Paths of Discovery
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GOING FROM QUARKS TO GALAXIES: TWO FINDINGS

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Introduction and Motivation

This talk is a brief summary of applications of power scaling laws in two different settings, in the micro- and the macro-world. The power scaling laws are widely used not only in physics, but also in life sciences, chemistry, and engineering. The remarkable scaling laws could be obtained by a combination of a few simple dimensional considerations with specific physical conjectures. The basis of method was presented for the first time by Galileo Galilei. Scaling ideas of Galileo it was later elaborated by Fourier, Lord Rayleigh and others and today is widely used in physics under the name of *Dimensional Analysis* [1]. The 2004 Nobel prize in Physics was awarded for revealing the 'asymptotic freedom' and 'infrared confinement' in QCD (Quantum Chromodynamics) by means of the renormalization group theory, which can be considered as the modern method for dealing with Galileo scaling.

The first part of this talk is based on common work with V. Matveev and A. Tavkhelidze [2] on the Dimensional Quark Counting Rules, later confirmed within the framework of QCD by G. Lepage and S. Brodsky [3].

The second part is dedicated to the suggestion of *spin-mass scaling rules in astrophysics* [8-12]. It is shown that these rules can be expressed by fundamental constants only without any adjustable parameter. A surprising resemblance between *angular momentum & mass* dependence of elementary particles and cosmic objects demonstrates remarkable unity of Nature on a huge scale. A probable solution of the old and most difficult problem of astrophysics – the problem of the origin of the rotation of planets, stars, galaxies and their systems – is proposed.

1. Scaling Laws and Quark Structure of Hadrons

A rise in interest in scaling laws in hadron physics was generated by the discovery of Bjorken scaling [4] and its generalization for lepton-hadron deep inelastic processes [5, 6]. This development was finally accomplished by the discovery of *Dimensional Quark Counting Rules* in exclusive processes [2] in 1973, before the development of QCD.

It is well known that, for understanding the structure of matter at smaller and smaller distances, it is necessary to collide particles with larger and larger momentum transfer. Transverse momentum $P_{\perp} \approx 10\, GeV/c$ corresponds to resolution of details at the distance of the order of $10^{-15}\, cm$.

For an exclusive two-body reaction $ab \to cd$ at high momentum $p_{\perp} \approx 10\, Gev/c$ transfer and fixed large scattering angle the Quark Counting Rule predict:

$$\frac{d\sigma^{ab \to cd}(s,t)}{dt} \sim \frac{1}{s^{n-2}} f\left(\frac{t}{s}\right) \tag{1.1}$$

where s and t are Mandelstam variables, s is the square of the total energy in the center-of-mass frame and t is the momentum transfer squared, $n = n_a + n_b + n_c + n_d$ is total number of constituents and n_i $i = a,b,c,d$ is the number of quarks in $1-$th hadron. The most interesting feature of the predicted exclusive cross-section is that it falls slowly, not as Gaussian or exponent, but as inverse power of, and the exponent of this power is directly related to the total number of quarks in scattering hadrons. This rule was derived in 1973 [2] and later confirmed experimentally in many exclusive measurements [7] and theoretically in the framework of perturbative QCD.

In [2] the asymptotic power law for electromagnetic form factors in particle and nuclear physics was also established. For hadronic or nuclear objects with constituents the corresponding form factor behaves as

$$F_n(t) \sim \frac{1}{t^{n-1}} \tag{1.2}$$

The amazing examples for agreement with the experiment are provided by the study of the form factors of pions, nucleons and light nuclei

$$F_{\pi}(t) \sim \frac{1}{t},\; F_{N}(t) \sim \frac{1}{t^2},\; F_{d}(t) \sim \frac{1}{t^5},\; F_{^3He}(t) \sim \frac{1}{t^8},\; F_{^4He}(t) \sim \frac{1}{t^{11}}. \tag{1.3}$$

