PHYSICS, COSMOLOGY AND EXPERIMENTAL SIGNATURES OF A POSSIBLE NEW CLASS OF SUPERLUMINAL PARTICLES

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The apparent Lorentz invariance of the laws of physics does not imply that space-time is indeed minkowskian. We consider a scenario where Lorentz invariance is only an approximate property of equations describing a sector of matter at a given scale and superluminal sectors of matter exist related to new degrees of freedom not yet discovered experimentally. The new particles would not be tachyons: they may feel different minkowskian space-times with critical speeds much higher than c (speed of light) and behave kinematically like ordinary particles apart from the difference in critical speed. Superluminal particles may provide most of the matter at cosmic scale, and be mainly dark. We present a discussion of possible theoretical, cosmological and experimental consequences of such a scenario, with particular emphasis on problems related to the identification of dark matter.

1 Lorentz invariance and superluminal sectors

1.1 Relativity and sine-Gordon solitons

In textbook special relativity, minkowskian geometry is an intrinsic property of space and time. However, a look to various dynamical systems would suggest a more flexible approach to the relation between matter and space-time. Lorentz invariance can be viewed as a symmetry of the equations of motion, in which case no reference to absolute properties of space and time is required. In a two-dimensional galilean space-time, the equation:

\[ \alpha \frac{\partial^2 \phi}{\partial t^2} - \frac{\partial^2 \phi}{\partial x^2} = F(\phi) \]  

(1)

with \( \alpha = 1/c_o^2 \) and \( c_o = \) critical speed, remains unchanged under "Lorentz transformations" leaving invariant the squared interval \( ds^2 = dx^2 - c_o^2 dt^2 \), so that matter made with solutions of equation (1) would feel a relativistic space-time even if the real space-time is actually galilean and if an absolute frame exists in the underlying dynamics beyond the wave equation. A well-known example is provided by the solitons of the sine-Gordon equation, obtained taking in (1): \( F(\phi) = (\omega/c_o)^2 \sin \phi \). A two-dimensional universe made of
sine-Gordon solitons plunged in a galilean world would feel a two-dimensional minkowskian space-time with the laws of special relativity. Information on any absolute rest frame would be lost by the solitons.

1-soliton solutions of the sine-Gordon equation are known to exhibit "relativistic" particle properties, e.g. \( E = E_0 \left( 1 - \frac{v^2}{c_0^2} \right)^{-1/2} \), where \( v \) is the soliton speed and \( E_0 \) its rest energy, so that everything looks perfectly "minkowskian" even if the basic equation derives from a galilean world with an absolute rest frame. Similarly, in the real world, the speed of light \( c \) could be just the sectorial critical speed of a part matter (the "ordinary" particles), instead of a universal critical speed deriving from absolute geometric properties of space and time as usually stated in relativity theory.

### 1.2 Superluminal particles

If Lorentz invariance is only an approximate property of equations describing a sector of matter above a given distance scale, and absolute frame (the "vacuum rest frame") can exist without contradicting the minkowskian structure of the space-time felt by "ordinary" particles (those with critical speed equal to \( c \)). Then, \( c \) will not necessarily be the only critical speed in vacuum: for instance, superluminal sectors of matter may exist related to new degrees of freedom not yet discovered experimentally. Such particles would not be tachyons: they may feel different minkowskian space-times with critical speeds \( c_i \gg c \) (the subscript \( i \) stands for the \( i \)-th superluminal sector), and behave kinematically like "ordinary" particles apart from the difference in critical speed. A superluminal sector of matter can be built as follows.

Ordinary free particles in vacuum usually satisfy a dalembertian equation, such as the Klein-Gordon equation for scalar particles:

\[
(c^{-2} \frac{\partial^2}{\partial t^2} - \Delta) \phi + m^2 c^2 (\hbar/2\pi)^{-2} \phi = 0
\]

where the coefficient of the second time derivative sets \( c \), the critical speed in vacuum (speed of light). Given \( c \) and the Planck constant \( \hbar \), the coefficient of the linear term in \( \phi \) sets \( m \), the mass. To study solutions of the wave equation, we consider the conserved observables:

\[
E = i (\hbar/2\pi) \frac{\partial}{\partial t}, \quad \vec{p} = -i (\hbar/2\pi) \vec{\nabla}
\]

and get plane wave solutions from which we can build position and speed operators. In the non-relativistic limit, it can be checked that \( m \) is indeed the inertial mass. With the conservative choice of leaving the Planck constant unchanged, superluminal sectors of matter can be generated replacing in the above construction the speed of light \( c \) by a new critical speed \( c_i \) for the \( i \)-th
superluminal sector. All previous concepts remain valid, leading to particles with positive mass and energy which are not tachyons. For inertial mass $m$ and critical speed $c_i$, the new particles will have rest energies:

$$E_{\text{rest}} = mc_i^2$$

which, for a given inertial mass, are much higher than the rest energies of "ordinary" particles. This generalization of the Einstein equation implies in particular that: a) in accelerator experiments, very high energies can be required to produce superluminal particles; b) cosmic ray events originating from superluminal particles can release very high energies.

1.3 A scenario with several critical speeds in vacuum

In what follows, we shall consider a scenario with several sectors of matter: a) the "ordinary" sector, made of "ordinary" particles with a critical speed equal to the speed of light $c$; b) one or more superluminal sectors, where particles have critical speeds $c_i \gg c$ in vacuum, and each sector is assumed to have its own Lorentz invariance with $c_i$ defining the metric.

If the standard minkowskian space-time is not a compulsory framework, we can conceive fundamentally different descriptions of space and time. Space-time can, for instance, be galilean, or minkowskian with an absolute critical speed $C \gg c$. Another possibility, requiring an absolute origin, would be to consider a $SU(2)$ spinorial space-time where time would correspond to the spinor modulus (a $SU(2)$ scalar, positive definite and therefore setting an arrow of time), and the three space dimensions would originate from the tangent hyperplane to the $S^3$ hypersphere of constant modulus in the $C^2$ (topologically equivalent to $R^4$) spinor space. In this tangent hyperplane, the three independent directions correspond to the three $SU(2)$ generators and therefore define a vector representation of $SU(2)$.

Even if each sector has its own "Lorentz invariance" involving as the basic parameter the critical speed in vacuum of its own particles, interaction between two different sectors will break both Lorentz invariances. The concept of mass, as a relativistic invariant, will become approximate and sectorial. In our approach, the vacuum is a material medium as suggested by recent results in particle physics, and the Michelson-Morley result is not incompatible with the existence of some "ether" defining an absolute local rest frame (the "vacuum rest frame"). If superluminal particles couple weakly to ordinary matter, their effect on the ordinary sector will occur at very high energy and short distance, far from the domain of successful conventional tests of Lorentz invariance. The actual structure of space and time will be found only by going beyond the above wave equations to deeper levels of resolution, similar to
the way high-energy accelerators explore the inner structure of "elementary" particles.

Our scenario is far from being the first case in which several critical speeds coexist in a medium. In a perfectly transparent crystal close to zero temperature, two critical speeds exist: the speed of sound and the speed of light.

2 Dynamics and cosmology

Mass mixing between particles from different sectors may occur and, although very weak, be more significant for very light particles (e.g. photons, neutrinos...). Since the graviton is an "ordinary" gauge boson, associated to ordinary Lorentz invariance, it is not expected to play a universal role in the presence of superluminal particles. Assuming that each superluminal sector has its own Lorentz metric $g_{[i] \mu \nu}$ (for the $i$-th sector), with $c_i$ setting the speed scale, we may expect each sector to generate its own gravity with a coupling constant $\kappa_i$ and a sectorial graviton traveling at speed $c_i$. "Gravitational" interactions between different sectors will be weak and concepts so far considered as very fundamental (e.g. the universality of the exact equivalence between inertial and gravitational mass) will become approximate sectorial properties.

If superluminal sectors couple to ordinary matter, they are expected to release "Cherenkov" radiation (e.g. spontaneous emission of particles whose critical speed is lower than the speed of the particle) in vacuum when they move at a speed $v > c$. Thus, superluminal particles will be eventually decelerated to a speed $v \leq c$. The nature and rate of "Cherenkov" radiation in vacuum will depend on the superluminal particle and can be very weak in some cases. In accelerator experiments, this "Cherenkov" radiation may provide a clean signature allowing to identify some of the produced superluminal particles.

