

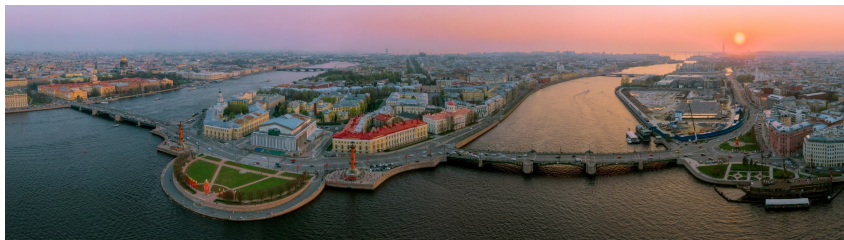
Dynamics of matter and energy

The lecture is dedicated to the memory of Professor P. A. Zhilin

A. M. Krivtsov

Peter the Great Saint Petersburg Polytechnic University

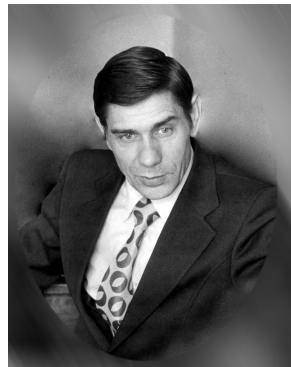
Institute for Problems in Mechanical Engineering RAS



The problem of rational description of general physical phenomena

Mechanics is a universal tool for describing almost any phenomena in the physical world. Methods borrowed from modern mechanics should be used to build a rational basis for general physical theories. Mechanical models help us achieve an intuitive understanding of physical phenomena and will play an important role in the development of new theories of the Universe¹.

Pavel A. Zhilin



¹Written down by A.M. Krivtsov from the words of P.A. Zhilin.

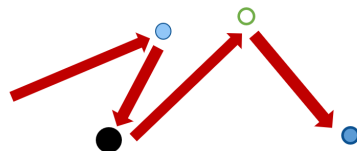
Some general phenomena

- Diffusive mass and energy transfer (classical diffusion and heat transfer)
- Dynamical mass transfer and wave energy transfer (dynamics of matter and ballistic heat transfer)
- Wave-particle duality in solid state physics (phonons and other quasiparticles)
- Wave-particle duality in quantum mechanics (any particles, especially the elementary ones)
- Kinetic description of wave processes: diffusive, anomalous, and ballistic (energy and heat transfer of various nature)

Diffusive and ballistic heat transfer

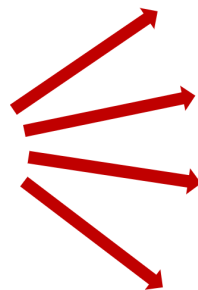
Diffusive heat transfer:

- Typical for macroscopic systems
- The result of reflection from defects and inhomogeneities
- Diffusive propagation of the elastic waves



Ballistic heat transfer:

- Realized in microsystems
- Observed in ultrapure materials
- Ballistic propagation of the elastic waves



Kinetic theory of heat transfer in solids

Waves are represented by *quasiparticles* (phonons), satisfying the kinetic theory of gases

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = \left(\frac{\partial f}{\partial t} \right)_{\text{coll}} \quad \text{Boltzmann transport equation}^2$$

Results:

- Heat conductivity in solids, especially in non-conducting crystals
- Second sound in solids

Open question:

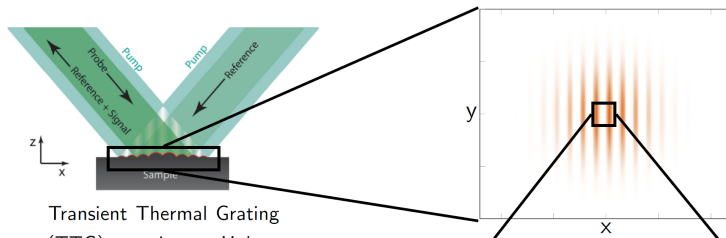
- Explicit connection with lattice dynamics

² f — distribution function, t — time, \mathbf{v} — *quasiparticle* velocity, $\left(\frac{\partial f}{\partial t} \right)_{\text{coll}}$ — collision term

