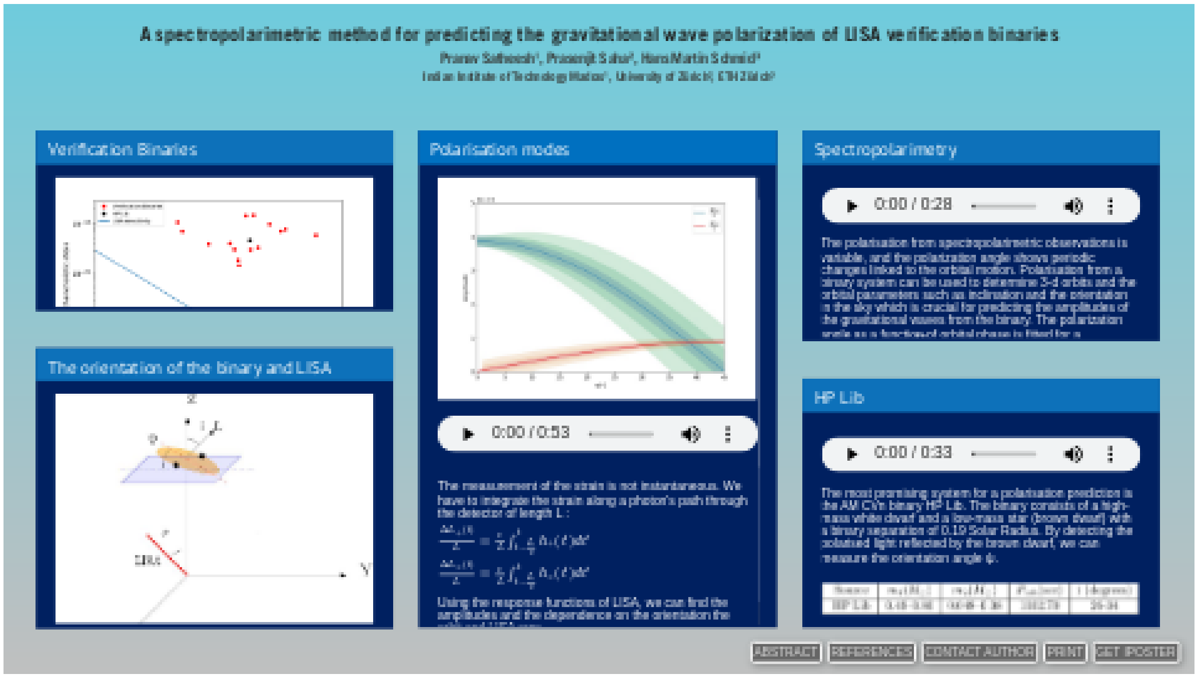
A spectropolarimetric method for predicting the gravitational wave polarization of LISA verification binaries



