Constraints on Alternative Theories of Gravity from Timing of Millisecond Pulsars

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Beyond the double pulsar

- *Is there anything else to be learned from timing other binary pulsars?*

- As it turns out, yes, there is, and a lot! **Asymmetric systems** (like pulsar-WD binaries) turn out to be excellent for testing alternative theories of gravity!

- This happens because alternative theories of gravity predict several effects on the orbits of these pulsars **that are very difficult to detect with the double pulsar.**
Orbital effects

- These post-GR orbital effects are:

1. **Dipolar gravitational wave emission** (tight orbits)

   \[
   \dot{P}_b^D = -2\pi n_b \frac{G_* M_c}{c^3} \frac{q}{q + 1} \frac{1 + e^2/2}{(1 - e^2)^{5/2}} (\alpha_p - \alpha_c)^2,
   \]

2. **Strong Equivalence Principle violations** (wide orbits) - see Freire, Kramer & Wex 2012 (CQG, invited review for Focus Issue on the Equivalence Principle)

   \[
   \Delta_p - \Delta_c \simeq \alpha_0 (\alpha_p - \alpha_c) \simeq \alpha_0 (\alpha_p - \alpha_0).
   \]

- These effects depend on the **difference of compactness between the two components of the binary**. That is why they can in principle be detected in asymmetric binaries, but less likely in double neutron star binaries.

- They are absent in general relativity. **Detecting them would falsify GR!**
Looking for dipolar gravitational waves

Problem: Millisecond Pulsar-WD systems generally have very low eccentricities!

- Hard to measure PK parameters and determine masses,
- Even harder to determine masses and have extra PK parameters for the GR tests.

Therefore, despite having much better timing precision that pulsars in DNSs, they are hard to use for GR tests!

- However, sometimes we get lucky!
• PSR J1738+0333 is a 5.85-ms pulsar in a 8.5-hour, low eccentricity orbit. It was discovered in 2001 in a Parkes Multi-beam high-Galactic latitude survey (Jacoby 2005, Ph.D. Thesis, Caltech).

• Initial timing solution obtained with Parkes allows a precise determination of the coordinates of the pulsar.

• This allows follow-up at other wavelengths: White Dwarf companion detected!

All pictures in this section: Antoniadis et al. (2012), MNRAS, 423, 3316
The WD is bright enough for a study of the spectral lines!

Fitting for these, we can measure the temperature \((9129 \pm 20 \text{ K})\) and surface gravity of the WD \((\log g = 6.55 \pm 0.07 \text{ dex})\).
Together with WD models, these measurements allow an estimate of the WD mass: $0.181^{+0.007}_{-0.005} \, M_\odot$.

These models have been tested in the MSP-WD system PSR J1909–3744, where WD mass is very well known from Shapiro delay (van Kerkwijk et al. 2013, in prep.).
Optical observations of PSR J1738+0333

- Shift in the spectral lines allows an estimate of the mass ratio:
  \[ q = 8.1 \pm 0.2. \]

- This allows an estimate of the orbital inclination (32.6 ± 1.0°) and the pulsar mass:
  \[ 1.46^{+0.07}_{-0.06} \, M_\odot. \]
Prediction:

- Once the component masses are known, we can make a prediction for the orbital decay of this system:

\[
\dot{P}_b^{GR} \approx - \frac{192 \pi}{5} \left( n_b T_\odot m_c \right)^{5/3} \frac{q}{(q + 1)^{1/3}}
\]

\[
= -27.7^{+1.5}_{-1.9} \text{ fs s}^{-1},
\]

... which is a change on the orbital period of \(-0.86 \mu\text{s per year}\)!

- In the presence of dipolar GW emission this quantity must be larger (in absolute value).

- *Can such a small change in the orbital period be detected?*
Arecibo timing

- This pulsar has been timed with the Arecibo Telescope since 2003.

