Testing theories of gravity using pulsars

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Background

Pulsars are rapidly-rotating and highly-magnetised neutron stars that emit radiation from their poles. This radiation is seen as a clock-like signal when observed from Earth, with strings of pulses at regular intervals, once per rotational period. These clocks are as reliable as the best atomic clocks but reside in strong gravitational fields so that by measuring the 'ticks' we can study strong-field gravity in ways impossible on Earth-bound laboratories. The pulsars that are of most interest are those in binary systems with another celestial object (white dwarf, another neutrons star or even planets).Binary star systems have a mass quadrupole that changes with time. This means they lose energy due to the emission of gravitational waves and the Keplerian parameters defining the orbit evolve in time.

Upon observation of a pulsar binary, the post-Keplerian (PK) parameters can be determined. These are parameters such as the the binary orbital period derivative $\dot{P}_\mathrm{b}$ that describe how the binary changes with time [2]. PK parameters can also contain theory specific parameters such as Einstein and Shapiro Delay [1] which are specific to General relativity (GR). Once two PK parameters have been measured, using the framework of a specific theory of a gravity the rest of the system is fully determinable. Thus if three parameters can be measured the system is over-determined and can be used as a test of validity of the theory of gravity: for N measured PK parameters one has $N-2$ independent tests of the theory. This is best shown on a mass-mass diagram (e.g. Figure 1). The PK parameters can be expressed as parametric curves in the binary masses — these curves must all intersect at one point.

Objectives

The first objective of this project is to investigate and determine the post-Keplerian parameters in terms of the binary masses for theories of gravity other than GR, including TeVeS (Tensor–vector–scalar gravity) and Jordan-Fierz-Brans-Dicke theory (a scalar-Tensor theory). Some predicted properties of these theories that differ from GR include an extra dipole contribution to the above mentioned $\dot{P}_\mathrm{b}$ and a time-varying Gravitational constant G [2]. The second objective is to determine what regions of the binary parameter space are best suited to tests of different theories of gravity. In this way we can design experiments to perform the relevant strong-field gravity tests; there may be currently know binary systems that could be used for this, or a need to wait for additional discoveries with under construction astronomical instruments.

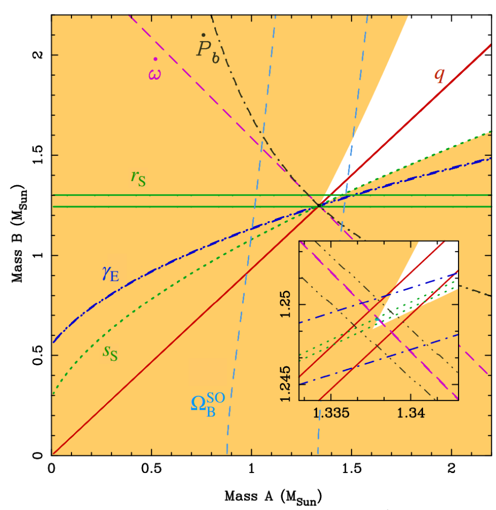

Figure 1: *Mass-mass diagram for the Double Pulsar system, the different PK parameters are shown with dashed lines. Then the chosen theory gravity's prediction for the PK parameters are plotted as functions of the two masses. This results in a curve for each PK parameter. These curves must cross each other. This point has the coordinates of the actual masses of the two bodies in the binary system. When the lines have error bars this point becomes an area. Any theory of gravity must satisfy this condition of all the parameters crossing at the same point otherwise there is reason to doubt its validity.*[3].

Tasks

- Understand orbital elements and PK parameterization in GR
- Determine expressions for orbital elements and PK parameters in alternative theories by solving the equations of motion, i.e. the field equations of the theory
- For alternative theories parameterise PK parameters in terms of the binary masses and compare to GR parametrization, i.e. compare curves in mass-mass plane
- Investigate orbital parameters, e.g. binary mass ratio, orbital size, eccentricity etc. to identify where deviations from GR in the PK parameters are maximised.

References

[1] M Kramer et al. "Strong-field gravity tests with the double pulsar". In: *Physical Review X* 11.4 (2021), p. 041050.

[2] Lijing Shao et al. "Testing gravity with pulsars in the SKA era". In: *arXiv preprint arXiv:1501.00058* (2014).

[3] Norbert Wex and Michael Kramer. "Gravity tests with radio pulsars". In: *Universe* 6.9 (2020), p. 156.