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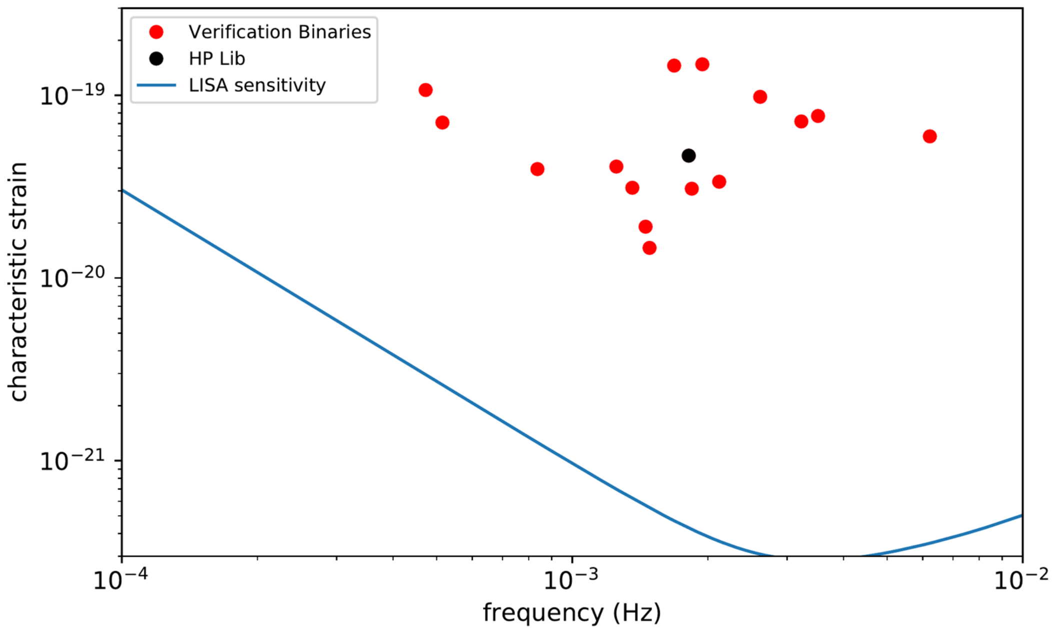
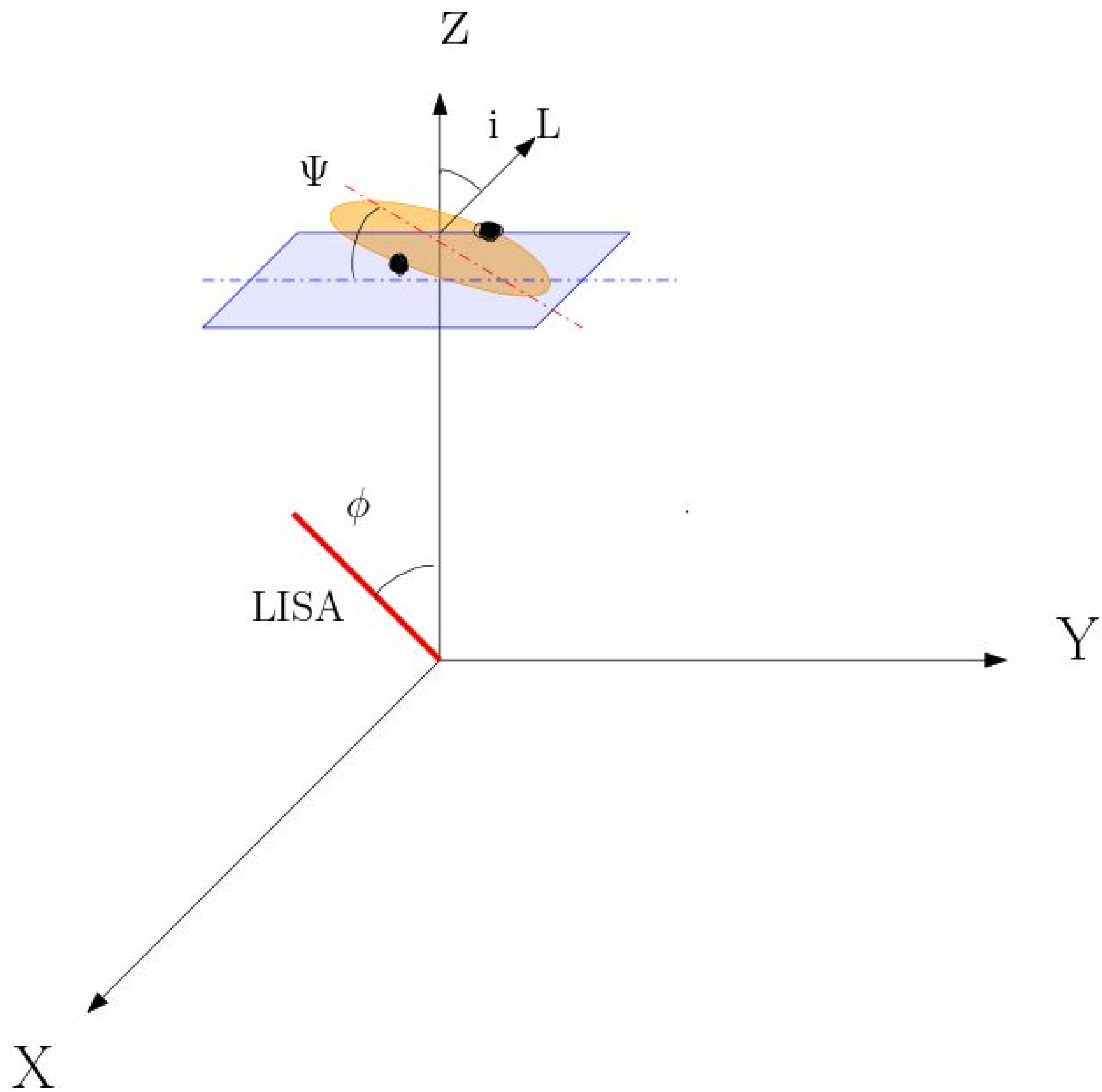
VERIFICATION BINARIES



