PROCEEDINGS OF SCIENCE

Could cataclysmic variables be sources of gravitational waves?

Rosa Poggiani[a,b,*]

[a] *Department of Physics "E. Fermi", University of Pisa, Italy;*

[b] *INFN, Sezione di Pisa, I-56127 Pisa, Italy;*

E-mail: rosa.poggiani@unipi.it

The detection of gravitational waves has started the field of multi-messenger gravitational wave astronomy. Cataclysmic variables are binary systems that are candidates for gravitational wave emission in the frequency band of space based interferometer LISA, scheduled for launch in 2034. This paper presents an estimation of the gravitational emission for a sample of more than one thousand cataclysmic variables using the distances estimated by the Gaia observatory. It will be shown that the strongest emission is expected from short period cataclysmic variables belonging to the WZ Sge and AM CVn families.

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1. Introduction

The first detection of gravitational waves from the binary black hole merger GW150914 [1] and from the binary neutron star merger GW170817 [2], followed by the large number of mergers collected in the GWTC-1 [3], GWTC-2 [4], GWTC-2.1 [6], GWTC-3 [5] catalogs have opened a new observational window in astronomy. The spectrum of gravitational waves extends over a broad range from 10^{-10} to 10^{4} Hz, covering a large variety of astronomical sources (Fig. 1) that require different detection techniques [43].

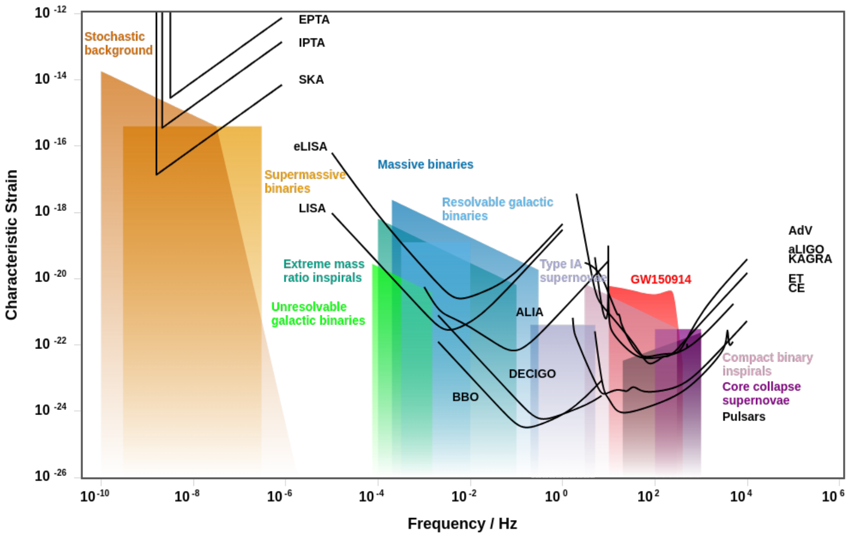

Figure 1: The spectrum of gravitational waves, built using the tool at http://gwplotter.com/

The Very Low Frequency region, below 10^{-5} Hz, that includes the gravitational emission from the stochastic background and supermassive binaries, is investigated using pulsar timing techniques. Recently, the evidence for a stochastic background has been presented by the NANOGrav Collaboration [7]. The Low Frequency region between 10^{-5} and 0.1 Hz includes radiation from the coalescence of supermassive black holes and extreme mass ratio systems, together with the emission of resolvable and unresolvable galactic binaries; the observations require space based interferometers. The High Frequency region, above a few Hz includes the mergers of stellar mass black holes, of neutron stars, of neutron star/black hole mergers, core collapse supernovae, pulsars, stochastic background and is presently explored with ground based interferometers.

Cataclysmic variables are binary systems where a white dwarf is accreting material from a secondary star [66]. As binary systems, they are expected to emit gravitational waves. As discussed below, the expected emission lies in the sensitivity band of the LISA interferometer. The space based laser interferometer LISA aims to detect gravitational waves in the frequency range from 10^{-5} Hz to 10^{-1} Hz, below the lower limit of the sensitivity band of ground based instruments, limited at low frequency by seismic noise. Differently from the mergers of black holes and neutron stars, multi-frequency electromagnetic observations of cataclysmic variables are available, providing accurate value for their sky position and several parameters, including the orbital period and the component masses. To date, some thousands cataclysmic variables are known, while the estimated total number in the Galaxy is of the order of 10^6 [35]. Since the measured orbital periods of cataclysmic variables range from some minutes to several hours, the expected gravitational emission occurring at twice the orbital frequency is in the LISA sensitivity range. In the same frequency region an astrophysical background from unresolved binary systems (galactic unresolved contact binaries, pairs of white dwarfs or neutron stars and cataclysmic binaries) is also expected [35], [19].

