Test of gravitational theories using apsidal motion in eclipsing binaries

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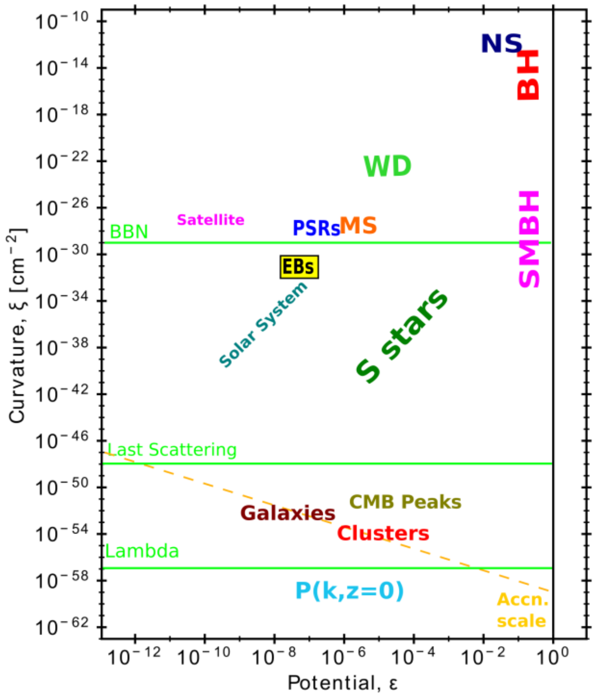
Context

- Back-and-forth between theory, observations and experiments
  → testing GR in a new energy regime : EBs

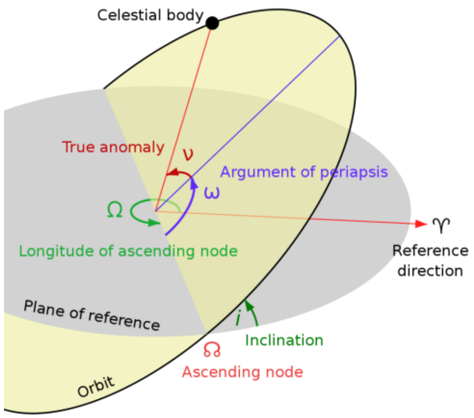
- How : Find a phenomena in EBs that contains a «measurable» relativistic quantity :
  → apsidal motion

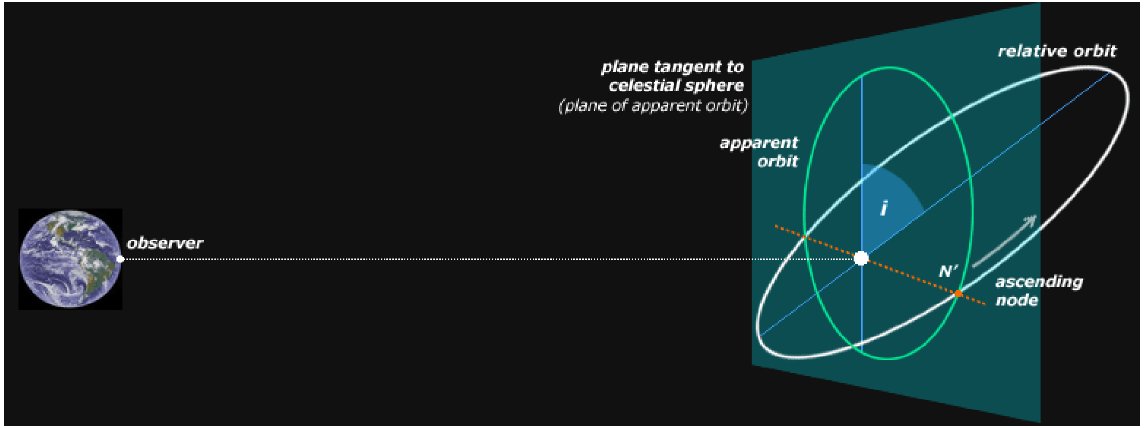
- Challenge : difficult to measure(precision). Solutions : TESS data



Argument of periastron ω and apsidal motion or precession/advance $\dot{\omega}$ (see p.72 of [3] for details)

- Orbital node, line of nodes, argument of periapsis(-astron).
- Apparent orbit, relative orbit(in primary's FoR) and absolute orbit(in CM of the system)
- Plane of reference for binary stars : plane of apparent orbit
- Line of nodes in binary stars : intersection between relative orbit and plane of reference.



