Introduction to Modern Physics : Special Relativity

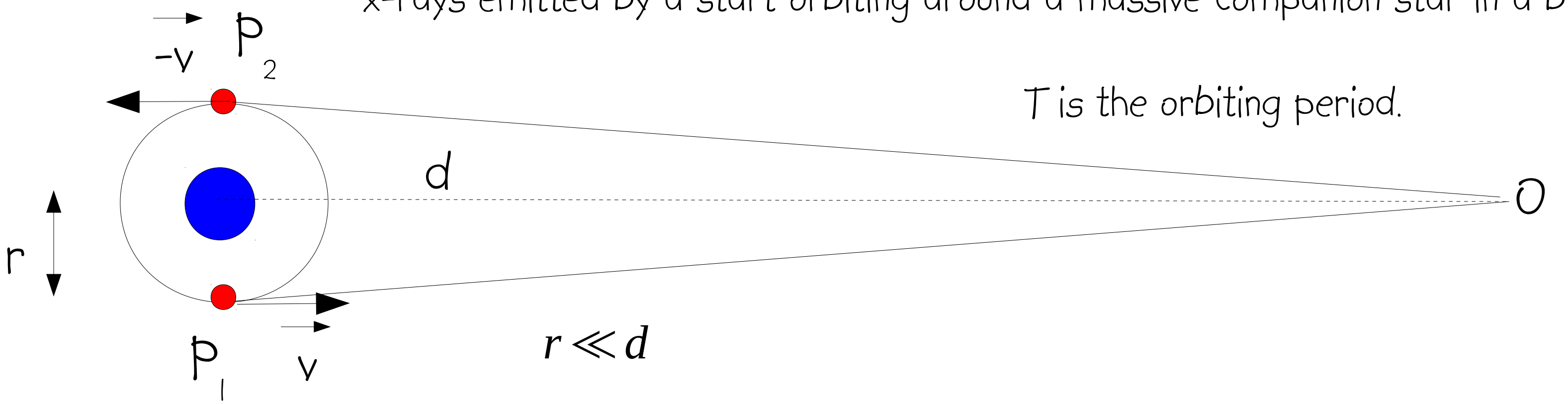
Lecture 3 : Experimental Tests

De Sitter's experiments

Suggested in 1913 by Willem De Sitter. Tests the independence of c upon the source velocity.

Repeated in 1977 with a X-ray source , K. Brecher, "Is the Speed of Light Independent of the Velocity of the Source ?", Phys. Rev. Lett. 39 1051–1054, 1236(E) (1977).

x-rays emitted by a start orbiting around a massive companion star in a binary-star system.



T is the orbiting period.

$r \ll d$

T_1 time for light to go from P_1 to 0 : $T_1 = \dfrac{d}{c+kv}$ where : $0 \leqslant k \leqslant 1,\;\; k=0 \text{ in SR}$

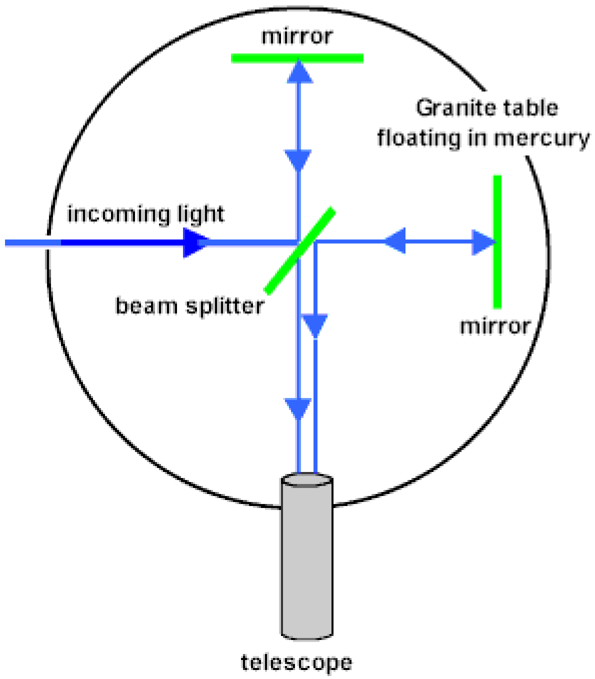
T_2 time for light to go from P_2 to 0 : $T_2 = \dfrac{d}{c-kv}$

