136. Gaia and gravitational waves

I WILL LOOK AT three areas in which Gaia is contributing to the field of gravitational wave research: in helping to identify 'verification binaries' for the ESA–NASA Laser Interferometer Space Antenna (LISA); in searches for the electromagnetic counterparts of gravitational wave sources; and in providing constraints on the stochastic gravitational wave background.

Gravitational waves are waves of the intensity of gravity generated by the accelerated masses of an orbital binary system that propagate outward (as waves) from their source at the speed of light. They were predicted by Einstein (1916) in his general theory of relativity.

Indirect evidence for them came in 1974 from the observed orbit decay of the Hulse–Taylor binary pulsar, which matched that predicted by general relativity as energy is lost to gravitational radiation. The first direct observation of gravitational waves was made in 2015, when a signal from the merger of two black holes was detected by the LIGO gravitational wave detectors in the US.

THE FIRST concept for a space mission to detect gravitational waves, LAGOS, was presented in the US in 1985, with LISA proposed to ESA within the 'Horizon 2000' programme in 1983. It was identified as the fourth 'cornerstone' mission within ESA's 'Horizon 2000 Plus' in 1995. It has continued its long gestation (and launch slippage) since. Full disclosure: from 2014–16, I chaired an external committee to advise the ESA Director of Science on its scientific and technical implementation. Launch is currently slated for 2038. China's TianQin project targets a similar launch schedule.

THE GRAVITATIONAL WAVE sources driving these missions' science are compact neutron star–black hole binaries, massive black hole binaries, extreme mass ratio 'inspirals', and compact white dwarf binaries.

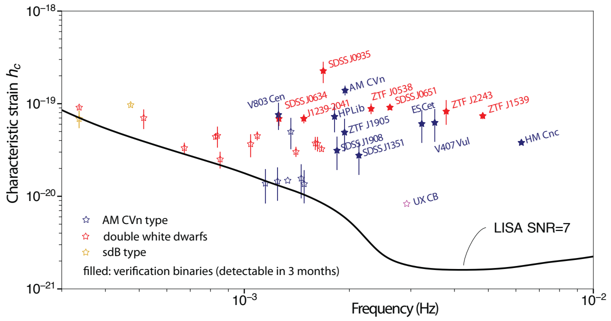
In this latter class, a large population of $\sim 10^7$ Galactic white dwarf binaries emits gravitational waves across the whole LISA band, 10^{-1} – 10^{-5} Hz. The majority will not be individually resolved, creating a stochastic gravitational wave 'foreground' below 3–5 mHz.

PRE-GAIA, around 25 short-period compact white dwarf binaries ($P \lesssim$ few hours) were considered to be 'guaranteed' LISA sources, and are often referred to as 'verification binaries'. Some 1000–10 000 are expected to be individually resolved and characterised by LISA.

Each signal is long lived, and almost monochromatic, with just a small drift in frequency over the mission due to gravitational wave emission or/and due to mass transfer. Each signal is characterised by 7–8 parameters, with typical signal-to-noise ratios expected to be 'moderate', up to about 100.

Ren et al. (2023) made a systematic search in Gaia EDR3 and, through cross-matching with the Zwicky Transient Facility DR8, identified 429 short-period white dwarf binaries from the phase-folded light curves: 220 eclipsing binaries of various types, and 209 ellipsoidal variation binaries. From their estimated gravitational wave amplitudes, they identified 6 new LISA candidates, bringing the total number of identified verification binaries to 31 for LISA, and to 18 for TianQin.

A similar search using Gaia DR3 was made by Kupfer et al. (2023). They gave an updated list of 48 candidate LISA binaries with measured properties derived from the Gaia distances. They found 16 new verification binaries (considered to be those detectable after 3 months), and 21 new sources detectable after 48 months. They include detached double white dwarfs, AM CVn binaries, one ultra-compact X-ray binary, and two hot subdwarf binaries, together tripling the number of known LISA binaries over the last few years.



Kupfer et al. (2023)

Can Gaia contribute to searches for the electromagnetic counterparts of gravitational wave sources? To date, the ground-based LIGO gravitational wave detector has made three 'runs', with a total of 90 detections: O1 (Sep 2015–Jan 2016) made the first three detections, all black hole mergers; O2 (Nov 2016–Aug 2017) made 8 detections, including 7 black hole mergers, and the first neutron star merger; and O3 (Apr 2019–Mar 2020) made the remaining 79, including the first detection of a neutron star–black hole merger. The much enhanced O4, with coordinated observations by LIGO, Virgo, and KAGRA, is due to start operations at the time of writing.