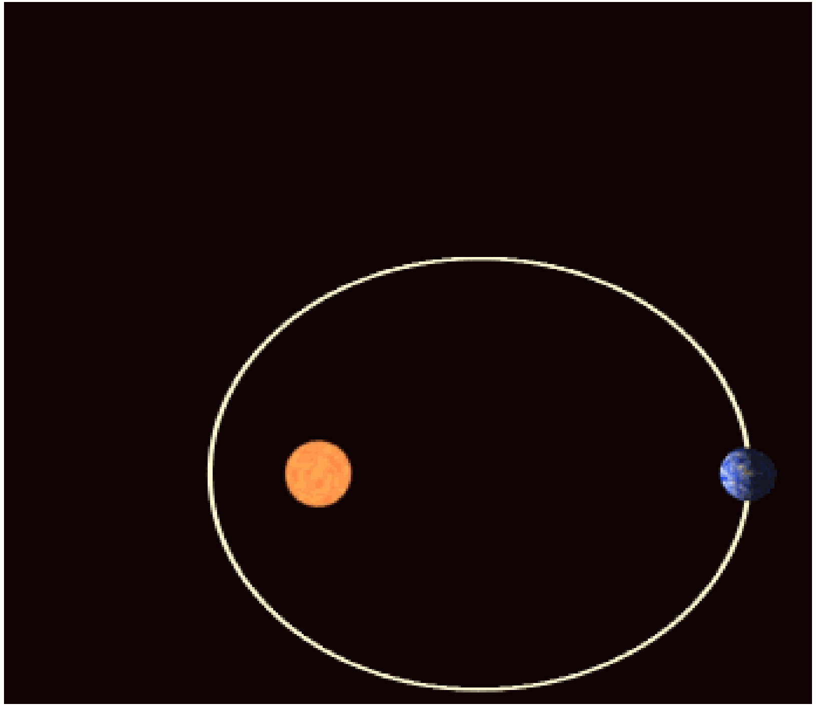


Argument of periastron ω and apsidal motion or precession/advance $\dot{\omega}$

- ω can vary(also corresponds to the rotation of Laplace-Runge-Lenz vector).
- Causes of apsidal motion : non-uniformity in gravitational field(quadrupole effects) or relativistic effects.
- $\dot{\omega} = \dot{\omega}_{cl} + \dot{\omega}_{rel}$

$$\dot{\omega}_{\rm rel} = 5.447 \times 10^{-4} \frac{(M_1 + M_2)^{2/3}}{(1 - e^2)\, P_{\rm a}^{2/3}} \text{ deg cycle}^{-1}$$

$$\dot{\omega}_{\rm cl} = 360 \times \sum_{i=1}^{2} \left(k_{2,i} c_i^{\rm rot} + k_{2,i} c_i^{\rm tid}\right) \text{ deg cycle}^{-1}$$



Eclipsing binaries

- Eclipsing binaries simulator

[1]

- Times of minimum light T_1 and T_2

Aims

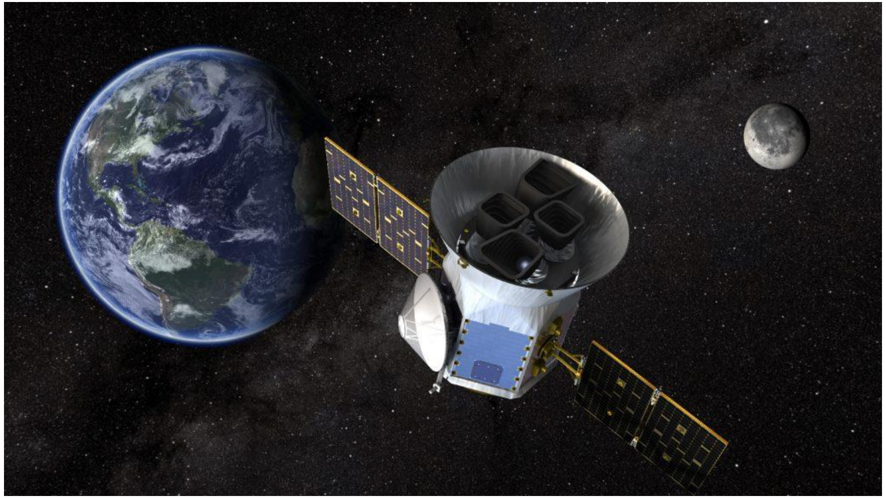
- Show that TESS' data can be used with EBs.
- Compute apsidal motions of EBs.
- Find systems where $\dot{\omega}_{rel}$ contributes to >60% to $\dot{\omega}$ so that they can reliably compute it.
- Compute $\dot{\omega}_{rel}$ and minimise the uncertainties.
- Compare it to GR's and other parametrised post-Newtonian gravitational theories' predictions :

$$\dot{\omega}_{\rm rel,mea} = \dot{\omega}_{\rm rel}\left(\frac{1}{3}(2 + 2\gamma - \beta) + \frac{1}{6}(2\alpha_1 - \alpha_2 + \alpha_3 + 2\zeta_2)\eta\right)$$