T_{12} the observed time difference between P_1 and P_2 : $T_{12} = \dfrac{T}{2} + T_2 - T_1 \simeq \dfrac{T}{2} - \dfrac{2\text{kvd}}{c^2}$

$$T_{21} = \frac{T}{2} + T_1 - T_2 \simeq \frac{T}{2} + \frac{2\text{kvd}}{c^2}$$

Experimentally $|k| < 2\ 10^{-9}$

Michelson-Morley experiments :



Conclusively conducted for the first time by M&M in 1887 .
It tests the isotropy of the modulus of the light velocity in vacuum.

If the modulus of the light velocity is not isotropic, the propagation of light in the interferometer arms are not the same even for equal arm lengths. Rotating the arms by 90° would then change the interference pattern as observed by the telescope.

If data is taken on different earth positions around the sun, this also tests the dependency of c as a function of all angles with respect to a given fixed direction in the universe.

The best results obtained so far give : $$\frac{\Delta c}{c} \leqslant 4.3\,10^{-15}$$

H. Müller et al. (2003) . Modern Michelson-Morley experiment using cryogenic optical resonators. Phys. Rev. Lett. 91 , 020401 .

Kennedy-Thorndike experiments :

It was carried-out for the first time by K&T in 1932. It tests the variation of the modulus of the light velocity in vacuum in long time survey during which the earth goes around its orbit.

It uses a MM type interferometer with asymmetric arm lengths, where the interference pattern is surveyed over long time periods (~1 year). Long time stability of the setup becomes then a very important issue.

Best results lead : $\frac{\Delta c}{c} \leqslant 1.6\,10^{-12}$

P. Wolf (2003), Tests of Lorentz invariance using a microwave resonator. Phys. Rev. Letters, 90 , 060402

MM and KT results can be combined together to constrain this expression :

$$c(v,\theta)=c\left(1+A\frac{v^2}{c^2}+B\frac{v^2}{c^2}\sin^2\theta\right)$$

where v and θ would reflect the state of motion of the observer with respect to an absolute preferred reference system.

$$|A| \leqslant 10^{-6}$$

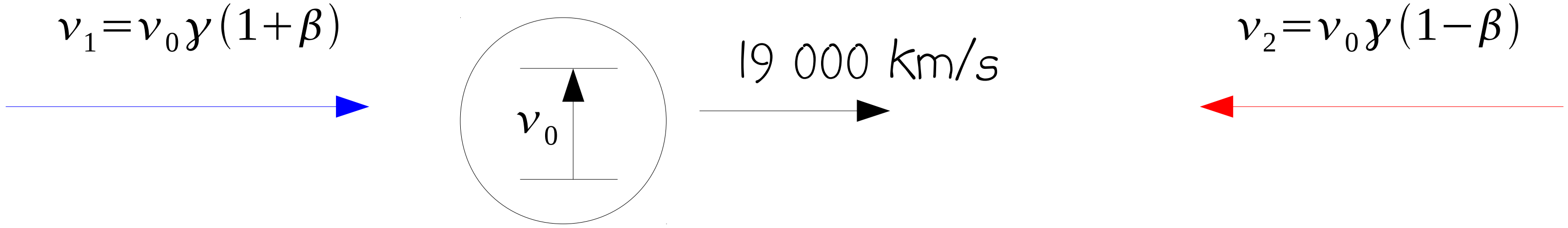
$$|B| \leqslant 3.7\,10^{-9}$$

Ives & Stilwell experiments :

Carried out by I&S in 1938 for the first time. They test the time dilation factor through the longitudinal Doppler effect.

