Newton force with a delay: 5th digit of G

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References

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Lazy Newton forces

Assumption: Newton force is emerging with a delay $\tau_G > 0$.

Simplest modification of Newton's instantaneous law:

$$\Phi(\vec{r}, t) = \int_0^\infty \frac{-GM}{|\vec{r} - \vec{x}_{t-\tau}|} \mathrm{e}^{-\tau/\tau_G} \frac{d\tau}{\tau_G}$$

Non-covariant! Needs a universal distinguished frame.
Covariant version: At each t, go to the co-moving—free-falling frame, calculate lazy Newton field, go back to your frame.

- co-moving (where velocity $\dot{\vec{x}}_t$ vanishes)
- free-falling (where gravity $\vec{g}$ vanishes)

Let's consrtuct the explicite covariant form.

Lazy Newton forces - covariant form

$$\Phi(\vec{r},t) = -GM\int_0^\infty \frac{1}{|\vec{r}-\vec{x}_{t-\tau}-\dot{\vec{x}}_t\tau+\vec{g}\tau^2/2|}\mathrm{e}^{-\tau/\tau_G}\frac{d\tau}{\tau_G}$$

Valid in any inertial frame in the presence of gravity $\vec{g}$.
Boost and acceleration invariance:

$$\begin{aligned}\vec{x}_t &\Longrightarrow \vec{x}_t - \vec{v}t - \vec{a}t^2/2\\ \vec{r} &\Longrightarrow \vec{r} - \vec{v}t - \vec{a}t^2/2\\ \vec{g} &\Longrightarrow \vec{g} - \vec{a}\end{aligned}$$

Let's see the background!

Background

Quantum foundations - speculative new physics:

- wave function of massive d.o.f.'s collapses spontaneously
- at average collapse rate $\sim \sqrt{G\rho^{\mathrm{nucl}}} \sim 1/\mathrm{ms}$
- gravity is emergent, created by wave function collapses
- at the same rate $1/\tau_G \sim 1/\mathrm{ms}$

Models:

- lazy Newton force in a distinguished inertial frame
- lazy Newton force covariant in any inertial frames

Fenomenology of a possible lag τ_G:

- non-covariant model:
  - astronomical/cosmological data completely exclude 1ms
  - Cavendish tests allow for lags 1ms or even longer
- covariant model:
  - astronomical/cosmological data are irrelevant
  - Cavendish tests may detect $\tau_G \sim 1\mathrm{ms}$

Newton's law restores for pure gravity

Covariant lazy Newton force:

$$\Phi(\vec{r},t) = -GM\int_0^\infty \frac{1}{|\vec{r}-\vec{x}_{t-\tau}-\dot{\vec{x}}_t\tau+\vec{g}\tau^2/2|}\mathrm{e}^{-\tau/\tau_G}\frac{d\tau}{\tau_G}$$

If non-gravitational forces are absent:

$$\vec{x}_{t-\tau} = \vec{x}_t - \dot{\vec{x}}_t\tau + \vec{g}\tau^2/2 + h.o.t. \quad \Rightarrow$$

$$\Phi(\vec{r},t) = -GM\int_0^\infty \frac{1}{|\vec{r}-\vec{x}_t|}\mathrm{e}^{-\tau/\tau_G}\frac{d\tau}{\tau_G} = -GM\frac{1}{|\vec{r}-\vec{x}_t|}$$

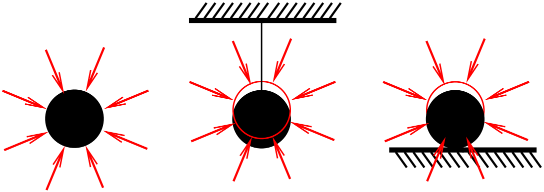
If all forces are purely gravitational (e.g.: solar system) then τ_G cancels and Newton law is restored.
Testing delay τ_G needs non-gravitational forces.

Static sources look displaced

In Earth gravity $g \sim 10^3 \mathrm{cm/s}^2$:
Static source ($\vec{x}_t \equiv \vec{x}$) is being under non-gravitational force $-M\vec{g}$.

$$\Phi(\vec{r},t) = -GM\int_0^\infty \frac{1}{|\vec{r}-\vec{x}_{t-\tau}-\dot{\vec{x}}_t\tau+\vec{g}\tau^2/2|}\mathrm{e}^{-\tau/\tau_G}\frac{d\tau}{\tau_G} \approx$$

$$\approx -GM\frac{1}{|\vec{r}-(\vec{x}_t-\vec{g}\tau_G^2)|} \quad \Rightarrow \text{vertical shift } \delta_G = g\tau_G^2 \ \sim 10\mu\text{m}$$

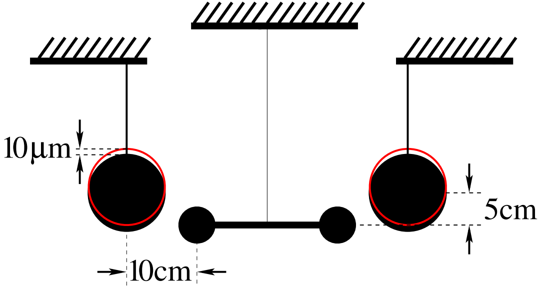


Position of static source looks 10μm upper vs geometric position.

Proposal of Cavendish test of $\tau_G \sim 1$ms

G is uncertain in 400ppm (5th digit)
Correction to G from vertical displacement $\delta_G \sim 10\mu$m at $L = 10$cm horizontal distance between source and probe:

- Planar setup: $G \to (1 - \frac{2}{3}\delta_G^2/L^2)G \quad \Rightarrow -0.01$ppm (9th digit)
- 45^o setup: $G \to (1 - \frac{6}{5}\delta_G/L)G \quad \Rightarrow -120$ppm, meaning correction -8 to G's 5th digit



Existing and future experimental bounds

Gravity's phase lag ϕ vs frequency ω for periodic sources.

Blue: excl.by pulsars; $\downarrow$'s: upper bounds by EötWash; Viol-Pink-Grey: soon testable in optomechanics [Yang et al. arXiv1504.02545].

I put Red Line $\phi/\omega \equiv \tau_G = 1$ms. Blue and $\sim$1kHz $\downarrow$ may be irrelevant.