Predictability in Science: Accuracy and Limitations
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PREDICTIONS IN ASTROPHYSICS AND COSMOLOGY

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Introduction

In 1962 an unexpected paradigm change occurred in particle physics: G. Chew and S. Frautschi discovered that spin and mass of hadrons are not independent quantities. Experimentally observed mesons and baryons appear to lie on nearly linear and parallel Regge trajectories. This has served as a source of inspiration for the present author for suggesting a remarkably simple cosmic Chew-Frautschi type spin-mass plot for astronomical objects – galaxies, stars and planets. Two fundamental points exist on this cosmic Chew-Frautshi plot, connected with Chandrasekhar and Eddington masses with corresponding angular moments, revealed by the author.

A Portion of History

> *The formation of a world starts with a rotatory motion*
> *which Nous (Νους) imparts to a Chaos (Χαος) .*
> Anaxagoras (500-428 BC)

During his studies of Mandelstam representation in nonrelativistic quantum mechanics Tullio Regge introduced the concept of moving poles in the plane of complex angular momentum. Geoffrey Chew and Steven Frautschi [1] transferred the Regge idea to relativistic hadron physics for grouping together hadronic particles with varying mass and spin into single family on Chew-Frautschi plot. This has had a great impact on the development of elementary particle physics, first leading to the Veneziano amplitude, dual resonance model and then to the concept of relativistic string.

Here we will outline an exciting new insight into the origin of cosmic rotation, provided by the application of the Chew-Frautschi paradigm in an astrophysical context [2]. It will become clear that, without invoking quantum-mechanical concepts, the rotation problem in astrophysics cannot be solved.

The problem of the origin of rotation in stars, galaxies and clusters is *l'Enfant terrible* of physics, astrophysics and cosmology.

What is the source of rotation in Mother Nature? This is an important question for understanding the origin, evolution and structure of celestial bodies and their systems. Rotation is a universal phenomenon and in all scales of the universe: from tiny quarks to huge galaxies we observe rotating objects. The universe is characterized by rotation at every scale: asteroids, planets and their moons, stars, interstellar clouds of gas, globular clusters, galaxies and their clusters rotate around central axes, and things orbit around one another 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). Understanding the universe is impossible without understanding the source of the rotational motion of cosmic bodies. Spin or angular momentum is a conserved quantity: the total amount of rotation in the whole universe must be constant. Rotation cannot occasionally appear or disappear, but is an innate, inborn, primordial and fundamental entity. When and how was the angular momentum acquired by celestial bodies? Can the rotation serve as the *Rosetta stone* of Astrophysics?

Despite the importance of the problem, surprisingly few attempts have been undertaken to understand the nature and origin of the angular momentum of stars and galaxies from the first principles. The earliest explanation of the origin of galaxy rotation was attempted in 1949 by F. Hoyle. He discussed the possibility of creating an angular momentum from the asymmetric gravitational coupling of protogalaxy with the surrounding matter. This mechanism was reinvestigated in greater details by Peebles (1969). Wieszacker (1951) and Gamow (1952) proposed alternative explanations of galaxy rotation due to primordial turbulence and vortices.

Much of what we present here is based on the work performed by the author in the 1970s-1980s in the Byurakan Astrophysical Observatory, Armenia.

Chew-Frautschi Paradigm

In elementary particle physics after the work of G. Chew and S. Frautschi it has become clear that spin J and mass m of hadrons are not independent but are inherently connected by simple relation [1]

$$J(m^2) = J(0) + J'(0)m^2 \tag{1}$$

where spin J is measured in the units of Planck's constant $\hbar=1.055\times10^{-34}J\cdot s$ and slope J' has the value $J'(0)\approx1/(GeV/c^2)^2\approx1/m_p{}^2$, with proton mass $m_p=1.673\times10^{-27}kg$.

Many physicists consider relation (1) as a very fundamental physical law, similar to the cardinal law $E=mc^2$. Neglecting $J(0)$ at large m relation (1) can be essentially rewritten in simpler form [1]:

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

This formula is well satisfied by experimental data obtained in high energy physics laboratories, as shown in Fig. 1 (see page 239), where a plot of spin J against the mass (squared) m^2 of different hadrons is represented – a celebrated Chew-Frautschi plot. The meson family falls almost perfectly on a nearly linear Regge trajectory. Mathematically this was like two heavy objects attached to the two ends of a rotating string.