2. Spin-Mass Scaling Laws and Origin of the Universe

At all scales of the Universe, from tiny elementary particles to huge celestial bodies, we observe rotating objects. Understanding the Universe is impossible without understanding the source of the spin or angular momentum of cosmic bodies. The Universe is filled with rotation: asteroids, planets and their moons, stars, interstellar clouds of gas, globular clusters, galaxies and their clusters rotate around a central axis, and everything orbits around everything else in a hierarchical manner (moons around their planet, planets around their star, stars around the center of their galaxy or globular cluster, galaxies around the center of their galaxy cluster). Spin or angular momentum is a conserved quantity: the total amount of rotation in the whole Universe must be constant. Rotation cannot just appear or disappear, but is innate, earliest, basic motion. When and how was the angular momentum acquired by celestial bodies? Can the rotation serve as the Rosetta Stone of Astrophysics? The problem of the origin of rotation in stars, galaxies and clusters is an open problem (*enfant terrible*) of astrophysics and cosmology. Here we will outline new insights into the origin of cosmic rotation, provided by the application of the Regge-Chew-Frautschi paradigm in astrophysical context.

Much of what we present here is based on [8]. In elementary particle physics after the works of T. Regge, G. Chew and S. Frautschi it has become clear that the spin J and mass m of hadrons are not independent quantities but are connected by a simple scaling relation

$$J = \hbar\left(\frac{m}{m_p}\right)^{2} \qquad (2.1)$$

where $\hbar = 1.055\times10^{-34}\ J{\cdot}s$ is Planck's constant and $m_p = 1.673\times10^{-27}\,kg$ is the proton mass. This formula is well satisfied by experimental data obtained in high energy physics laboratories. The present author suggested following the extension of (2.1), using dimensional analysis and similarity considerations:

$$J = \hbar\left(\frac{m}{m_p}\right)^{1+\frac{1}{n}} \qquad (2.2)$$

The number $n = 1, 2, 3$ in exponent takes the integral value n characterizing the spatial dimensionality (shape) of a spinning object. The choice

$n=2$ for galaxies, their clusters and superclusters, and $n=3$ for planets and stars are in brilliant agreement with the observations:

$$n=1: \quad J=\hbar\left(\frac{m}{m_p}\right)^{2}, \quad \textit{string (hadrons)} \tag{2.3}$$

$$n=2: \quad J=\hbar\left(\frac{m}{m_p}\right)^{3/2}, \quad \textit{disk (galaxies)} \tag{2.4}$$

$$n=3: \quad J=\hbar\left(\frac{m}{m_p}\right)^{4/3}, \quad \textit{ball (stars)} \tag{2.5}$$

These relations represent a surprising resemblance between *spin & mass* dependence of elementary particles and cosmic objects. It seems it is *the first time in the history of astronomy and physics that the spin of celestial bodies has been predicted from known mass using fundamental constants only.*

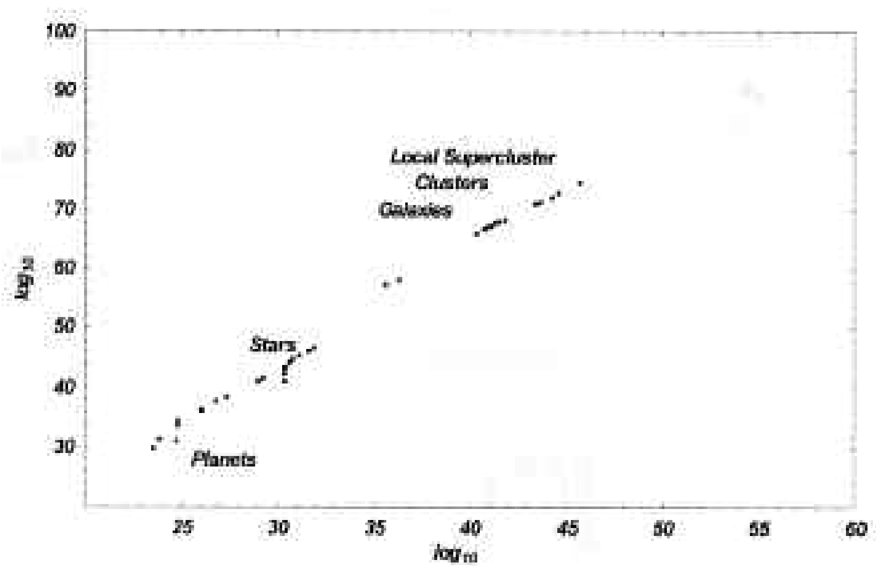

Fig. 1. Observational data on spins versus masses for diverse celestial objects. SI units are used.

