Clocks and Gravity

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Airlie
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Clocks and Gravity

Well known issues

- Gravitational redshift
  - Important effect within Einstein’s General Relativity
  - Needed for clock synchronization on Earth
  - Needed for GPS
- Universality of gravitational redshift
  - Important for the structure of General Relativity

Points made here

- Clocks are a universal tool
- Clocks have many important practical applications
- Most space missions may profit from clocks onboard
- Time and position are independent observables
- Technology and Fundamental Physics
Outline

1 The situation of standard physics
   • The status
   • Applications
   • Problems?
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2 Search for Quantum Gravity
   • Need for Quantum Gravity
   • On strategies for the search for QG effects
   • Observation vs. Experiment
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   - Anomalies
   - Solar system anomalies
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7. Final remark: Technology and Fundamental Physics
Structure of standard physics

Einstein Equivalence Principle

- Universality of Free Fall
- Universality of Gravitational Redshift
- Lorentz Invariance

Matter determines gravity

Equations of motion for matter
- Maxwell-equation
- Dirac-equation

Gravity determines dynamics

General Relativity
- Gravity = Metric
- Einstein-equations
The present situation

All aspects of Lorentz invariance are experimentally well tested and confirmed

Foundations
Postulates
- \( c = \text{const} \)
- Principle of Relativity
The present situation

All aspects of Lorentz invariance are experimentally well tested and confirmed

Foundations
Postulates
- \( c = \text{const} \)
- Principle of Relativity

Tests = Clock tests
- Independence of \( c \) from velocity of the source
- Universality of \( c \)
- Isotropy of \( c \)
- Independence of \( c \) from velocity of the laboratory
- Time dilation
- Isotropy of physics (Hughes–Drever experiments)
- Independence of physics from the velocity of the laboratory
Many aspects of the Universality of Free Fall are experimentally well tested and confirmed.

Postulate

In a gravitational field all structureless test particles fall in the same way.
The present situation

Many aspects of the Universality of Free Fall are experimentally well tested and confirmed.

**Postulate**
In a gravitational field all structureless test particles fall in the same way.

**Tests**
UFF for
- Neutral bulk matter
- Charged particles
- Particles with spin
No test so far for
- Anti particles
The present situation

Many aspects of the Universality of the Gravitational Redshift are experimentally well tested and confirmed

Postulate

In a gravitational field all clocks behave in the same way

\[ g \]

\[
\text{Clocks and Gravity}
\]
The present situation

Many aspects of the Universality of the Gravitational Redshift are experimentally well tested and confirmed.

Postulate

In a gravitational field all clocks behave in the same way.

Tests (= Clock tests)

UGR for
- Atomic clocks: electronic
- Atomic clocks: hyperfine
- Molecular clocks: vibrational
- Molecular clocks: rotational
- Resonators
- Nuclear transitions (Mössbauer effect)

No test so far for
- Anti clocks
Universal tool

Clocks are a universal tool for testing space–time properties

**GR:** Physics of position and time (trajectories of particles and light rays)

**SR:** Based solely on clock comparison experiments

**UGR:** clock comparison experiment
The situation of standard physics

Clocks

Clocks of different nature exhibit a different dependence on fundamental constants

### Scaling of transition energies (in units of Rydberg energy)

- **Hyperfine energies** \[ g(m_e/m_p)\alpha^2 f(\alpha) \]
- **Vibrational energies in molecules** \[ \sqrt{m_e/m_p} \]
- **Rotational energies in molecules** \[ m_e/m_p \]
- **Fine-structure energies** \[ \alpha^2 \]
- **Electronic energies (incl. relativistic effects)** \[ f(\alpha) \]
- **Cavity frequency** \[ 1/\alpha \]
- **Weak interaction splitting/Zeeman frequency** \[ G_F \]
Development of good clocks $\Rightarrow$ clocks on aircraft: Experiment by Hafele and Keating 1968 to test time dilation

We shall do the same today: Put the best clocks on spacecraft and test clock effects!
All predictions of Einstein’s General Relativity are experimentally well tested and confirmed.

Foundations

The Einstein Equivalence Principle

- Universality of Free Fall
- Universality of Gravitational Redshift
- Local Lorentz Invariance
The present situation

All predictions of Einstein’s General Relativity are experimentally well tested and confirmed

Foundations

The Einstein Equivalence

Principle

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Predictions from GR

- Solar system effects
  - Perihelion shift
  - Gravitational redshift
  - Deflection of light
  - Gravitational time delay
  - Lense–Thirring effect
  - Schiff effect
- Strong gravitational fields
  - Binary systems
  - Black holes
- Gravitational waves
- Cosmology
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The situation of standard physics

Applications

SR ensures uniqueness of timekeeping in moving frames
GR ensures uniqueness of timekeeping in gravitational fields