Best results obtained in Heidelberg : G. Saathoff (2003) Improved test of time dilation in special relativity. Phys. Rev. Letters, 91, 190403

$\nu_1 = \nu_0 \gamma (1+\beta)$ $\qquad$ $\nu_2 = \nu_0 \gamma (1-\beta)$



$^7Li^+$ accelerated ions

The two-level atomic transition is induced in a resonant way by a blue-shifted beam on the left and red-shifted beam on the right.

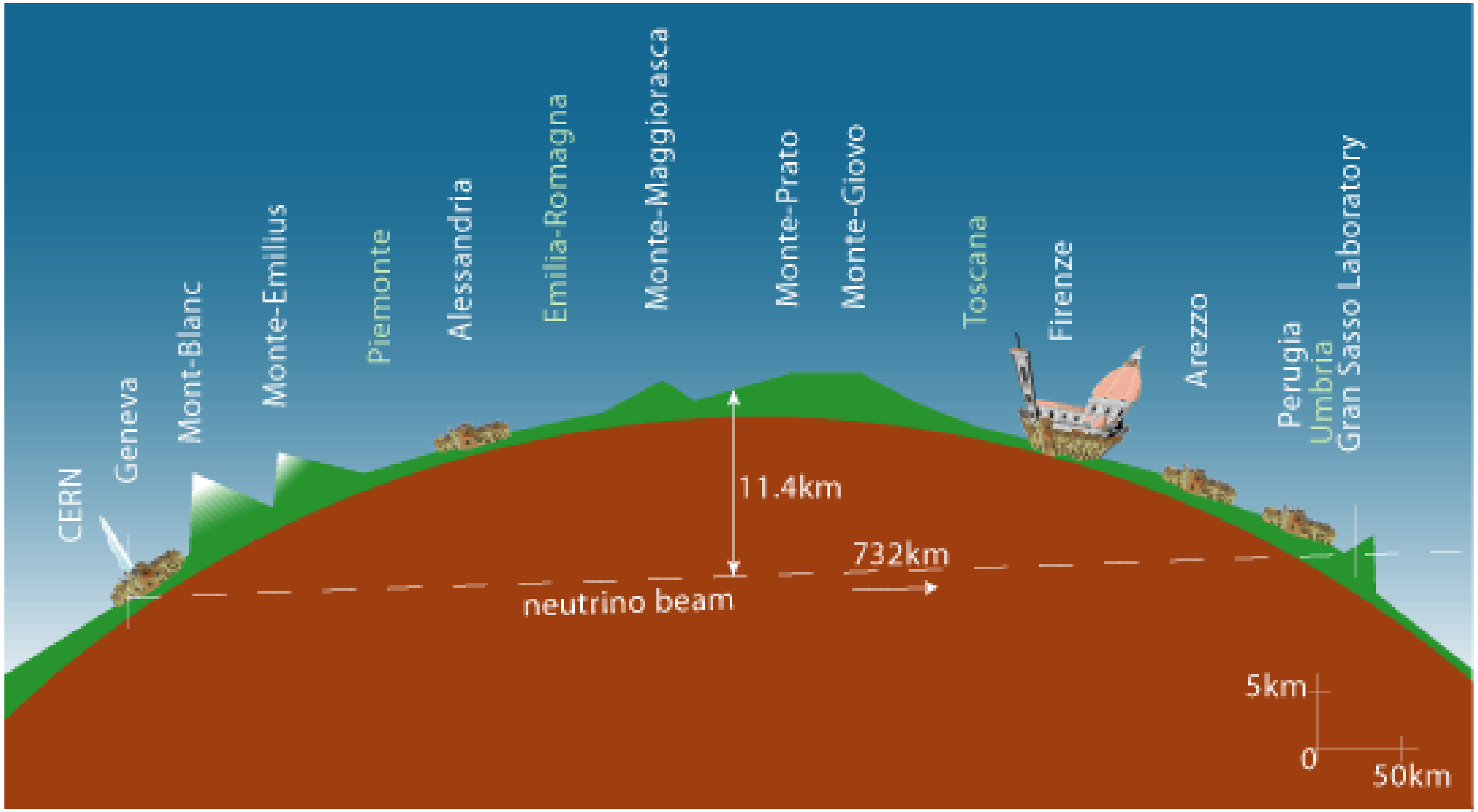
$$\frac{\nu_1 . \nu_2}{\nu_0^2} = \gamma^2 (1-\beta^2) \simeq (1 + 2\alpha(\beta^2 + 2\vec{\beta}_0 \cdot \vec{\beta}))$$