The gravitational wave emission of binary systems has been previously investigated by [19, 30, 31, 35, 38, 42, 61]. It can be estimated with the knowledge of some basic parameters: orbital period, distance, masses of components. This paper presents the estimation of the gravitational emission for more than one thousand cataclysmic variables, using the distance estimates in the Gaia DR2 release [26].

The paper will firstly summarize the physical properties of the cataclysmic variable population, orbital period and component masses, that are relevant for the estimation of the gravitational emission, in Section 2. The distances to cataclysmic binaries will be discussed in Section 3. The main features of the LISA interferometer will presented in Section 4. Finally, the estimation of the gravitational wave emission will be presented in Section 5 for more than one thousand systems, a sample larger than in previous estimations [18], [41], [49], [50].

2. The Cataclysmic Variable Population

The number of cataclysmic variables is steadily growing thanks to high cadence all sky surveys and to multi-frequencies observations. The historical catalog of cataclysmic variables by Ritter and Kolb [53, 54], available online [1], contains the main properties of more than 1400 systems. The sample of cataclysmic variables discussed in this paper includes the systems in the Ritter and Kolb catalog, completed with recently discovered systems.

The orbital period is known for a large number of cataclysmic variables, more than 1500 systems, to date. The period distribution, clearly showing the period gap, is reported in Fig. 2.

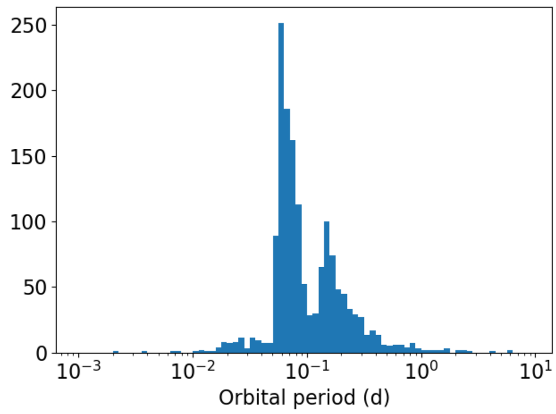

Figure 2: Distribution of the orbital periods of cataclysmic variables

We will show that the cataclysmic variable classes of major interest for gravitational wave emission are the short period ones, the WZ Sge systems, about one hundred systems with periods in

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

60-90 minutes range [36], and AM CVn systems, more than fifty systems with periods in the 5-65 minutes range [51].

The masses of the primary and secondary stars are, on the other hand, known only for a small fraction of the known cataclysmic systems. The distribution of the masses of the primary (about 170 systems) and of secondary stars (about 150 systems) are shown in Fig. 3, left and right.

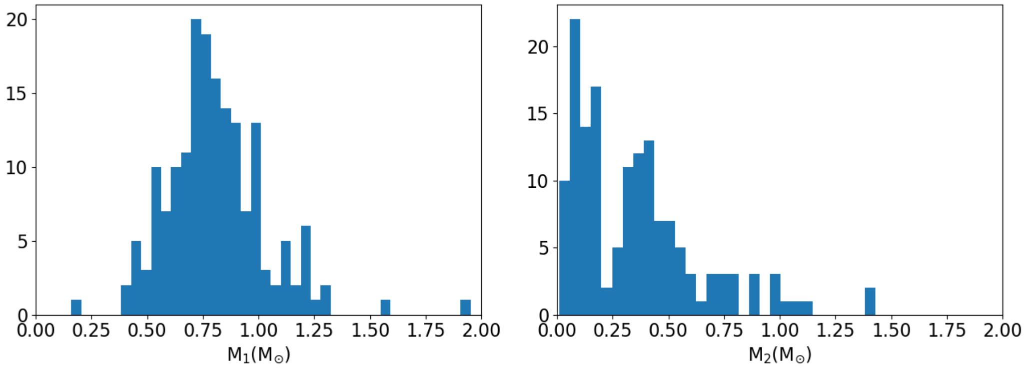

Figure 3: Distribution of the masses of the primary (left) and secondary (right) stars