For galaxies, their clusters and perhaps for the Universe itself Fig. 1 represents observational data on the $\log_{10}-\log_{10}$ plot for a whole spectrum of astronomical objects (see [11] and references therein). Fig. 2 is a pure theoretical construct and presents three straight lines

$$J = \hbar\left(\frac{m}{m_p}\right)^{4/3} = 53.114\times m^{4/3} \tag{2.6}$$

$$J = \hbar\left(\frac{m}{m_p}\right)^{3/2} = 1.5412\times 10^{6}\times m^{3/2} \tag{2.7}$$

$$J_{Kerr} = \frac{Gm^2}{c} = 2.226\times 10^{-19}\times m^2 \tag{2.8}$$

where J_{Kerr} is gravitational Kerr spin-mass relation for maximally rotating black hole.
The coordinates of the intersection points are

$$m_{Edd} = m_p\left(\frac{\hbar c}{Gm_p^2}\right)^2, \quad J_{Edd} = \hbar\left(\frac{\hbar c}{Gm_p^2}\right)^3 \tag{2.9}$$

$$m_{Ch} = m_p\left(\frac{\hbar c}{Gm_p^2}\right)^{3/2}, \quad J_{Ch} = \hbar\left(\frac{\hbar c}{Gm_p^2}\right)^2 \tag{2.10}$$

These points can be named as

$$\textit{Eddington point} \Rightarrow \{m_{Edd}, J_{Edd}\} \tag{2.11}$$

$$\textit{Chandrasekhar point} \Rightarrow \{m_{Ch}, J_{Ch}\} \tag{2.12}$$

The *Eddington point* corresponds to the crossover of the Regge trajectory for disk-like objects with Kerr angular momentum. In the same manner the *Chandrasekhar point* corresponds to the crossover of the Regge trajectory for the ball with J_{Kerr}.

Fig. 3 represents an additive sum of Fig.1 and Fig. 2 and, in some sense, is a generalized Chew-Frautshi plot in astrophysics.

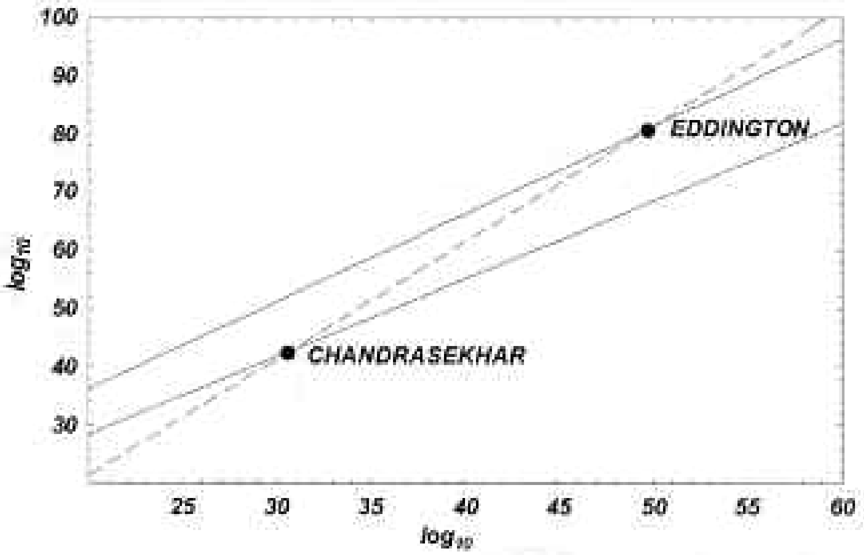

Fig. 2. Three theoretical straight lines are shown on the log-log plane.
a). The lower uninterrupted line

$$\log J = 1.725 + \frac{4}{3}\log m,$$

is a logarithmic representation of the formula (2.6) for three-dimensional ball-like objects.
b). The upper uninterrupted line