Methods and samples used

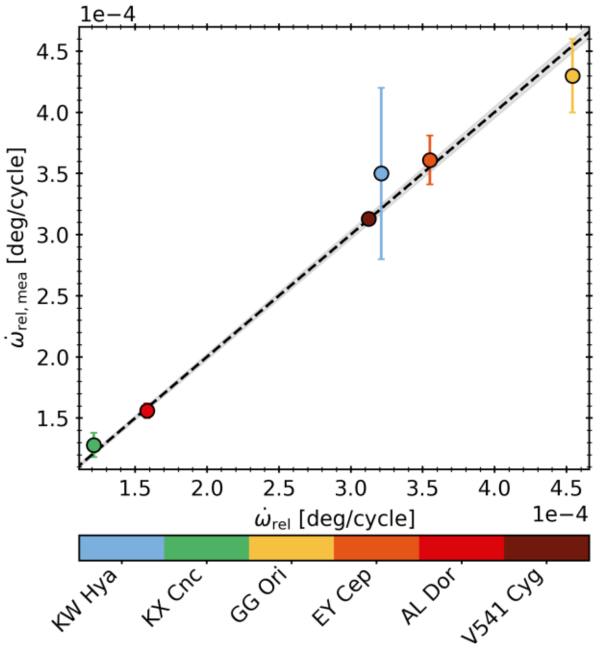
- TESS light curves : variation in the difference between first and secondary minima.
- Proportionality between this variation and $\dot{\omega}$. Then the measured relativistic part is obtained by subtracting the classical part.
- "Marginal gains" :
  1. Sample selection(> 60% $\dot{\omega}_{rel}$)
  2. Model selection for the classical term
  3. Longer time baselines
  4. Precise fundamental properties : 2% or better masses and radii.
  5. Systems with weird parameters are discarded. They present non-negligible rotational effects : Rossiter-McLaughlin or a third body(Kozai) etc…
  6. Bisectors to cope with stellar activity

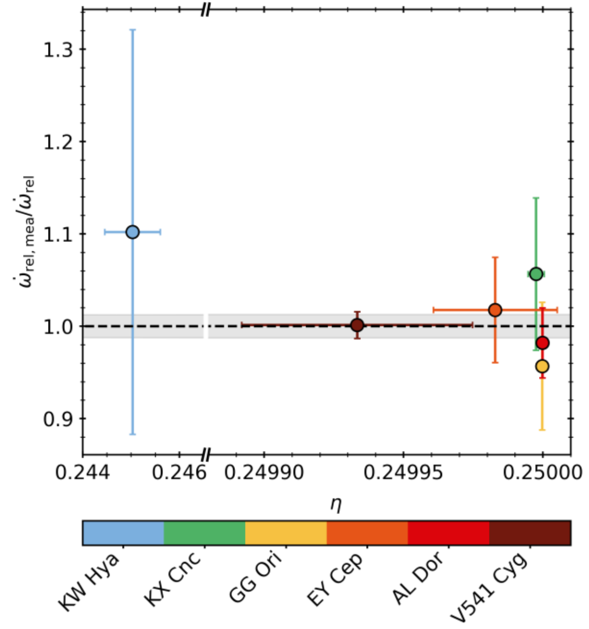
$$\frac{d(T_2 - T_1)}{dt} = \frac{\dot{\omega} P_a}{180}\left(\sum_{i=0}^{2}(-1)^i A_{2i+1}(2i+1)\frac{e^{2i+1}}{2^{2i}}\sin[(2i+1)\omega_0]\right)$$



Results

- More precise apsidal motion for nine(five new) binaries was computed.
- Six systems had sufficient precision to test GR and PPN theories
- GR wins again





Conclusion

- TESS provides quality measurements for EBs but not sufficient !
- Statistics is as or even more important
  - Sample selection
  - Modelling
  - Time baseline etc…

- Observations are concordant with GR predictions.
- Up to 1% uncertainty ! Impressive.
- But first study so needs to be extended with new measurements of apsidal motion using TESS. Not many samples : 6.

Thank you for your attention !

References :

1. https://www.eso.org/public/videos/eso1311b/
2. Baroch D. et al, Analysis [...] TESS data (2021)
3. *The binary stars*, Aitken R. (1918)
4. Binary stars dynamics
5. And Wikipedia naturally ☺