- One of the projects with more time allocated: we have obtained 17376 pulse time-of-arrival measurements with a precision better than 5 µs, and with weighted r.m.s. of 1.56 µs.

- This is a rather unusual dataset, which yields extremely precise system parameters!

Times of arrival

![Graph showing times of arrival with residuals and phase versus date in MJD and year.](image)
Times of arrival
Timing parameters

- Spin period (at MJD 54600.0001776275): \(0.005850095859775683 \pm 0.000000000000000005\) s

- Orbital period: \(8^h 30^m 53.9199264 \pm 0.0000003\) s

- Semi-major axis of the pulsar’s orbit, projected along the line of sight: \(102957453 \pm 6\) m.

- Eccentricity: \((3 \pm 1) \times 10^{-7}\). This means that the orbit deviates from a circle by \((5 \pm 3)\) µm!

- Proper motion: \(7.037 \pm 0.005\) mas yr\(^{-1}\), \(5.073 \pm 0.012\) mas yr\(^{-1}\).

- Parallax: \(0.68 \pm 0.05\) mas.

- Orbital decay: \(-(25.9 \pm 3.2) \times 10^{-15}\) ss\(^{-1}\) (or \(0.8 \pm 0.1\) µs yr\(^{-1}\))

\[
\dot{P}_b^{\text{Int}} = \dot{P}_b - \dot{P}_b^{\text{Acc}} - \dot{P}_b^{\text{Shk}}.
\]
General relativity does it – again!

For each constraint on the masses, the corresponding curves (calculated using a gravity theory in the case of the orbital decay) must meet on a mass-mass diagram. For 1738+0333, GR passes the test with flying colors! However, the test has low relative precision (8-σ). Is it useful?
This is the most constraining binary pulsar test ever!* 

- Some alternative theories of gravity predict much larger orbital decay in a system containing a neutron star and a white dwarf.

- Because of this, PSR J1738+0333 already represents the best constraint on alternative theories of gravity! For Tensor-Scalar theories of Gravity, current limits are derived from it and Cassini.

- Precision of the limits on JFBD theory will soon surpass the Cassini test!

* For some classes of alternative gravity theories
This is the most constraining binary pulsar test ever!*

- Tensor-Vector-Scalar theories (based on Bekenstein’s 2004 TeVeS theory) can also be constrained, but in this case PSR J1738+0333 is not enough.

- Improvements in the timing precision of the double pulsar (PSR J0737−3039) will be essential to constrain regions near linear coupling. To be published soon (Kramer et al 2013).

- TeVeS and all non-linear friends will become mathematically inconsistent theories.

* For some classes of alternative gravity theories
So what?

We don’t know many things...

What caused cosmic inflation?
What is Dark Matter?
What is Dark Energy?

- Instead, could our understanding of gravity be at fault?

- MANY alternative theories of gravity have been proposed – TeVeS in particular is a relativistic formulation of Milgrom’s (1983) Modified Newtonian Dynamics (MOND), which attempts to explain Dark Matter.

- Thus, falsifying TeVeS has implications beyond gravity.
Summary

• MSP-WD systems are now – for the first time – being productively used to test GR!

• Because of the asymmetry of the components and the timing precision, these tests are very constraining for alternative theories of gravity.

  ... will keep improving, particularly with new systems, already better than anything that might be feasible with LIGO/VIRGO inspirals (see Talk by John Antoniadis)

• Strong complementarity with the double pulsar – together can rule out TeVeS!

• This has implications for our knowledge of the laws and contents of the Universe.

• These systems also have implications for our knowledge of the fundamental properties of spacetime, like Lorenz Invariance for the gravitational sector (see talk by Lijing Shao).
... but wait, there’s more!

Along the same vein, we have the results on PSR J0348+0432 – see Nobert’s talk!
Thank you!

For questions, comments, contact me at pfreire@mpifr-bonn.mpg.de,

…or visit my website at http://www.mpifr-bonn.mpg.de/staff/pfreire.