SR: Constancy of speed of light

3 \times 10^{-15}

4 \times 10^{-8}

8 \times 10^{-8}

10^{-4}

3 \times 10^{-7}

unknown ageing of prototype

GR ensures uniqueness of definition of mass

SR & GR = Physics of space and time \equiv fundamental metrology
Metrology
Time scales

Earth rotation

- Universal Time of type 0
- Universal Time of type 1
- Greenwich Mn. Sidereal Time

Time of daily life

Atomic, pulsar time

- Universal Time Coordinated
- International atomic time
- Global Position. System
- Pulsar time

Most precise time definition

Coordinate models

- Terrestrial time
- Barycentric time
- Geocentric coord. time
- Barycentric coord. time
- Galactic coord. time

Time and coordinates for astrophysics
Practical application: Clocks and climate research
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- Excess Length-of-Day (LOD): Observed vs. Modeled Core Angular Momentum
- Universal Time (UT1): Observed vs. Ocean Tidal Angular Momentum
Practical application: Clocks and Earth dynamics

Clocks are of help to measure:
- warming of oceans
- motion of Earth’s crust, ...
- ...

The situation of standard physics

Applications

C. Lämmerzahl (ZARM, Bremen)
Practical application: Clocks and positions
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C. Lämmerzahl (ZARM, Bremen)
Problems?

Issues to be resolved

- Need for Quantum Gravity
- Gravity "anomalies"
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The need for Quantum Gravity

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Problem

Incompatibility of quantum theory and General Relativity

Wish

Unification of all interactions

- Avoiding Singularities
- Resolving the problem of time

Need of modifications of standard physics → search for modifications
## Possible effects

### Possible geometry relevant effects
- Anisotropic speed of light
- Anisotropy in quantum fields
- Violation of UFF, UGR
- Birefringence
- Anomalous spin–coupling
- Anomalous coupling of charge
- Anomalous dispersion
- Newton / Coulomb potential
- Nonlinearities
- Charge non–conservation
- Active – passive mass and charge

### Other possible effects
- Decoherence
- Modified interference
- Non–localities

### Structure of parameters
- Usually: parameters are assumed to be constant
- In unification scenarios: parameters depend on time and position, through scalar fields (dilaton, quintessence, varying $e$) $\rightarrow$ scalar–tensor theories

### Many of them typically clock tests

Clocks are an important device in the search for QG
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Strategy: Exploration of new regimes

Standard physics experimentally well proven for standard energies, velocities, distances, ...
Search for new effects $\Rightarrow$ need to go to non-standard situations:
Strategy: Exploration of new regimes

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Search for new effects ⇒ need to go to non–standard situations:

Non–standard situations

Extreme high energies. Deviations from the standard dispersion relation

Extreme low energies. Space–time fluctuations, decoherence may affect quantum systems at temperatures lower than 500 fK achieved in BECs
Strategy: Exploration of new regimes

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Extreme large distances.

- Dark energy, dark matter, Pioneer anomaly
- Ultra–low frequency gravitational waves (early universe)

Extreme small distances. Higher dimensional theories: violation of Newton’s law at small (sub–mm) distances
Strategy: Exploration of new regimes

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### Non-standard situations

**Extreme high energies.** Deviations from the standard dispersion relation

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**Extreme large distances.**
- Dark energy, dark matter, Pioneer anomaly
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**Extreme small distances.** Higher dimensional theories: violation of Newton’s law at small (sub–mm) distances

**Extreme long timescales.**
- Search for space–time fluctuations in terms of \(1/f\)–noise
- Time dependence of constants

**Extreme short timescales.** Short time scales \(\leftrightarrow\) large energies
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Observations vs. Experiment

Comparison: high energy cosmic ray observation ↔ low energy laboratory exp.
Observations vs. Experiment

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Astrophysical observations

- Availability of ultra high energies of more than $10^{21}$ eV
- No systematic repeatability
- No unique interpretation
Observations vs. Experiment

Comparison: high energy cosmic ray observation ↔ low energy laboratory exp.

Astrophysical observations

- Availability of ultra high energies of more than $10^{21}$ eV
- No systematic repeatability
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Laboratory search (including space)

- Only small energies are available
- Repeatability of the experiment, **systematic variation** of initial and boundary conditions, used for:
  - Identification of cause
  - Improvement of precision of result
- Ultra–low temperatures, ultrastable devices like optical resonators can be obtained in the laboratory / in space only
**Observations vs. Experiment**

**Comparison:** high energy cosmic ray observation $\leftrightarrow$ low energy laboratory exp.

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Due to stability and repeatability of experiments, laboratory searches for quantum gravity effects may be as promising as astrophysical observations.
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# Space conditions

Particular space conditions and corresponding tests

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C. Lämmerzahl (ZARM, Bremen)