$$\log J = 6.176 + \frac{3}{2}\log m,$$

corresponds to the formula (2.7) for two-dimensional disk-like objects.
c). The dashed line corresponds to the Kerr angular momentum (2.8)

$$\log J = -18.651 + 2\log m$$

In his Nobel lecture Chandrasekhar put the question: ‘Why are stars as they are?’ and answered that it is because the following combination provides a correct measure of stellar masses:

$$m_0\left(\frac{hc}{Gm_p^2}\right)^{3/2}$$

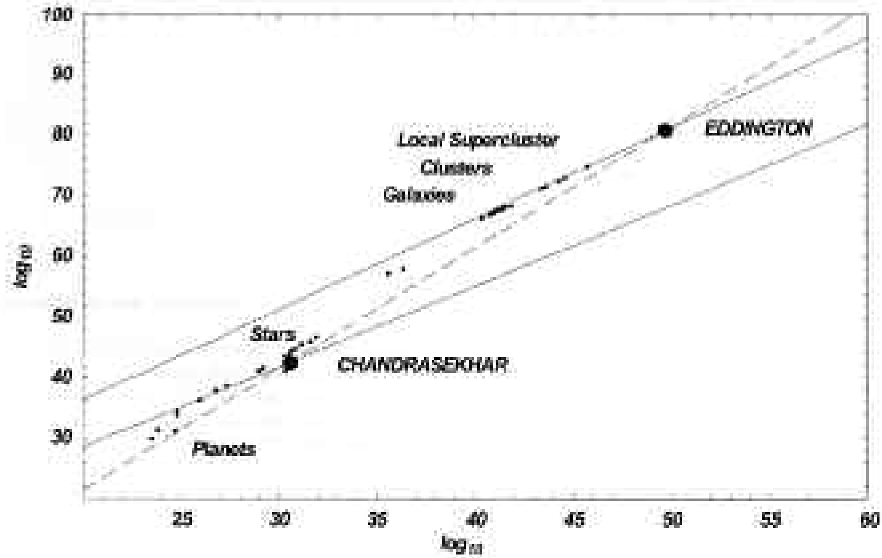

Fig. 3. Joining observation and theory. The angular momentum of planets and stars is well described by the ball Regge trajectory. Galaxies and their clusters are very close to the disk trajectory. Two interception points of the Kerr spin (dashed line) are named Chandrasekhar and Eddington points and their coordinates have fundamental meaning.

This answer is correct, but seems incomplete. We must add that the 'stars are as they are' because also the combination

$$\hbar\left(\frac{\hbar c}{G m_p^{2}}\right)^{3/2}$$

provides a correct measure of stellar spins.

Remark about 'dark matter'. The possible existence of dark matter within the galactic halo at first was proposed by Fritz Zwiky some 40 years earlier in his studies of behavior of galaxies in clusters. This deduction was made from the premise of the stability of clusters and thus of the applicability of the virial theorem. An alternative explanation was proposed by Soviet Armenian astronomer Victor Ambartsumian [13] who considered the possibilities for the existence of a non-stability and (nongravitational) source of total positive energy in clusters. The same reasoning could be applied to the problem of flat rotation curves in spiral galaxies. We need no dark matter to explain the observed flatness of rotation curves if rotation is non-stationary and some unknown source continuously creates angular momentum within a galaxy. It is possible to attribute the increase of angular momentum to the activity of the nuclei of galaxies. The supermassive remnant with a Regge-like spin, located at the center of a galaxy could be a primary reason for the rotational activity of galaxies. The challenge of 'missing mass' and 'missing angular momentum' is serious, but not fatal. As noted e.g. in [14]: 'The need for missing mass disappear if one admits that galaxies and galactic clusters might not be in (dynamic) equilibrium'.

4. Concluding Remarks

This talk serves to demonstrate in what way power scaling laws could be equally useful in the description of physics at very small and very big distances. The success of these applications is witnessed by the unity and simplicity of Nature in the range from elementary particles up to clusters of galaxies and the Universe itself.

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