left(\frac{M}{M_\odot}\right)^{\frac{2}{3}} \left(\frac{100pc}{r}\right) \left(\frac{f}{10^{-3}Hz}\right)^{\frac{2}{3}} \tag{5.1}$$

where $M = M_1 + M_2$, $\mu = \frac{M_1 M_2}{M_1 + M_2}$, M_1, M_2 are the masses of the primary and secondary star, r the distance of the cataclysmic and f the gravitational wave frequency.

The strain h for about one thousand cataclysmic variables investigated in the present paper is shown in Fig. 4 together with LISA sensitivity and the confusion noise. The strain of systems with known masses and of systems with estimated masses are reported with different symbols.

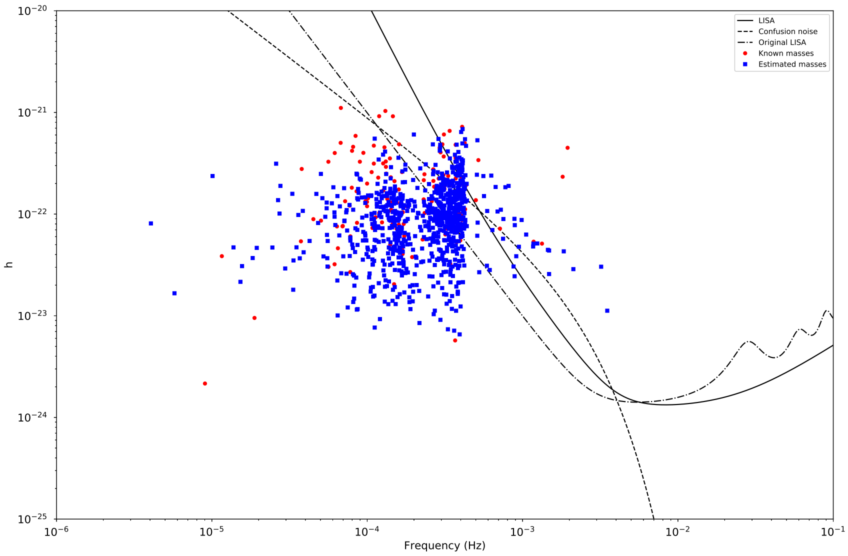

Figure 4: Gravitational wave emission of cataclysmic variables with known masses (red circles) and with estimated masses (blue squares); the solid curve is the instrumental sensitivity of the new design LISA interferometer [16], the dash-dotted line of the original LISA [41], the dashed line is the binary confusion noise [10]

The low frequency sensitivity, below a few mHz, is dominated by the acceleration noise produced by residual spurious forces acting on the test masses, while the high frequency sensitivity, above some tens mHz, is dominated by the laser shot noise. The high frequency sensitivity decreases because the gravitational radiation wavelength becomes smaller than twice the interferometer arm length and is no more able to complete the back and forth trip in the arm. In addition to the instrumental noise, space based interferometers are limited by an astrophysical background, the confusion noise caused by the unresolved population of galactic close binaries [37], [20]. The solid and dash-dot curves in Fig. 4 are the sky averaged sensitivity of the new LISA design [16], with an arm length of 2.5×10^6 km, an acceleration noise based on the LISA Pathfinder performances, a confusion noise estimated by [10], and of the LISA original design with 5 million km arm length [41] [2]. The dashed curve is the contribution of the confusion noise, the astrophysical background produced by unresolved binary systems [37], [20], as discussed by [10]. An observation time of 2 years is assumed. The majority of detectable systems are AM CVn objects [48] and short period systems, such as WZ Sge stars.

6. Conclusions

The present estimation of gravitational wave emission from cataclysmic variables includes about one thousand systems, a sample much larger than in previous estimations. The strongest sources are AM CVn and short period WZ Sge systems.

References

[1] B. P. Abbott et al., *PRL* **116** (2016) 061102.

[2] B. P. Abbott et al., *PRL* **116** (2016) 241103.

[3] B. P. Abbott et al., *PRL* **118** (2017) 221101.

[4] B. P. Abbott et al., *ApJ* **851** (2017) L35.

[5] B. P. Abbott et al., *PRL* **119** (2017) 141101.

[6] B. P. Abbott et al., *PRL* **119** (2017) 161101.

[7] B. P. Abbott et al., *PRX* **9** (2019) 031040.

[8] T. Ak et al., *NewA* **12** (2007) 446.

[9] T. Ak et al., *NewA* **13** (2008) 133.

[10] P. Amaro-Seoane et al., arXiv:1702.00786.

[11] P. Amaro-Seoane et al., *CQG* **29** (2012) 124016.

[12] P. Amaro-Seoane et al., *GW Notes* **6** (2013) 4.

[13] F. Antonucci et al., *CQG* **29** (2012) 124014.

[14] M. Armano et al., *PRL* **116** (2016) 231101.

