Gravitational Properties of Light

Dennis Rätzel
Department of Physics
University of Vienna
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dennis.raetzel@univie.ac.at
Einstein's equations

\[ G_{\mu\nu}(g) = \frac{8\pi G}{c^4} T_{\mu\nu} \]

- Energy-momentum is source of the gravitational field
  - light gravitates as it has energy-momentum
Why of interest?

- Laser light well controllable:
  - geometry
  - energy-momentum
  - entanglement

→ source of specific gravitational fields

- At the moment not experimentally accessible
Why of interest?

- A different perspective on light
- Properties of light are inherent in modern physics
  - Were used to derive special and general relativity
  - Often the basis for alternative space time theories
- New insights for quantum gravity
"Gravitational properties of light – The gravitational field of a laser pulse“ *

D. Rätzel, M. Wilkens and R. Menzel,
Linearized version of Einstein's equations

\[ g = \eta + h \]

\[
\left[ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right] h_{\mu \nu} = \frac{16\pi G}{c^4} \left( T_{\mu \nu} - \frac{1}{2} \eta_{\mu \nu} T \right)
\]

- Are wave equations
- Excitations propagate with speed of light
  → Gravitational field of laser pulse differs significantly from that of massive matter
- Can be solved as retarded potential
  → Analytical solution for general polarizations
The metric perturbation

- All components are proportional to a single function

\[ h^p = |h_{\mu\nu}| \]
Boxed shaped pulse moving along the z-axis from its emission to its absorption
The metric perturbation

\[ ct = 16.30 \text{ in units of } L \]

\[ |h_{\mu\nu}| \]
The metric perturbation

\[ |h_{\mu\nu}| \]
The metric perturbation

\[ |h_{\mu\nu}| \]
The effect of the laser polarization

- Linear polarization results in oscillations of the gravitational field
Physical content → tidal forces

Curvature component

$R_{0x0x}$

- negative → stretching in $x$
- positive → contraction in $x$
Physical content → tidal forces

- Non-zero tidal forces localized in spherical shells
- Which are not causally connected to the pulse during its propagation

→ Physical effect only due to emission and absorption
Acceleration of a test particle

- Geodesic equation for trajectory $\gamma(T)$

$$\ddot{\gamma}^\mu = -\Gamma^\mu_{\rho\sigma} (g) \dot{\gamma}^\rho \dot{\gamma}^\sigma$$

Christoffel symbols $\Gamma^\mu_{\rho\sigma} (g)$

- Test particle at rest in the lab frame

$$\ddot{\gamma}^\mu = -c^2 \Gamma^\mu_{00} (g)$$
Acceleration of a test particle at rest in the lab frame

- Absorption → repulsion
Acceleration of a test particle at rest in the lab frame

- Emission
  → attraction
Acceleration of a test particle at rest in the lab frame

- Decreases with the inverse of the distance
- Points at the momentary position of the pulse in the lab frame (not the retarded position)

- Emission → attraction
Deflection by a strong laser

- National Ignition Facility: \( P = 10^{15} \text{W} \)
- At a distance: \( \rho = 1\text{mm} \)

\[
\ddot{\gamma}^{\mu} = -c^2 \Gamma^{\mu}_{00}(g) \approx -\frac{4GP}{c^3 \rho} \approx -10^{-18} \frac{\text{m}}{s^2}
\]

- Comparative to gravitational attraction due to massive object of 1 ng at \( \rho = 1 \text{mm} \) → extremely small
Highly oscillating with adjustable periodicity

→ Could be an application for detectors of high frequency gravitational fields → quantum systems
Summary

Gravitational effect of a laser pulse

- confined to spherical shells associated with emission and absorption
- emission → attraction, absorption → repulsion (decreases with the inverse of the distance to the pulse)
- oscillations with twice the light frequency for linear polarization (none for circular polarization)
- oscillations with pulse periodicity
- extremely small -> Is a detection possible?
Thank you very much!

Publications
with M. Wilkens and R. Menzel

- arXiv:1607.01310
accepted for publication in PRD