Tied Strings, Caged Chameleons and MOND's Lair: Constraining Gravity in the Low Acceleration Limit using LISA Pathfinder

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LISA Pathfinder

First test mass in free-fall in one direction

Second test mass + space craft to follow First

Sensitivity to account for numerous sources

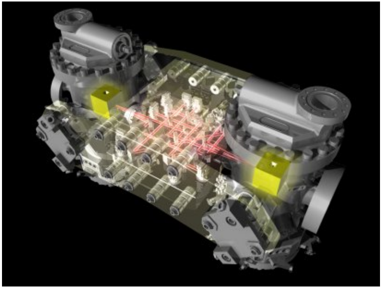

Figure: www.esa.int/spaceinimages

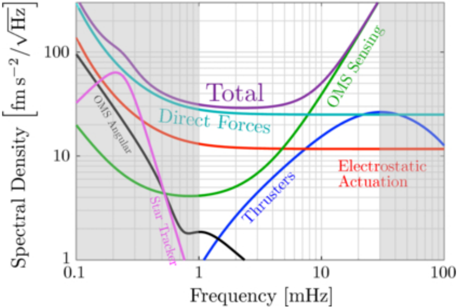

Figure: Antonucci et al 2012 Class. Quantum Grav. **29** 124014

Pathfinder as a Gradiometer

Pathfinder aims to measure the Acceleration Gradient along test mass axis

High precision measurements means sensitivity to subtle changes in the Gravitational Potential

Changes typically buried in Newtonian Background - Need to reduce this to uncover 'signals'

Saddle point could be the answer...

What is the Saddle Point? (I)

Effective potential between two orbiting bodies given by

$$\Phi_{eff} = -\frac{GM_1}{|\vec{r}-\vec{r}_1|} - \frac{GM_2}{|\vec{r}-\vec{r}_2|} - \frac{1}{2}\frac{G(M_1+M_2)}{R^3}|\vec{r} - \vec{r}_{com}|^2$$

$\vec{r}_i/\vec{r}_{com}$ = vector to i'th mass / centre of mass

Balance between Gravitational terms and Centrifugal term - Roche Lobe structure

What is the Saddle Point? (II)

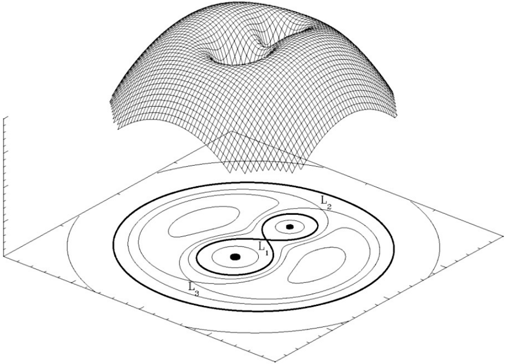

Figure: source: *http : //hemel.waarnemen.com/Informatie/ Sterren/samenvatting$_p$roefschrift.html*

Saddle Point is the located between the two masses in orbit

Determines many features of astrophysical dynamics, e.g. contact binaries and accretion

Local acceleration ~ 0

Testing Gravity: Quasilinear MOND (I)

MOND - MOdified Newtonian Dynamics. Diverse and explains some problems

$$\vec{\nabla} \cdot \left(\nu \left(\frac{|\vec{g}_N|}{a_0} \right) \vec{\nabla} \left(\Phi_N + \phi \right) \right) = 4\pi G \rho$$

$$4\pi G \rho_{PDM} = - \left(\frac{1}{a_0} \nu' \left(\frac{|\vec{g}_N|}{a_0} \right) \vec{\nabla} |\vec{g}_N| \right) \cdot \vec{g}_N$$

Type II MOND EOS given above
Trenkel & Wealthy (2014), Magueijo & Mozaffari (2012)

Testing Gravity: Quasilinear MOND (II)

ρ_{PDM} dependent on local Newtonian acceleration - Perfect for SP mission!

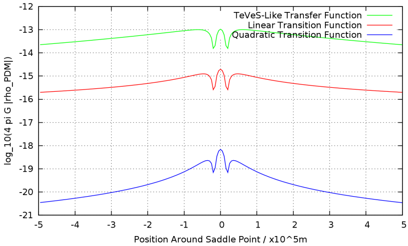

Figure: Reproduced graphs using new code

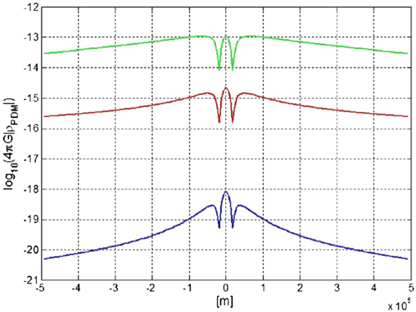

Figure: Trenkel & Wealthy (2014)

$$\nu(y) = 1 - \frac{k}{4\pi} + \left(\frac{1}{y^2} + \left(\frac{k}{4\pi}\right)^4\right)^{1/4} \text{ - TeVeS Like} \qquad \nu(y) = \frac{1}{2} + \left(\frac{1}{y} + \frac{1}{4}\right)^{1/2} \text{ - Linear}$$

$$\nu(y) = \frac{1}{2} + \left(\frac{1}{y^2} + \frac{1}{16}\right)^{1/4} \text{ - Quadratic}$$