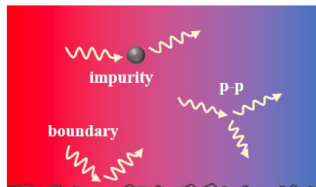
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3. R. Peierls. Zur kinetischen Theorie der Wärmeleitung in Kristallen. Annalen der Physik, 395(8):1055–1101, 1929.
4. S. Huberman, R.A. Duncan, K. Chen, B. Song, V. Chiloyan, Z. Ding, A.A. Maznev, G. Chen, and K.A. Nelson. Observation of second sound in graphite at temperatures above 100 k. Science, 364(6438):375–379, 2019.
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Kinetic description of heat transfer in solids



Transient Thermal Grating
(TTG) experiment, Huberman [4] (June 23, 18:25 Plenary)



Phonon scattering mechanisms,
Chen [7] (June 22, 10:10 Plenary)



TTG simulation, Falco and
Borisenkov (June 22, 15:00 Room B)

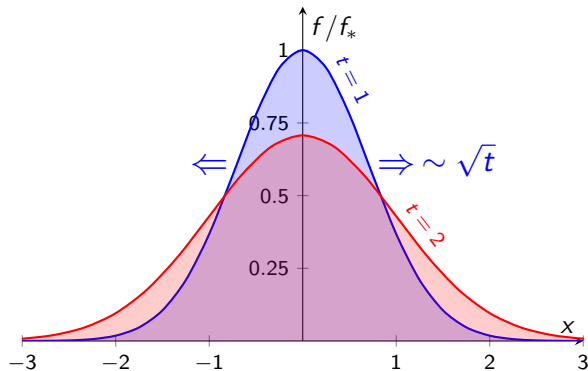
Diffusive transfer of mass or energy

- Diffusion equation

$$\dot{\rho} = \beta_{\rho} \rho''.$$

- Heat transfer equation

$$\dot{T} = \beta_T T''.$$



Spatial distribution of the transferred quantity at different moments of time; $f = f(x, t) \in \{\rho, T\}$; $f_* = f(0, 1)$.

Here ρ and T are the density and temperature, β_{ρ} and β_T are the diffusion and thermal conductivity coefficients, point and stroke are derivatives in time t and coordinate x .

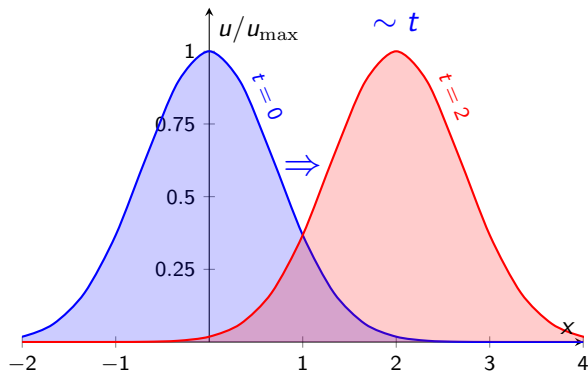
Wave transfer of mass or energy

- Wave equation (of the first order)

$$\dot{u} = cu'.$$

- General solution

$$u(x, t) = \varphi(x - ct).$$



Here $u = u(x, t)$ is a function of coordinate and time (perturbation of the medium), c is the wave velocity.

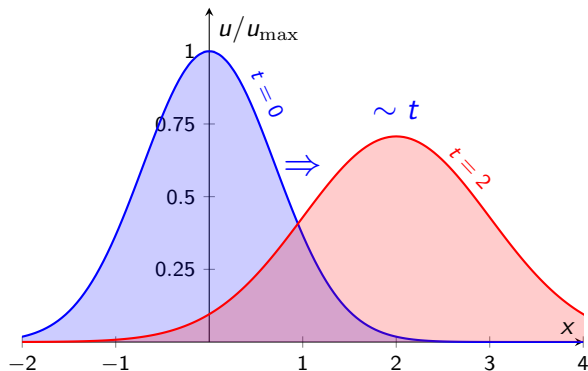
Wave transfer with dispersion

- System of wave equations

$$\dot{\varphi} = c(v)\varphi'.$$

- General solution

$$u(x, t) = \int_{-\infty}^{\infty} \varphi(x - c(v)t) dv.$$



Here $u = u(x, t)$ is a function of coordinate and time (perturbation of the medium), c is the wave velocity.