[15] M. Armano et al., *PRL* **120** (2018) 061101.

[16] S. Babak et al., *PRD* **95** (2017) 103012.

[17] J. Bailey, *MNRAS* **197** (1981) 31.

[18] T. G. Barnes and D. S. Evans, *MNRAS* **174** (1996) 489.

[19] F. Barone et al., *GRG* **24** (1992) 323.

[2] http://www.srl.caltech.edu/šhane/sensitivity/

[20] P. L. Bender and D. Hils, *CQG* **14** (1997) 1439.

[21] G. Berriman et al., *MNRAS* **217** (1985) 327.

[22] G. Berriman et al., *A&ASS* **68** (1987) 41.

[23] K. Beuermann et al., *A&A* **412** (2003) 821.

[24] K. Beuermann et al., *A&A* **419** (2004) 291.

[25] K. Beuermann, *A&A* **460** (2006) 783.

[26] A. G. A. Brown et al.. *A&A* **616** (2018) A1.

[27] R. A. Downes and H. W. Duerbeck, *AJ* **120** (2000) 2007.

[28] G. Dubus et al., *A&A* **617** (2018) 26.

[29] H. W. Duerebeck, *IBVS* **4731** (1991).

[30] C. R. Evans et al., *ApJ* **323** (1987) 129.

[31] R. L. Forward and D. Berman, *PRL* **18** (1967) 1071.

[32] Gaia Collaboration et al., *A&A* **595** (2016) A1.

[33] Gaia Collaboration et al., *A&A* **616** (2018) A1.

[34] T. E. Harrison et al., *ApJ* **515** (1999) L93.

[35] T. E. Harrison et al., *AJ* **127** (2004) 460.

[36] T. E. Harrison et al., *ApJ* **767** (2013) 7.

[37] D. Hils et al., *ApJ* **360** (1990) 65.

[38] T. Kato, *PASJ* **67** (2015) 108.

[39] C. Knigge, *MNRAS* **372** (2006) 484.

[40] V. M. Lipunov et al., *A&A* **176** (1987) L1.

[41] LISA Study Team, 1998, in *LISA Pre-Phase A Report. 2nd Edition*, **Publication MPQ-233** (1998) Max-Plank Institute for Quantum Optics, Garching.

[42] B. E. McArthur et al., *ApJ* **520** (1999) L59.

[43] B. E. McArthur et al., *ApJ* **560** (2001) 907.

[44] M. T. Meliani et al., *A&A* **358** (2000) 417.

[45] V. N. Mironovskii, *SvA* **9** (1966) 752.

[46] C. J. Moore et al., *CQG* **32** (2015) 015014.

[47] C. J. Moore et al., *CQG* **32** (2015) 055004.

[48] G. Nelemans et al., *MNRAS* **349** (2004) 181.

[49] A. Özdönmez et al., *MNRAS* **461** (2016) 1177.

[50] A. F. Pala et al., arXiv:1907.13152.

[51] J. Patterson, *ApJS* **54** (1984) 443.

[52] J. Patterson, *MNRAS* **411** (2011) 2695.

PoS(GOLDEN2019)054

[53] R. Poggiani, in *Volume 315 - The Golden Age of Cataclysmic Variables and Related Objects IV (GOLDEN 2017)*, PoS(GOLDEN 2017)008.

[54] G. Ramsay et al., *A%A* **604** (2017) A107.

[55] G. Ramsay et al., *A&A* **620** (2018).

[56] T. F. Ramseyer, *ApJ* **425** (1994) 243.

[57] H. Ritter and U. Kolb, *A&A* **404** (2003) 301.

[58] H. Ritter and U. Kolb, *Acta Polytech. CTU Proc.* **2** (2015) 21.

[59] G. H. A. Roelofs et al., *ApJ* **666** (2007) 1174.

[60] B. E. Schaefer, *MNRAS* **481** (2018) 3033.

[61] P. Selvelli and R. Gilmozzi, *A&A* **622** (2019) 622.

[62] A. J. Slavin et al., *MNRAS* **276** (1995) 353.

[63] D. A. Smith and V. S. Dhillon, *MNRAS* **301** (1998) 767.

[64] K. S. Thorne, in *Three Hundreds Years of Gravitation* (1987) 330, Cambridge University Press, Cambridge, eds. S. Hawking and W. Israel.

[65] J. R. Thorstensen, *AJ* **126** (2003) 3017.

[66] J. R. Thorstensen et al., *AJ* **136** (2008) 2107.

[67] R. A. Wade, *AJ* **87** (1982) 1558.

[68] R. A. Wade eta al., *PASP* **112** (2000) 614.

[69] B. Warner, *Cataclysmic Variable Stars* (1995), Cambridge University Press, Cambridge

[70] R. F. Webbink et al., *ApJ* **314** (1987) 653.

PoS(GOLDEN2019)054