Testing Gravity: Quasilinear MOND (III)

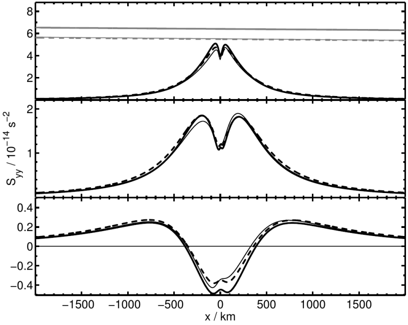

Figure: Transverse MOND stress signal (b=25, 100 and 400km with Moon and Newtonian in grey) - Magueijo & Mozaffari (2012).

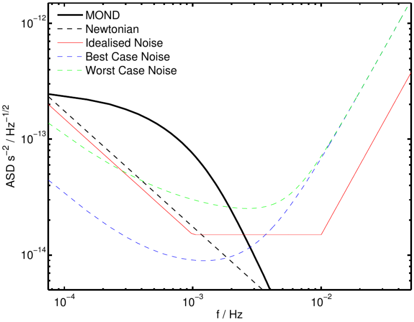

Figure: Amplitude Spectral Densities for comparison with noise budget and Newtonian Background - Magueijo & Mozaffari (2012).

Testing Gravity: Randall-Sundrum Model (I)

Theory using extra dimensions to 'dilute' the hierarchy problem (Gabella (2006))

New metric and Einstein equations given by

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

$$G_{MN} = R_{MN} - \tfrac{1}{2}g_{MN}R = \kappa^2 T_{MN}$$

Column of Graviton modes, each exponentially suppressed by increasing mass:

$$V(r) = V_0(r) + \sum_{n=1}^{\infty} V_n(r)$$

$$= -\tfrac{G_N}{r} + \sum_{n=1}^{\infty} \left(-\tfrac{G_N}{r} k^3 L^2 \cos\left(m_n L_z - 5\pi/4\right) e^{-m_n r}\right)$$

Testing Gravity: Randall-Sundrum Model (II)

Many formulations to this theory: diversity of 'signals'

Another form of potential offered by Callin & Ravndal (2004) given by

$$V\left(r=\left|\vec{r}_1-\vec{r}_2\right|\right)=\frac{Gm_1m_2}{r}\left(1+\Delta\left(r\right)\right)$$

$$\Delta=\frac{8}{3\pi^2}\int_0^\infty \frac{e^{-mr}}{J_1^2\left(\frac{m}{\mu}\right)+Y_1^2\left(\frac{m}{\mu}\right)}\frac{dm}{m}$$

Expand Δ in limit $\mu r >> 1$ to find signal from TM-TM relative motion - 'Drift mode'?

Testing Gravity: Chameleons (I)

Explain Dark Energy whilst maintaining Equivalence Principle in Solar System

Introduce dynamic scalar field, varying at the Hubble time H_0

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{pl}^2}{2}R - \frac{1}{2}\left(\partial\phi\right)^2 - V\left(\phi\right)\right] - \int d^4x\mathcal{L}_m\left(\psi_m^{(i)}, g_{\mu\nu}^{(i)}\right)$$

$$g_{\mu\nu}^{(i)} = e^{2\beta_i\phi/M_{pl}}g_{\mu\nu}$$

Testing Gravity: Chameleons (II)

Solutions for ϕ depend on local density

$$\nabla^2\phi = V_{,\phi} + \sum_i \frac{\beta_i}{M_{pl}\rho_i e^{\beta\phi/M_{pl}}}$$

Field remains 'hidden'

Change the force between two masses - can this be measured?

Highly dependent on treatment of system... Thin shell? Range of fifth force? β_i?

Discussion and Further Work

NOMAD: insight to MOND and parameter contraints

Many more theories could be tested

No review of low energy limits exist - Post Newtonian Expansions are non-trivial!

Further work:

- Finish MOND analysis
- Evaluation of High energy theories
- Template construction
- Provide summary of Newtonian limits