The Laser Interferometer Space Antenna (LISA) will be the first gravitational wave observatory in space. LISA will be operating in the low-frequency part of the gravitational wave spectrum (0.1 mHz –1 Hz). We expect to observe lots of ultra-compact binaries with orbital periods shorter than a few hours in this range. Out of these Ultra-Compact Binaries, AM CVn type binaries are of particular interest. Due to their strong GW signals, they are guaranteed to be detected on the LISA band. These are termed ‘verification binaries’. The figure illustrates the characteristic strains of the identified verification binaries that are well within the sensitivity curve of LISA.

THE ORIENTATION OF THE BINARY AND LISA



There are two modes of polarisation for gravitational waves called the 'plus' and the 'cross' polarisation. A Gravitational Wave interferometer measures a time-dependent strain:

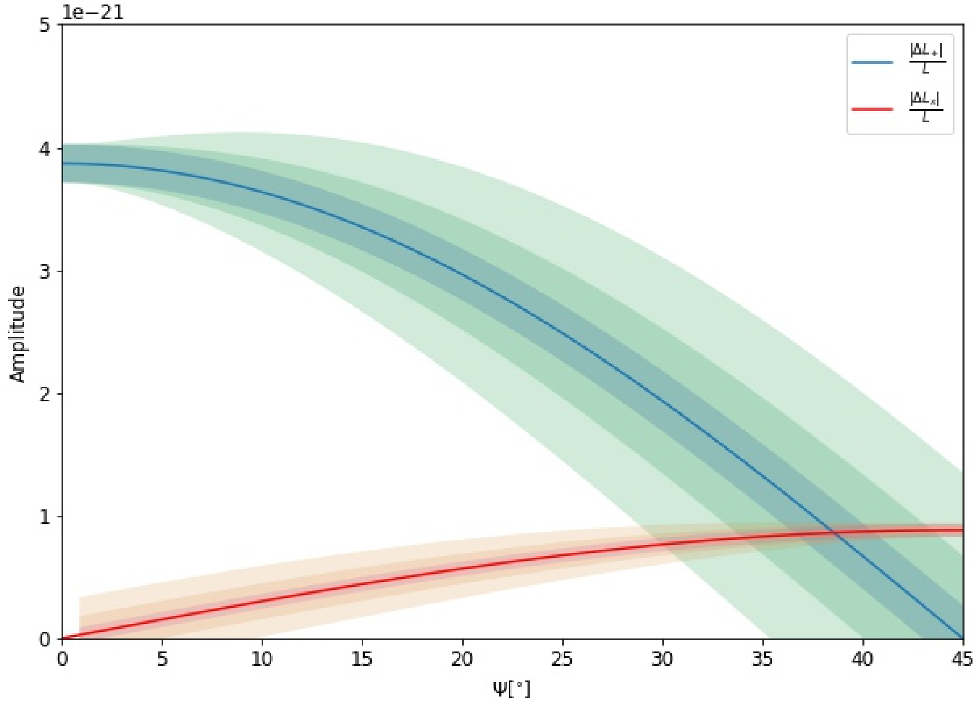
$$\frac{\delta l}{l} = (h_+ F_+ + h_\times F_\times)$$

Where F+ and Fx are the response functions of the instrument. A binary of mass m1 and m2 the gravitational wave polarisations are given by:

$$\begin{pmatrix} h_+ \\ h_\times \end{pmatrix} = \frac{8GE}{c^4 D} \begin{pmatrix} \frac{1}{2}(1+\cos^2\iota) \\ i\cos\iota \end{pmatrix} \exp(i\omega t)$$

where E is the orbital energy and ω is twice the orbital frequency. The angle is the inclination í between the angular momentum vector of the binary to the line of sight vector as seen in the figure. We take the z-axis to be the line of sight. The binary has a position angle ψ which applies a rotation to h + and h × and is the polarization angle. LISA has three interferometer arms in a triangle. For our purposes, however, it is enough to consider a single arm. We take this arm to be in the x-z plane and at angle ϕ with respect to the line of sight.