where β refers to the velocity of the moving clock (the Li ion) and β_0 to the velocity of the observer with respect to a preferred reference system in the universe.

$|\alpha| \leqslant 2.2\,10^{-7}$ $\qquad$ $\alpha = 0$ in SR

Neutrino time of flight measurements :

Neutrinos are neutral and almost massless particles. They very weakly interact with matter. Neutrinos may cross the earth without interacting at all.



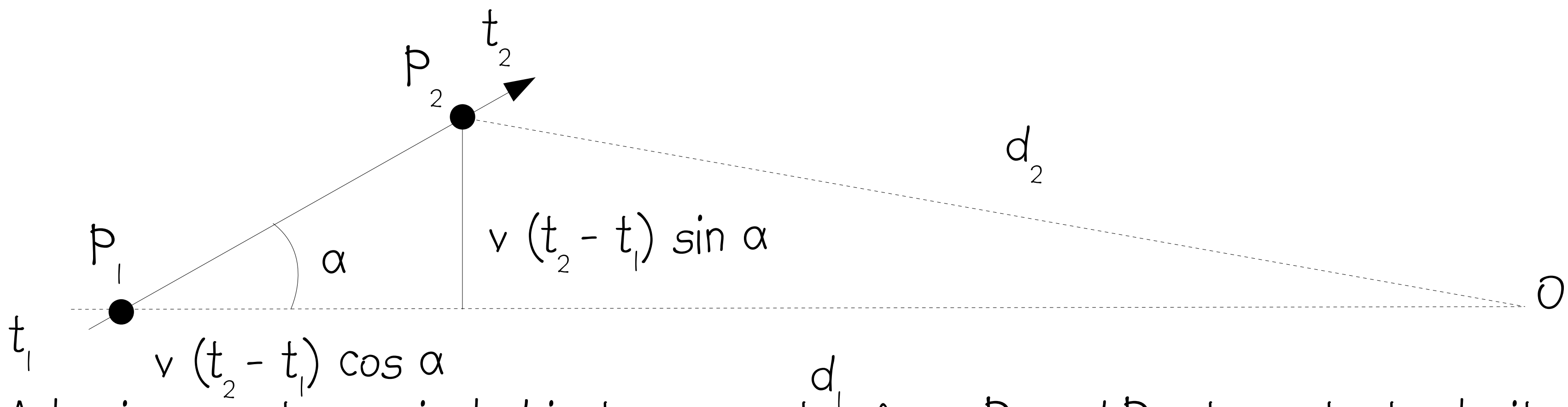
Time of flight measured from CERN to Gran Sasso in Italy by ICARUS.

http://arxiv.org/abs/1203.3433

$$\frac{\Delta c}{c} \leqslant 6\,10^{-6}$$

Superluminal velocities ?

Apparent superluminal velocities may be visually observed in the universe. Here's an example :



A luminous astronomical object propagates from P_1 and P_2 at constant velocity $v < c$.