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Mass transfer and energy transfer (1D)

- The system of interacting particles

$$m_n \ddot{x}_n = F_n.$$

- Total mass

$$m = \sum_{n=1}^N m_n = \text{const.}$$

- Static moment

$$\mu = \sum_{n=1}^N m_n x_n.$$

- Inhomogeneous chain ($n \in \mathbb{Z}$)

$$m_n \ddot{u}_n = F_{n-\frac{1}{2}} - F_{n+\frac{1}{2}}.$$

- Total energy

$$E = \sum_n E_n = \text{const.}$$

- First moment of energy

$$M = \sum_n E_n \xi_n,$$

wher ξ_n is the particle reference position.

Center of mass and center of energy

- Center of mass

$$x_c = \frac{\mu}{m} = \frac{\sum_n m_n x_n}{\sum_n m_n}.$$

- Momentum

$$p = \dot{\mu} = \sum_n m_n \dot{u}_n.$$

- The velocity of the center of mass

$$v_c = \frac{p}{m} \quad \Leftrightarrow \quad p = m v_c.$$

- Center of energy

$$x_c = \frac{M}{E} = \frac{\sum_n E_n \xi_n}{\sum_n E_n}.$$

- Total energy flux

$$h = \dot{M} = \sum_n \dot{E}_n \xi_n.$$

- The velocity of the center of energy

$$v_c = \frac{h}{E} \quad \Leftrightarrow \quad h = E v_c.$$

Inhomogeneous chain: explicit formulas

- Total energy

$$E = \sum_n E_n = \sum_n \left(\frac{1}{2} m_n v_n^2 + \Pi_{n+\frac{1}{2}} \right).$$

- Total energy flux

$$h = \frac{1}{2} \sum_n (v_{n+1} + v_n) F_{n+\frac{1}{2}} a_{n+\frac{1}{2}}.$$

Here the following designations for the particle velocity and the bond length are used:

$$v_n = \dot{u}_n, \quad a_{n+\frac{1}{2}} = \xi_{n+1} - \xi_n;$$

for the force and the potential energy:

$$F_{n+\frac{1}{2}} = F_{n+\frac{1}{2}}(u_{n+1} - u_n), \quad \Pi_{n+\frac{1}{2}} = \Pi_{n+\frac{1}{2}}(u_{n+1} - u_n).$$

Equations of dynamics

- Balance of the momentum

$$\dot{p} = F.$$

- The theorem of the center of mass motion

$$m\dot{v}_c = F.$$

- Net force

$$F = \sum_n F_n.$$

- Balance of the total energy flux

$$\dot{h} = \Phi.$$

- Dynamics of the energy center

$$E\dot{v}_c = \Phi.$$

- Net force analogue

$$\Phi = ?$$

According to Newton's 3rd law, internal forces do not contribute to the net force. The force analogue is calculated on the base of the chain dynamics equations.

Inhomogeneous chain: explicit formulas

Net force analogue

$$\Phi = \sum_n \left(\Phi_n^{(a)} + \Phi_n^{(C)} + \Phi_{n+\frac{1}{2}}^{(m)} \right).$$

Local force analogues caused by inhomogeneity of the stiffness, length, mass:

$$\Phi_n^{(a)} = \left(\frac{v_n^2}{4} \left(C_{n+\frac{1}{2}} + C_{n-\frac{1}{2}} \right) + \frac{F_{n+\frac{1}{2}} F_{n-\frac{1}{2}}}{2m_n} \right) \left(a_{n+\frac{1}{2}} - a_{n-\frac{1}{2}} \right),$$