The missing values of the primary ad secondary masses can be estimated using the approach by [41]. The mass of the primary star has been estimated using the unweighted average of the systems in three separate regions: below the period gap, in the period gap and above the period gap:

$$M_1 = 0.77 M_\odot \text{ below period gap} \quad (1)$$

$$M_1 = 0.78 M_\odot \text{ in period gap} \quad (2)$$

$$M_1 = 0.84 M_\odot \text{ above period gap} \quad (3)$$

The mass of the secondary has been estimated deriving a mass-period relation from the updated sample of cataclysmic variables, following the approach by [59]. After removing systems with periods larger than ten hours, the fit of the secondary mass versus the orbital period is:

$$M_2(M_\odot) = 0.017 + 0.090 P(hr) \quad (4)$$

3. The Distance to Cataclysmic Variables

The estimation of the distance of cataclysmic variables has a long history. The initial distance compilations included a few tens systems at most [21, 47, 48]. The infrared K band magnitude of the secondary star has been used to set limits on the cataclysmic variable distances, with the K surface brightness related to the $V - K$ colour index through a linear relation [17], later updated by [20, 22, 52]. Since near infrared photometry does not allow to separate the contribution of the secondary star and of the accretion disk, only distance limits can be set [21, 64]. Other approaches to distance estimation involve modeling for the secondary star filling the Roche lobe [37] and the calibration of absolute magnitude on 2MASS infrared data [8, 9]. In the case of novae, the distance can be estimated using the expansion parallax of their shells [27, 58, 65] or via reddening-distance relations based on the red clump giants on colour-magnitude diagrams [45].

Before the advent of Gaia, the parallax based distances, either ground based [62, 63] or space based [23, 24, 29, 32–34, 39, 40, 55], were available for about fifty cataclysmic variables. Gaia data releases have provided high precision parameters for a large number of Galactic objects [25, 26], in particular the DR2 data release has provided the position, proper motion, multi-band photometry, radial velocities and parallaxes for nearly 1.7 billion stars in the Galaxy [26]. Among these objects, the release includes thousands of cataclysmic variables, whose properties have been used to test the Disk Instability Model (DIM) [28], derive a new maximum magnitude versus rate of decline (MMRD) relationship [57], calibrate the novae distance [56], build the first volume-limited sample of cataclysmic variables within 150 pc and estimate a space density of $4.8^{+0.6}_{-0.8} \times 10^{-6}$ pc^{-3} [46].

4. The LISA Interferometer

The emission frequencies of gravitational radiation from cataclysmic variables are in the sensitivity band of space based interferometers. The initial LISA design used a constellation of three spacecraft in heliocentric orbit lagging the Earth by 20 degrees, with an arm length of 5 million km [60]. The eLISA design has a shorter arm length [10, 11], with three arms and six laser links between three identical spacecrafts in a triangular formation, separated by 2.5 million km, being scheduled for launching in 2034. The spacecraft constellation will orbit the Sun in a triangle shaped configuration centered in the ecliptic plane and trailing the Earth by about 20 degrees, with the triangle plane inclined by 60 degrees with respect to the ecliptic. The three spececrafts will be centered on the free falling test masses they contain, that will be both the end of the optical length and a geodesic reference. Each test mass will be a 46 mm Au-Pt alloy cube, inside the Gravitational Reference Sensor (GRS) using capacitive sensing. Each spacecraft will contain two units Gravitational Reference Sensor+free-falling test mass. Due to the large distance between spacecrafts, the lasers will be used in transponder mode, sending beams that are replicated at the end station, phase locked to the incident beam, and sent back. A virtual standard interferometer will be built offline using the Time-Delay Interferometry (TDI) technique. The eLISA concept and the related technologies have been successfully demonstrated by LISA Pathfinder (LPF) [13–15]. The eLISA interferometer will monitor the whole sky, measuring the two polarizations of gravitational waves at the same time, in the frequency band ranging from about 10^{-5} Hz to about 10^{-1} Hz [12].