O measures the time interval : $$\Delta t = t_2 - t_1 - \frac{(d_1 - d_2)}{c}$$

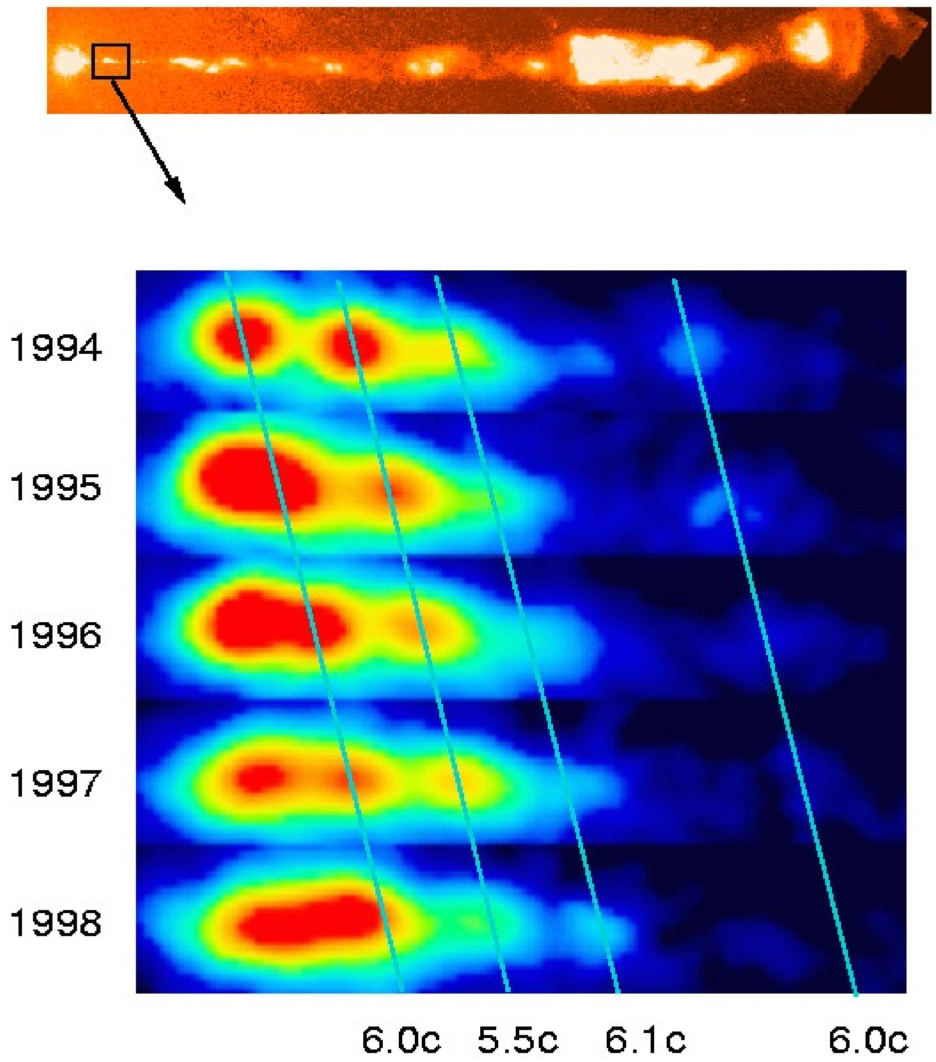
$$d_2 \simeq d_1 - v(t_2 - t_1)\cos\alpha \qquad \Delta t = (t_2 - t_1)(1 - \beta\cos\alpha)$$

During this time interval, O observes the apparent travelled distance $v\,(t_2 - t_1)\sin\alpha$

Finally the apparent velocity as measured by O is : $$V_O = c\,\frac{\beta\sin\alpha}{1-\beta\cos\alpha}$$

For a fixed velocity, the max value is obtained for $\cos\alpha = \beta$: $V_O^{max} = \gamma v$ which may exceed c if v is big

Superluminal Motion in the M87 Jet



To learn more :

-Special Relativity : A first encounter , Domenico Giulini, Oxford University Press

-http://math.ucr.edu/home/baez/physics/Relativity/SR/experiments.html

-Special Relativity and Its Experimental Foundations, Yuan-Chung Chang & Yuan-Zhong Zhang

-Relativité restreinte, Claude Semay et Bernard Silvestre-Brac, Dunod

-The Feynman lectures on physics, volume I , Addison-Wesley