While black hole mergers generate only gravitational waves, the (first) neutron star–neutron star merger GW 170817 was also detected as a gamma-ray burst (by the Fermi Burst Monitor) and, in the optical, as a kilonova powered by the radioactive decay of r-process nuclei synthesised in the ejecta (Abbott et al., 2017).

Gravitational wave sources are typically located on the sky only to within a few hundred square degrees, but Gaia, as an all-sky multi-epoch photometric survey, has the potential to routinely search for their electromagnetic counterparts. Kostrzewa-Rutkowska et al. (2020) accordingly developed an extension to the Gaia Science Alerts system, essentially alerting on each detection of a previously unknown source, with one alert per field of view transit, rather than requiring the usual, and more secure, detection in both fields. At the price of more false alerts, their simulations of run O3 suggest that some 16% of gravitational wave events should fall in sky regions observed by Gaia within 7 days, providing about 21 candidates per day from the whole sky. Implementation of this alert mode is ongoing (Hodgkin et al., 2021).

I have already mentioned the stochastic gravitational wave 'foreground' generated by Galactic white dwarf binaries, but the other area of relevance to Gaia is the extent to which it might provide constraints on the stochastic gravitational wave *background*.

Various theoretical scenarios suggest that a gravitational wave background is generated in the early Universe, whether as a result of inflation, cosmic strings, or 'colliding bubbles' during first-order phase transitions, such as the electroweak phase transition, each predicting a specific form of the gravitational wave spectrum (e.g. Allen, 1997; Caprini & Figueroa, 2018).

The general idea underpinning the possible detection of such a stochastic background is that gravitational waves from a point source, such as a star or quasar, passing over a telescope in gravitational 'free fall', will cause a time-varying shift in the apparent position of the source, i.e. the waves cause spurious proper motions (Pyne et al., 1996; Damour & Esposito-Farèse, 1998). The angular displacement is order of h, being the magnitude of the gravitational wave field at the telescope.

For distant sources, the effect of the waves passing over the telescope is far greater than from either the waves passing over the source, or over the photon trajectory between the source and telescope. The fact that the apparent motions are determined by the gravitational wave field at the telescope then implies that the motions are coherent across the whole sky, and the relative motion of two nearby sources is proportional to their angular separation.

To date, observational constraints on a stochastic gravitational wave background include those from Big Bang nucleosynthesis (e.g. Allen, 1997), VLBI astrometry (e.g. Gwinn et al., 1997), and irregularities in millisecond pulsar timing (e.g. Jenet et al., 2006). Indeed in June 2023, four groups announced the detection of such a background signal in the pulsar timing data.

From its early days, it was evident that Gaia could place useful limits on the energy flux of primordial gravitational waves (Perryman et al., 2001). Depending on the gravitational wave frequency, two regimes were later identified (Klioner, 2018): that where the effects of gravitational waves directly influence the derived proper motions of astrometric sources (from which its greatest sensitivity is over the range $10^{-11} < f < 10^{-8}$ Hz), and the regime where the effects mostly appear in the residuals of the standard astrometric solution (Klioner, 2014). Other theoretical work on the prospects for Gaia has continued (Mihaylov et al., 2018; Wang et al., 2022).

A number of papers are reporting early results. From 300 000 quasars in Gaia EDR3, Liao et al. (2021) suggest that a quadrupole anisotropy in their parallaxes provides evidence that the mass-energy density of the stochastic gravitational waves is $\Omega_{\rm GW} \sim 0.0073h^{-2}$.

Aoyama et al. (2021) examined the quadrupole moment of the proper motions of 400 000 quasars from Gaia EDR3 to derive $\Omega_{\rm GW} < (0.964 \pm 3.804) \times 10^{-4}$ at $f < 10^{-9}$ Hz, or $(30\,{\rm yr})^{-1}$.

Jaraba et al. (2023) similarly used quasar proper motions from DR3 to derive an upper limit on the stochastic gravitational wave background over the range $4.2 \times 10^{-18} - 1.1 \times 10^{-8}$ Hz, of $\Omega_{\rm GW} \lesssim 0.087h^{-2}$.

These early results, based on Gaia data with recognised systematics, nonetheless point to improved prospects and constraints from future data releases.

Meanwhile, if $\Omega_{\rm GW}$ is near the present upper limits, the effect would cause proper motion shifts of ~ 1 nanoarcsec yr^{-1} in individual positions. This would not prevent optical astrometry from achieving a further 2–3 orders of magnitude accuracy advance over Gaia. And with it, nanoarcsec astrometry would have excellent prospects of making a detailed detection of any cosmological gravity wave background.