POLARISATION MODES



The measurement of the strain is not instantaneous. We have to integrate the strain along a photon's path through the detector of length L :

$$\frac{\Delta L_+(t)}{L} \equiv \frac{c}{L}\int_{t-\frac{L}{c}}^{t} h_+(t')dt'$$
$$\frac{\Delta L_\times(t)}{L} \equiv \frac{c}{L}\int_{t-\frac{L}{c}}^{t} h_\times(t')dt'$$

Using the response functions of LISA, we can find the amplitudes and the dependence on the orientation the orbit and LISA arm:

$$\frac{\Delta L_+(t)}{L} = \frac{G\mu R^2\omega\, cos(2\psi)\, cos(\phi)(3+cos(2\iota))sin\left(\frac{L\omega}{c}\right)}{c^3 dL}$$

$$\frac{\Delta L_\times}{L} = -\frac{4G\mu R^2\omega\, sin(2\psi)cos(\phi)cos(\iota)sin\left(\frac{L\omega}{c}\right)}{c^3 dL}$$

The plot shows the dependence of the amplitude on the orientation angle. The shaded areas represent the uncertainty in amplitudes corresponding to the error in Δψ = {2,5,10} degrees. To accurately measure the amplitudes we need to have a prediction of the polarization angle.

SPECTROPOLARIMETRY

The polarisation from spectropolarimetric observations is variable, and the polarization angle shows periodic changes linked to the orbital motion. Polarisation from a binary system can be used to determine 3-d orbits and the orbital parameters such as inclination and the orientation in the sky which is crucial for predicting the amplitudes of the gravitational waves from the binary. The polarization angle as a function of orbital phase is fitted for a 'polarimetric orbit'[2].

HP LIB

The most promising system for a polarisation prediction is the AM CVn binary HP Lib. The binary consists of a high-mass white dwarf and a low-mass star (brown dwarf) with a binary separation of 0.19 Solar Radius. By detecting the polarised light reflected by the brown dwarf, we can measure the orientation angle ψ.

Source	$m_1(M_\odot)$	$m_2(M_\odot)$	$P_{\rm orb}$(sec)	i (degrees)
HP Lib	0.49–0.80	0.048–0.08	1102.70	26-34

From the source properties, we estimate a which will be sufficient for detection. The flux is given by:

$$\frac{1}{4}\left(\frac{R}{1\ AU}\right)^2\left(\frac{M}{M_\odot}\right)^{-2/3}\left(\frac{P}{P_\oplus}\right)^{-4/3}$$

The amount of light received by the brown dwarf is ≈ 0.64 % which we estimate will have enough signal-to-noise ratio to be detected by telescopes.

ABSTRACT

Verification binaries are compact Galactic binaries with orbital periods of a few hours are gravitational wave sources in the mHz regime that are expected to be detected by the Laser Interferometer Space Antenna (LISA) and other future GW detectors. Binary system parameters such as the inclination, orientation and distance are needed to provide an accurate prediction of the gravitational wave strain. A full gravitational wave polarisation prediction requires resolving the orientation of the binary orbit in the sky. We suggest that spectropolarimetry could be used to detect the polarized light originating at the brighter star but scattered off the fainter star, and hence measure the orientation of a verification binary. A good candidate is a cataclysmic variable (AM CVn) HP Lib.

REFERENCES

- [1] Apostolates, T. A., Cutler, C., Sussman, G. J., & Thorne, K. S. 1994, Phys. Rev. D, 49, 6274
- [2]Schmid, H. M., “Montecarlo Simulations of Raman Scattered OVI Emission Lines in Symbiotic Stars”, Astronomy and Astrophysics, vol. 254, p. 224, 1992.
- [3]Cornish, N. J. & Larson, S. L. 2001, Classical and Quantum Gravity, 18, 3473
  Cutler, C. 1998, Physical Review D, 57, 7089–7102
- [4]Baumgartner, S., “Towards a polarization prediction for LISA via intensity interferometry”, Monthly Notices of the Royal Astronomical Society, vol. 498, no. 3, pp. 4577–4589, 2020. doi:10.1093/mnras/staa2638.
- [5] Patterson, J., Fried, R. E., Rea, R., et al. 2002, PASP, 114, 65
  Roelofs, G. H. A., Groot, P. J., Benedict, G. F., et al. 2007, The Astrophysical Journal, 666, 1174–1188