Probing Modified Gravity via Wide Binaries

Charalambos Pittordis
Supervisor: Dr W. J. Sutherland

Queen Mary University of London

c.pittordis@qmul.ac.uk

August 28, 2017
Problem: Weak-Scale Gravity

Environments where Dark Matter (DM) hypothesis is needed

GR/Newton
- Best description of gravity
- Works very well and tested with high accuracy on Solar System scales
- Can explain weak-field limit, i.e., flat rotation curves, large scale structures & CMB, with the inclusion of DM
- **But**, DM hasn’t been directly detected...!!

Modified Gravity theories
- Against the idea of ”Exotic” DM to describe weak-scale effects
- They modify GR eqn’s with some extra ”stuff” (aka Tensors, Vectors, Scalars)
- Use modification of GR to explain weak-scale gravity
- **But**, difficult to test Modified Gravity...!!
Wide-binaries (WB) are isolated stellar binary systems with a very large separation ($>7kAu$); but, still gravitationally bound, can survive up to the Jacobi radius $r \sim 1.7pc$.

The gravitational acceleration within WB pairs is equivalent to that of a stellar body orbiting the galactic center at a distance $>8kpc$ (in DM is dominant regions).

$\sim 80\%$ of stars in Milky Way galaxy are stellar binary systems. WBs have been challenging to select in the past, but WBs can be readily selected with GAIA data.

There is almost certainly No DM in WB systems. Also, they may be tidally disrupted, but if so, they un-bind in few Myr.
Tidal Disruptions (break in Power-Law)

- Number of WB vs WB separation distribution follows a specific Power-law,
  [Yoo et al, 2003 & Quinn et al 2009]

- Halo MACHOs would disrupt WBs above certain separations, lack of a 'break' in Power-Law can set upper limits on MACHOs.

- Very Wide WB’s \((r > 10^5 \text{Au}, \sim \text{Jacobi radius})\) more fragile to disruptions by MACHOs \(M \sim 10 M_\odot\).

- (Yoo et al, 2003 & Quinn et al 2009) Sample of WB’s, expect break in Power-law with MACHOs \(M > 50 M_\odot\).

Therefore, MACHOs \(M > 50 M_\odot\) "Nearly" Ruled out!
Fig. 2.— Binary distributions as a function of semi-major axis. 100,000 binaries are generated following an arbitrarily chosen flat ($\alpha=1$) distribution represented as a thick solid line. The halo density is set to be $\rho_H$. The squares, triangles and circles represent binary distributions for three different masses of perturber, after $T=10$ Gyrs evolution. The fitting curves for each model are shown as dashed lines.

Fig. 5.— The best-fit final binary distributions for various perturber masses, assuming that the initial distribution is a power-law. The halo density is set to be $\rho_H$. The observed halo binary distribution (Fig. 1) is shown for comparison. A model with $1000 \, M_\odot$ perturber deviates significantly from the observations while a model with $10 \, M_\odot$ is quite consistent with them.

(End of the MACHO Era, Yoo et al, 2003)
Testing Gravity with WB

How we probe Gravity

- Compare with weak-field limit between GR/Newton and popular Modified Gravity Theories., (e.g. MOND, TeVeS, Emergent Gravity and MOND + External Field Effect (EFE))

- Produce simulations and integrate WB orbits for each theory

- Compute their observables, (i.e., Relative Velocity vs Projected Radius)

- Model the predicted distributions for the on-going GAIA mission and future ESO’s 4MOST.
**Observables**

- GAIA gives projected separation and transverse velocity difference.
- Ground-based telescopes give radial velocity difference.
- Have $5/6$ components (missing one is the line-of-sight separation of the stellar pair).
- Can estimate masses from distance, colour, spectra.
- Convenient to 'scale' by circular velocity at $r_p$, $V_C(r_p)$.
  \[ V_C(r_p) > V_C(r_{true}), \text{ so } \frac{V_{3D}}{V_C(r_p)} \leq \frac{V_{3D}}{V_C(r_{true})} \]
- \[ \frac{V_{3D}}{V_C(r_p)} \leq \sqrt{2} \] for Keplerian orbits.
- Distribution depends on (unknown) distribution of eccentricities, but not very strongly.
- Model the eccentricity, $(e)$ distribution using (Tokovinin & Kryaeva 2015), (flat or $f(e) = 1.2e + 0.4$).
- Simulate orbits, (observe) at random phase & alignment.
Relative Velocity, \( \left( \frac{V_{3D}}{V_C(r_p)} \right) \) vs Projected Radius \( r_p \)

GR, TeVeS, MOND and EG

![Graph showing Relative Velocity vs Projected Radius](image)
Histograms at various \( r_p \), GR, TeVeS, MOND, EG

---

Charalambos Pittordis (QMUL)  Probing Modified Gravity  August 28, 2017  9 / 16
$r_p \sim 20 - 28.2 \text{ kAu}$

$V_{3D}/V_C(r_p)$

$V_{3D}/V_C(r_p)$

$r_p \sim > 40 \text{ kAu}$
Relative Velocity, \( \left( \frac{V_{3D}}{V_C(r_p)} \right) \) vs Projected Radius \( r_p \)

\( GR \) and \( EFE \sim [0, 0.5, 1, 1.5]a_o \)
Histograms at various $r_p$, $GR & EFE \sim (0, 0.5, 1, 1.5)a_0$
'Tricky' part, due to the Solar neighbourhood $EFE \sim 1.5a_o$
90%ile of $V_{3D}/V_C(r_p)$ at various slices of $r_p$. 

<table>
<thead>
<tr>
<th>Grav-Model</th>
<th>$5 - 7$ kAu</th>
<th>$10 - 14.1$ kAu</th>
<th>$20 - 28.2$ kAu</th>
<th>$&gt; 40$ kAu</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-GR</td>
<td>1.1554</td>
<td>1.1286</td>
<td>1.1256</td>
<td>1.008</td>
</tr>
<tr>
<td>EFE-1.5$a_o$</td>
<td>1.1925</td>
<td>1.1791</td>
<td>1.1372</td>
<td>1.0288</td>
</tr>
<tr>
<td>EFE-1.0$a_o$</td>
<td>1.1962</td>
<td>1.1979</td>
<td>1.1942</td>
<td>1.0674</td>
</tr>
<tr>
<td>EFE-0.5$a_o$</td>
<td>1.2537</td>
<td>1.2672</td>
<td>1.2745</td>
<td>1.1422</td>
</tr>
</tbody>
</table>
Conclusion

- WB are good probes for Modified Gravity (especially in the weak-field limit) due to:
  - Not being tidally disrupted by other gravitating sources, even DM.
  - There is No DM present within the WB system, just two stars orbiting.
  - WB have gravitational accelerations \( a \leq a_o = 1.2 \times 10^{-10} \text{ms}^{-2} \).

- \( EFE \ll a_o \) results in large differences in observables.
- \( EFE \sim 1.5a_o \) makes differences a lot smaller; but still potentially observable.
- We have made predictions for missions such as GAIA and ESO’s 4MOST
  (telescopes that can observe relative motions \( \sim 10^{-1} \text{kms}^{-1} \)).
Thank you for listening