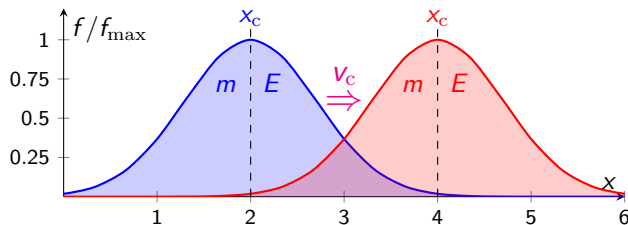
$$\Phi_n^{(C)} = \frac{(a_{n+\frac{1}{2}} + a_{n-\frac{1}{2}}) v_n^2}{4} \left(C_{n+\frac{1}{2}} - C_{n-\frac{1}{2}} \right), \quad \Phi_{n+\frac{1}{2}}^{(m)} = \frac{a_{n+\frac{1}{2}} F_{n+\frac{1}{2}}^2}{2} \left(\frac{1}{m_{n+1}} - \frac{1}{m_n} \right).$$

Potential energy, strength, and generalized bond stiffness:

$$\Pi_{n+\frac{1}{2}} = \Pi_{n+\frac{1}{2}}(u_{n+1} - u_n), \quad F_{n+\frac{1}{2}} = \Pi'_{n+\frac{1}{2}}(u_{n+1} - u_n), \quad C_{n+\frac{1}{2}} = \Pi''_{n+\frac{1}{2}}(u_{n+1} - u_n).$$

Analogy in the transfer of mass and energy

mass	m	E	energy
static moment	μ	M_1	moment of energy
momentum	p	h	energy flux
net force	f	Φ	force analogue
center of mass	x_c		center of energy
mass transfer velocity	v_c		energy transfer velocity



Effective characteristics for the energy distribution

Effective mass, static moment, momentum, force:

$$m = E/c^2, \quad \mu = M/c^2, \quad p = h/c^2, \quad f = \Phi/c^2,$$

where c is the characteristic velocity of wave propagation in the medium.

In particular, the following relation is fulfilled

$$E = mc^2.$$

Energy dynamics

Carrier: is a transmission medium for energy (something that can mediate the propagation of energy).

Body of energy: is an energy distribution in a carrier moving according to the analogue of the Newton's second law.

Phantom: is an effective (imaginary) body of matter, having the mass distribution proportional the energy distribution in the corresponding body of energy.

Dynamics of energy: is a physical theory describing motion of energy bodies and corresponding phantoms as induced by effective forces.

Example: motion of a phantom in a one-dimensional chain

Particle masses and bond lengths are the same:

$$m_n = m_e, \quad a_n = a.$$

Phantom dynamics:

$$m\ddot{x}_c = f.$$

Expression for the net force of

$$f = \frac{a}{2c^2} \sum_n \left(C_{n+\frac{1}{2}} - C_{n-\frac{1}{2}} \right) v_n^2.$$

- Constant stiffness: $C_n = C$. There is no force, the motion is uniform:

$$x_c = x_0 + v_c t.$$

- Linearly increasing stiffness: $C_n = Dn$. Constant force, equidistant motion:

$$x_c = x_0 + v_0 t + \frac{Da}{4m_e} t^2.$$

- Inverse stiffness: $C_n = A/n$. Newton's force, motion in a gravitational field:

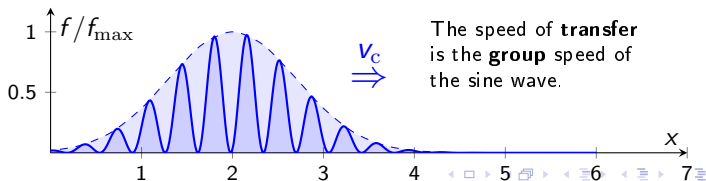
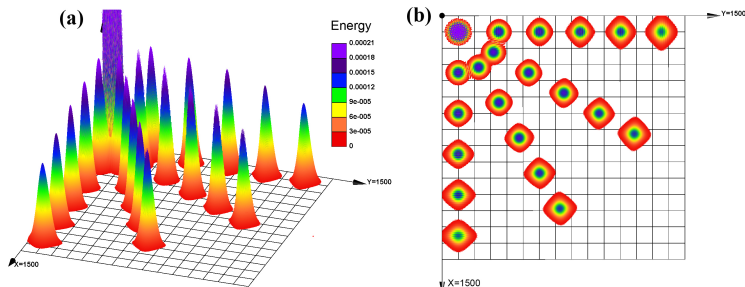
$$\ddot{x}_c = -\frac{Aa}{2m_e} \frac{1}{x_c^2}.$$

Phantoms in a two-dimensional lattice

Transverse oscillations of a square homogeneous harmonic lattice.