5. Gravitational Wave Emission of Cataclysmic Variables

The gravitational wave emission of cataclysmic variables has been previously estimated by [18], [41] (both with about 160 systems each), [49] (about 500 systems), [50] (about one thousand systems). The estimation described in the present paper extends the previous work [50] with the addition of recently discovered systems.

Being binary systems, cataclysmic variables are expected to emit gravitational waves at twice the orbital frequency and higher harmonics. Since the orbits are progressively circularized during the evolution, the contribution of harmonics can be neglected. The gravitational wave strain produced by a binary system is [61]:

$$h = 8.7 \times 10^{-21} \left(\frac{\mu}{M_\odot}\right) \left(\frac{M}{M_\odot}\right)^{\frac{2}{3}} \left(\frac{100pc}{r}\right) \left(\frac{f}{10^{-3}Hz}\right)^{\frac{2}{3}} \tag{5}$$

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

The strain h for the cataclysmic variables investigated in the present paper is reported in Fig. 4, together with the sensitivities of original LISA and eLISA and the confusion noise, for an observation time of 2 years. The estimates are labelled according to the cataclysmic variable classification: dwarf novae, nova-likes, novae, WZ Sge systems, AM CVn systems, unclassified cataclysmic variables.

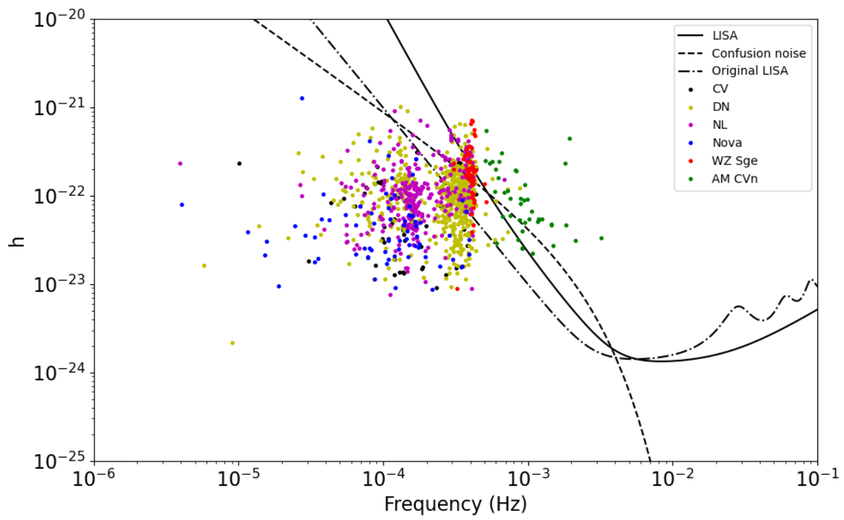

Figure 4: Gravitational wave emission of cataclysmic variables of different classes: WZ Sge systems (WZ Sge, red circles), AM CVn systems (AM CVn, green circles), dwarf novae (DN, yellow circles), nova-likes (NL, magenta circles), novae (N, blue circles), unclassified cataclysmic variables (CV, black circles); the solid curve is the instrumental sensitivity of the new design LISA interferometer [16], the dotted line of the original LISA [60], the dashed line is the binary confusion noise [12]

The low frequency sensitivity of eLISA/LISA, below a few mHz, is dominated by the acceleration noise produced by the residual forces acting on the test masses. The high frequency sensitivity, above some tens mHz, is dominated by the laser shot noise. The solid curve in Fig. 4 is the sky averaged sensitivity of the new LISA design [16], with an arm length of 2.5× 10^6 km and an acceleration noise based on LISA Pathfinder performances. The dash-dotted curve is the sensitivity of the LISA original design with 5× 10^6 km arm length [60]. Space based interferometers will also be affected by an astrophysical background, the confusion noise, caused by the unresolved population of galactic close binaries [19, 35]. The dashed curve is the contribution of the confusion noise as estimated by [12]. Confusion noise is dominating the instrumental sensitivity noise in the milliHertz region. The majority of detectable systems are AM CVn objects [44] and short period systems, such as WZ Sge stars.

6. Conclusions

Cataclysmic variables are promising gravitational wave sources in the sensitivity band of the space based interferometer LISA. The present paper has estimated the gravitational emission for more than one thousand systems, showing that the most promising sources are WZ Sge and AM CVn systems.

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