Airlie, May 23, 2006
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Particular space conditions and corresponding tests

**Space conditions**

- Free fall – no gravitational force
- Large differences in the gravitational potential
- Huge distances
- Large velocities
- Low noise
- Well-defined clocks

**Tests**

- Test of Universality of Free Fall
- Test of Universality of Gravitational Redshift
- Measurement of absolute gravitational redshift
- Test of Lorentz invariance
- Long time for accumulating small forces
- Newton at large distances
- Low frequency gravitational waves
Space conditions

Particular space conditions and corresponding tests

- Free fall – no grav. force → Test of UFF
- Large diff. in grav. pot. → Long accumul. small forces → Test of UGR
- Huge distances → absolute gravitat. redshift
- Large velocities → Relativistic gravity
- Low noise → Newton at large distances
- Well–defined time → low frequency gravit. waves → Test of LI

MICROSCOPE
STEP, GG, HYPER
GP-B
HYPER
ACES, OPTIS, PARCS, SUMO, SPACETIME, RACE

C. Lämmertz (ZARM, Bremen)
Example: OPTIS

OPTIS = OPtical Tests of the Isotropy of Space
Mission for improved tests of Special and General Relativity

Objectives: Michelson–Morley, Kennedy–Thorndike, time dilation, UGR, absolute redshift, periheleon shift, Lense–Thirring, Yukawa (→ poster)
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But: Dark clouds over General Relativity?

Unexplained observations
Gravity anomalies (in Universe and within Solar system)  

But: Dark clouds over General Relativity?

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- Satellite velocities are too large by a few mm/s after fly-bys
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**Increase of Astronomical Unit** *(Krasinski & Brumberg 2005, Pitjeva 2005)*  
Distance Earth–Sun increases by $\sim 10$ m/cy
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<td><strong>Quadrupole and octopole anomaly</strong> <em>(Tegmark et al 2004, Schwarz et al 2005)</em></td>
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### But: Dark clouds over General Relativity?

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- Non–Newtonian acceleration of Pioneer spacecraft toward the Sun

**Flyby anomaly** (ESA and NASA communications)
- Satellite velocities are too large by a few mm/s after fly–bys

**Increase of Astronomical Unit** (Krasinski & Brumberg 2005, Pitjeva 2005)
- Distance Earth–Sun increases by $\sim 10$ m/cy

**Quadrupole and octopole anomaly** (Tegmark et al 2004, Schwarz et al 2005)
- Quadrupole and octopole of CMB are correlated with Solar system ecliptic

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**Is the gravitational physics in the Solar system really well understood?**

Gravity on large scales? $\leftrightarrow$ influence of DM and/or DE?

Additional exploration with clocks!

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C. Lämmerzahl (ZARM, Bremen)
Outline

1. The situation of standard physics
   - The status
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   - Need for Quantum Gravity
   - On strategies for the search for QG effects
   - Observation vs. Experiment

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7. Final remark: Technology and Fundamental Physics

C. Lämmerzahl (ZARM, Bremen)
The Pioneer anomaly

The observation (Anderson et al 1998, 2002)

- Measured constant acceleration

\[ a_{\text{Pioneer}} = (8.74 \pm 1.33) \cdot 10^{-10} \text{ m/s}^2 \]

- Acceleration constant and toward the Sun

New information from

- Clock on new DSGE
- Drift of clocks on Earth may simulate the effect → clock comparison
Theoretical considerations

- Cosmological influence orders of magnitude too small in order to explain the Pioneer anomaly (e.g. C.L. & Dittus 2005, Giulini & Matteo 2006)
- Yukawa describing galactic rotation curve can be used to describe Pioneer anomaly (Dittus & C.L. 2005)
- Cosmological constant cannot be responsible for Pioneer anomaly (Kagramanova, Kunz & C.L. 2006)
Outlook: New mission
Outlook: New mission

- Active spacecraft, passive test mass
- Accurate tracking of test mass
- 2-step-tracking
  - Radio: Earth — spacecraft
  - Laser: spacecraft — test mass
- Flexible formation: varying distance
- Test mass is at environmentally quiet distance from spacecraft $\sim 200 \text{ m}$
- Occasional manoeuvres to maintain formation

New Pioneer Explorer should be equipped with stable clock

For Pioneer anomaly:

$$\frac{\Delta_{\text{Pioneer}}}{\nu} = \frac{1}{c^2} \int_{\text{Jupiter}}^{90 \text{ AU}} a_{\text{Pioneer}} dx = 10^{-13}$$
The flyby anomaly