The force is zero, the motion is uniform.

Calculations by N.M. Bessonov in collaboration with J.A. Baimova.



The speed of **transfer** is the **group** speed of the sine wave.

Phantom structure:

Dispersion of mass and energy

- A set of free particles

$$m_n \ddot{x}_n = 0.$$

- Moment of inertia

$$\theta = \sum_{n=1}^N m_n x_n^2.$$

- The central moment of inertia

$$\theta = \sum_{n=1}^N m_n (x_n^2 - x_c^2).$$

- The Hooke chain ($n \in \mathbb{Z}$)

$$m_e \ddot{u}_n = C(u_{n+1} - 2u_n + u_{n-1}).$$

- 2nd moment of energy

$$M_2 = \sum_n E_n \xi_n^2.$$

- 2nd central moment of energy

$$M_c = \sum_n E_n (\xi_n^2 - x_c^2).$$

Kinetic energy

Differential relation between the inertia tensor and kinetic energy

$$\ddot{\theta} = 4K.$$

Proof (for a set of free particles):

$$\ddot{\theta} = 2 \sum_{n=1}^N m_n (x_n \dot{x}_n) \dot{} = 2 \sum_{n=1}^N m_n (x_n \ddot{x}_n + \dot{x}_n^2) = 2 \sum_{n=1}^N m_n v_n^2 = 4K = \text{const.}$$

Central quantities

$$\theta = \theta_c + m x_c^2, \quad K = K_c + \frac{1}{2} m v_c^2, \quad \ddot{\theta}_c = 4K_c.$$

K_c characterizes the energy of expansion relative to the center of mass.

Kinetic energy



K_c characterizes the kinetic energy of expansion relative to the mass center of the cloud

Inertia radius and energy radius

- Radius of inertia

$$\rho = \sqrt{\frac{\theta_c}{m}}.$$

- Kinetic energy of the system

$$K_c = \frac{1}{4}\ddot{\theta}_c = \text{const.}$$

- Energy radius

$$\rho = \sqrt{\frac{M_c}{E}}.$$

- Kinetic energy of the phantom

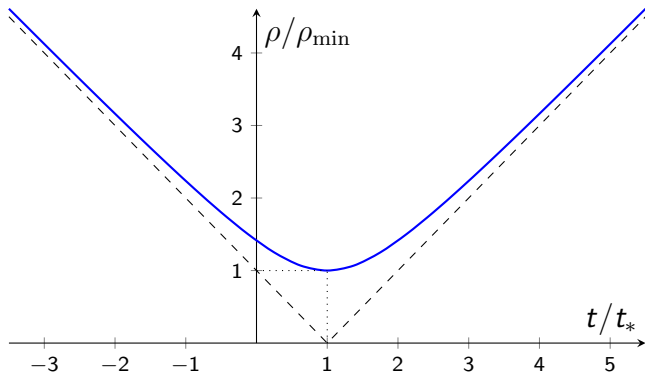
$$K_c = \frac{1}{4c^2}\ddot{M}_c = \text{const.}$$

Dispersion rate

$$v_\rho = \sqrt{\frac{2K_c}{m}} \Leftrightarrow K_c = \frac{mv_\rho^2}{2}.$$

Evolution of the inertia radius

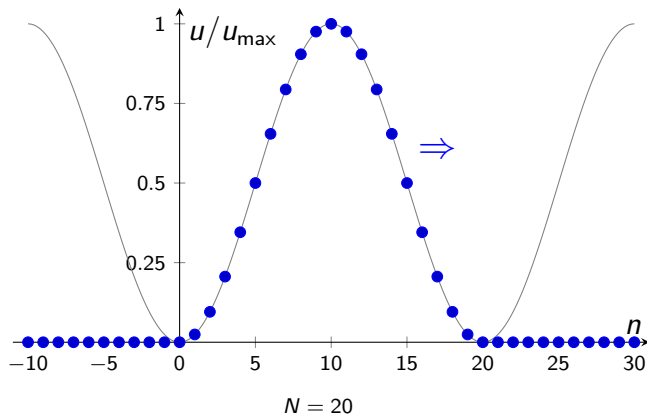
Dependence of the radius on time: $\rho = \sqrt{\rho_{\min}^2 + v_{\rho}^2(t - t_*)^2} \approx v_{\rho}|t - t_*|$.