If each sectorial Lorentz invariance is expected to break down below a critical distance scale $k_i^{-1}$, $k_o^{-1}$ for the ordinary sector, where the $k_i$ and $k_o$ are critical wave vector scales, we can expect the appearance of critical temperatures $T_o$ and $T_i$ defined by:

$$kT_o \approx \hbar c k_o,$$
$$kT_i \approx \hbar c_i k_i$$

(5)

defining phase transitions in field theories, as well as in the very early Universe. These singularities seem to prevent conventional extrapolations to a Big Bang limit. Above $T_o$, the Universe may have contained only superluminal particles and dynamical correlations have been able to propagate much faster than light. This invalidates standard arguments leading to the so-called "horizon problem" and "monopole problem". Conventional Friedmann equations will not hold in the new scenario, and the need for inflation is far from obvious. In the
above considered spinorial space-time, the Big Bang limit can possibly be related to the absolute origin in the spinor space. In this approach, it seems impossible to set a "natural time scale" based on extrapolations (e.g. to Planck time) from our knowledge of the low energy sector. Arguments leading to the "flatness" and "naturalness" problem, as well as the concept of the cosmological constant and the relation between critical density and Hubble's "constant" (one of the basic arguments for ordinary dark matter at cosmic scale) should be reconsidered. Superluminal particles may have played a cosmological role leading to substantial changes in the "Big Bang" theory. They can be very abundant and even provide nowadays most of the (dark) matter at cosmic scale, therefore leading the present evolution of the Universe.

3 Superluminal particles and dark matter identification

If superluminal particles are very abundant, they can, in spite of their expected weak coupling to "ordinary" gravitation, produce some observable gravitational effects. It is not obvious how to identify the superluminal origin of a collective gravitational phenomenon, but signatures may exist, e.g. in gravitational collapses or if it were possible to detect superluminal gravitational waves. We do not in general expect concentrations of superluminal matter to follow those of ordinary matter, but this is not excluded, e.g. in the presence of coupled gravitational singularities involving several sectors. If astrophysical concentrations of superluminal particles produce high-energy particles, cosmic rays may provide a unique way to detect such objects. Direct detection of particles from superluminal matter around us, e.g. in underground and underwater detectors, should not be discarded. At very high energy, they can escape the Greisen-Zatsepin-Kuzmin cutoff and be at the origin of the highest-energy events. At lower energies, they can produce detectable signals.

3.1 Superluminal primaries

High-energy superluminal particles can be produced from acceleration, decays, explosions... in astrophysical objects made of superluminal matter, or from "Cherenkov" emission in vacuum by particles with higher critical speed. They can reach the earth and undergo collisions inside the atmosphere, producing many secondaries like ordinary cosmic rays. They can interact with the rock or with water near some underground or underwater detector, coming from the atmosphere or after having crossed the earth. Contrary to neutrinos, whose flux is attenuated by the earth at energies above $10^6 \text{ GeV}$, superluminal particles will in principle not be stopped by earth at these energies. Such primaries can release most of their energy in inelastic collisions, and rather
high energies (with momentum transfer of the order of the incoming momen-
tum) in elastic scattering. Low-energy superluminal particles can also produce
detectable events. At $v \approx c$ (after ”Cherenkov” deceleration in vacuum), su-
perluminal primaries can produce recoil protons and neutrons in the GeV range
and inelastic events of higher energies. Such events would be detectable, e.g.
in Cherenkov detectors for neutrino astronomy, even at very small rates. In
cryogenic detectors, unconventional recoil spectra (e.g. indicating an escape
velocity much above $10^{-3}c$) can be a signature for superluminal dark matter.

3.2 Ordinary primaries

Annihilation of pairs of slow superluminal particles, releasing very high kinetic
energies from the relation $E = mc^2$, can be a source of high-energy ordinary
and superluminal cosmic rays. Decays and ”Cherenkov” radiation in vacuum
can produce similar effects. Thus, ordinary cosmic rays can be produced any-
where and not just near astrophysical objects made of ordinary matter.

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