Observation

- After satellite flybys at Earth the velocity is too large by a few mm/s

GEGA1:
Two-way S–band
Doppler residuals & range residuals
The flyby anomaly

Observation

- After satellite flybys at Earth the velocity is too large by a few mm/s

NEGA:
Two–way X–band
Doppler residuals & range residuals
The flyby anomaly

Observation

- After satellite flybys at Earth the velocity is too large by a few mm/s

NEGA:
Two–way X–band
Doppler residuals & range residuals

New information from:
- Better time resolution of velocity increase: continuous observation
- Clock on spacecraft
- Observation of Mars flyby (Rosetta)
Increase of Astronomical Unit

Observation
Various groups reported
- Krasinsky & Brumberg 2005: $15 \pm 4$ m/cy
- Pitjeva 2005: $7 \pm 1$ m/cy

Remarks / Questions
- $\dot{G}$ excluded by LLR
- Mass loss of Sun leads only to 1 m/cy
- Influence of cosmic expansion by many orders of magnitude too small
- Interplanetary plasma?
- Effect can again be simulated by drift of clocks
Possible questions

- Influence of cosmic expansion? \((a_{\text{Pioneer}} \approx cH)\)
- Something wrong with weak gravity?
- Do clocks on Earth behave properly?

Clocks

Clocks are essential in helping to explore
- Pioneer anomaly
- Flyby anomaly
- Secular increase of AU
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Gravity = geometry = metric + connection = clock and particle motion
For the full exploration of gravity one needs position and time

Measurement of time

- Clocks measure proper time related to $dx^\mu$

$$T = \int_{\text{worldline}} ds$$

with

$$ds^2 = g(x, dx), \quad g(x, \lambda dx) = \lambda^2 g(x, dx)$$

- For Riemannian space–time metric $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

$$T = \int_{\text{worldline of clock}} \sqrt{g_{\mu\nu} dx^\mu dx^\nu} \approx \int (1 - U + \dot{x}^2) dx^0 + \int g_0 dx^i$$

- Two clocks at different positions: gravitational redshift
**Gravity, geometry, clocks, and particle motion**

### Motion of particles

- **Equation of motion for particles: Weak Equivalence Principle**

\[
0 = v^\nu \partial_\mu v^\nu + H^\mu(x, v) = \{ \frac{\mu}{\rho\sigma} \} v^\mu v^\sigma + h^\mu(x, v)
\]

- **3–acceleration**

\[
\ddot{x}^i = \partial_i U + (\partial_i h_j - \partial_j h_i) \dot{x}^j + \Upsilon^i + \Upsilon^i_j \dot{x}^j + \Upsilon^i_{jk} \dot{x}^j \dot{x}^k + \ldots
\]

- **Equation of motion respects UFF but violates Einstein’s elevator**
- **Such terms may play a role in Pioneer anomaly or flyby anomaly**
- **Need of precise clocks for tracking of satellites in order to determine these terms**

Time and orbit of spacecraft are **independent** observables. Only in Einstein’s General Relativity both are governed by the space–time metric. Spacecraft should carry clocks onboard.
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Summary

- Clocks are needed for most space projects
- Clocks are essential for the search of quantum gravity effects
- Clocks will play an important role in resolving current gravity puzzles

- C.L. & Dittus 2000
- Dittus, C.L & Turyshev 2007 (forthcoming book (Springer) on space technologies and missions)
Gravity plays a major role in modern physics

Outlook: experiment/observation in gravitational physics

Data basis improves

- New gravitating systems: binary pulsar $\rightarrow$ new tests of GR, non-linearities, ...
- Longer data span: LLR $\rightarrow$ $\dot{G}/G$, equivalence principle, ...
- Longer data span: ephemerides $\rightarrow$ increase of AU
- Improved data from new measurements: Planck $\rightarrow$ cosmology, quadrupole, ...
- UHECR: Auger, .... $\rightarrow$ dispersion relation, search for QG, ...
- Gravitational waves $\rightarrow$ black holes, binary systems, ...
- Satellite navigation $\rightarrow$ flyby
- New Horizon mission
- New Pioneer mission ....

Vastly increasing knowledge about gravity ...

Gravity is a very dynamic field – new important applications for daily life
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Technology vs. Fundamental Physics

From Philosophy of Science:

⇒ ”Fundamental Physics makes technological progress possible”
⇐ ”Technology stimulates scientific inventiveness”, e.g. Einstein–Poincaré simultaneity (Gallison 2003)

Not possible: To have solely technological development (Carrier 2006):

⇐ ”... practical challenges cannot appropriately be met without treating problems in basic science ... applied research naturally grows into basic science ... Applied research tends to transcend applied questions for methodological reasons. A lack of deeper understanding of a phenomenon eventually impairs the prospects of its technological use. ... Uncovering the relevant mechanisms and embedding them in a theoretical framework is of some use typically for ascertaining or improving the applicability of a finding. Scientific understanding makes generalizations robust ... Treating applied questions appropriately requires not treating them exclusively as applied questions.”

Even the demand of mere technology needs Fundamental Physics.
Final Conclusion