The dependence is valid for both the radius of inertia and the energy radius.

Evolution of the Phantom (1D)

A phantom based on a single sine wave.

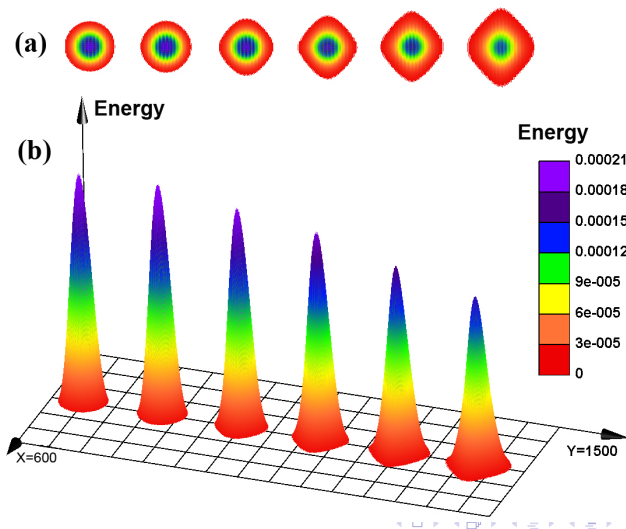


N	v_c/c	v_ρ/c
2	0.00	0.50
3	0.50	0.35
5	0.81	0.19
10	0.95	0.07
20	0.99	0.02
50	1.00	0.01

Evolution of the Phantom (2D)

Motion and dispersion of a phantom in a two-dimensional square lattice.

Calculations by
N.M. Bessonov in
collaboration with
J.A. Baimova.

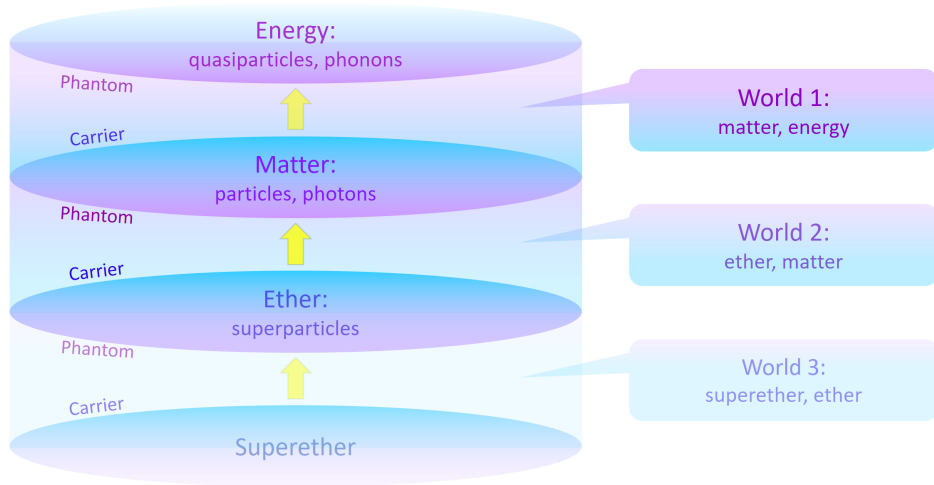


Application of energy dynamics for the description of quantum, electromagnetic, and relativistic phenomena

The basic principle

- Any body of matter can be represented as a phantom in a certain carrier.
- The phantom represents the energy distribution in the carrier, therefore the phantom is a fundamentally different entity than the carrier.
- The carrier for the phantom is a kind of space where the phantom moves.

The worlds hierarchy



P. A. Zhilin in paper "Reality and Mechanics" (1996) has considered a sequence of ethers as a conceptual model for description of general physical phenomena.

Questions / answers

Now, using ideas of energy dynamics, let us suggest qualitative answers to some open questions of modern physics.

What is wave-particle dualism?

- The phantom, initially localized in a certain area of the carrier, moves at a constant speed, gradually dispersing.
- Either motion or dispersion prevails depending on the initial conditions.
- If the speed of motion is significantly higher than the speed of dispersion, then the phantom is perceived as a particle.
- In the opposite case, the behavior of the phantom corresponds to our intuitive perception of a wave.

What is the nature of gravity?

- If the phantom has a sufficiently large mass, then the corresponding energy distribution leads to a notable deformation of the carrier.
- In the deformed carrier the speed of other phantoms is not constant, which is perceived as an action of gravitational force.
- This, in particular, explains the long-range effect inherent in gravity.

What is the curvature of space?

- The space for the phantom is the structure of the carrier.
- The energy clot described by the phantom deforms the carrier, and this deformation is perceived as a curvature of the space.
- This explains the curvature of space by massive bodies, described by general theory of relativity.

How can time slow down?

- The time for the phantom is counted by the vibrations of the carrier particles.
- Nonlinear oscillations are characterized by a decrease in frequency with an increase in amplitude.
- If the phantom has a sufficiently high energy, then this leads to a decrease in the frequency of vibrations, which is perceived as a time slowing down.
- This explains the time slowing down in the gravitational field of massive bodies, described by general theory of relativity.

How can light propagate in empty space?

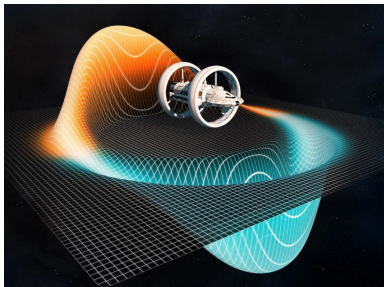
- There is no empty space, the space is filled with a carrier.
- Light (electromagnetic waves) is an energy propagating in the carrier.
- For the observed electromagnetic wavelengths, the transfer velocity of the corresponding phantom significantly exceeds its dispersion speed, which explains the corpuscular properties of light.

Why was the ether not detected?

- When trying to find the ether, it was perceived as matter, a kind of substance.
- This leads to a contradiction that massive bodies move in this substance without any resistance.
- According to the presented concept, the phantom and the carrier, and, consequently, matter and ether, are fundamentally different entities.
- The phantom just represents an energy distribution in the carrier, and the corresponding energy distribution can move in the carrier without any resistance.
- On the other hand, the carrier for the phantom is kind of space, but not a substance, and this challenges the carrier detection.

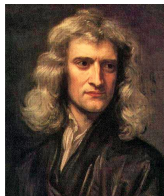
Why is it impossible to move faster than the speed of light?

- Any motion of matter is a propagation of energy in the carrier.
- In a linear theory, energy cannot propagate faster than the maximum wave propagation velocity in the carrier.
- In a nonlinear theory, a faster propagation of strong waves is possible, but it is associated with the deformation of the carrier, and, therefore, with the curvature of space.



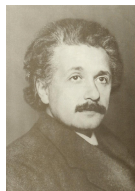
This is analogous to the phenomenon of faster-than-light travel caused by the Alcubierre metric, which is in consistence with general relativity.

M. Alcubierre. The warp drive: hyper-fast travel within general relativity. *Classical and Quantum Gravity*. 1994. **11** (5), 73–77.



Tis unconceivable that inanimate brute matter should (without the mediation of something else which is not material) operate upon & affect other matter without mutual contact... Gravity must be caused by an agent acting constantly according to certain laws, but *whether this agent be material or immaterial* is a question I have left to the consideration of my readers.

I. Newton. A letter to Richard Bentley. Cambridge. 25 February 1693.



According to the general theory of relativity *space without ether is unthinkable*; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time... But this *ether may not be thought of as* endowed with the quality characteristic of *ponderable media*.

A. Einstein. Ether and the theory of relativity. An address delivered on May 5th, 1920, in the University of Leyden.

Thank you for your attention!

Additional information:

A. M. Krivtsov. Dynamics of matter and energy. ZAMM. 2022

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