An interesting recollection about the discovery of this relation can be found in the recent interview of S. Frautschi [4]:

> Mandelstam pointed us...that the high-spin particles shouldn't be treated as isolated individuals but as parts of families, and you should organize the calculation around the exchange of the whole family – the spin-one member, the spin-three, the spin-five, and so on...
>
> In particular, our treatment of Regge poles had an equal-spacing feature between masses of successively higher spin – actually, the rule was that the spin went as the mass squared, if you followed the family up to higher masses. Nowadays, both of those developments – exponential growth in particle species and the equal spacing of mass squared in the spin family – are viewed as outgrowths of string theory.
>
> So Geoffrey Chew and I had stumbled upon evidence for strings, although we thought we were working on an entirely different problem.

Geoffrey Chew (see Fig. 2) was a charismatic leader of an 'S-matrix approach' to hadron physics, which, among other things, lead indirectly to the early discovery of *string theory*. Together with several collaborators, in the 1960s-1980s he developed a *bootstrap* approach to subatomic particle physics in which all particles are treated 'democratically', no particle being more fundamental that any other. Contrary to the Greek philosopher Democritus, who conjectured that a reality is constructed out of fundamental building blocks called atoms, Chew's doctrine was in route with another ancient Greek philosopher, Anaxagoras, who postulated the concept of '*Everything in Everything*'.[1]

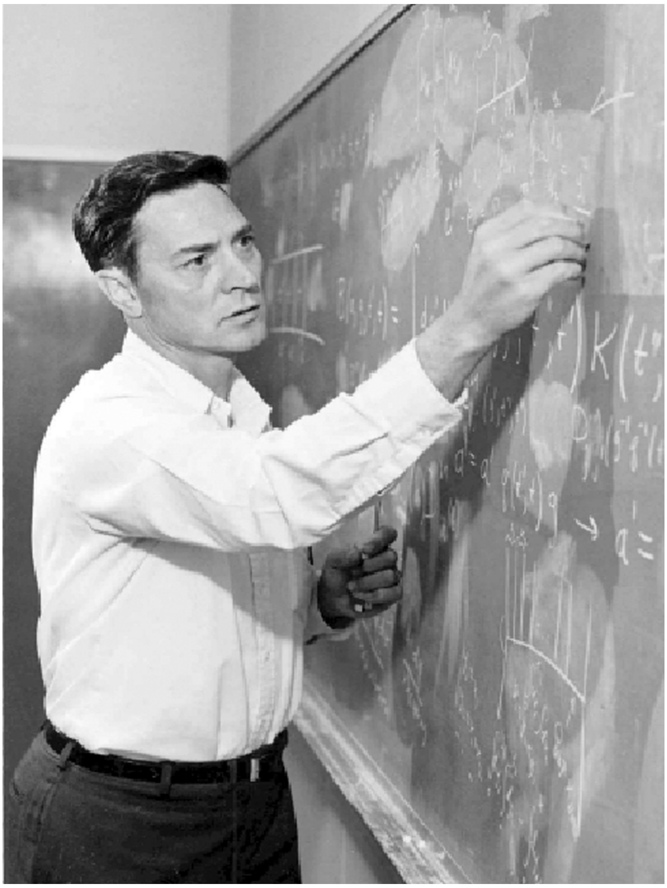

Figure 2. Geoffrey Chew in the 1960s, Lawrence Berkeley National Laboratory, University of California, Berkeley. Courtesy of the Emilio Segré Visual Archives, American Institute of Physics. Taken from [5].

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[1] An introduction to the modern string theory can be found in the book [6]. An interesting review, *cum grano salis,* of string theory developments is given in the philosophical and socio-historical essay by Bert Schroer [7].

Bridging Micro and Macro

Dimensional analysis and scaling considerations allowed extending string-like (one-dimensional) formula (1) to multi-dimensional case [2]

$$J = \hbar \left(\frac{m}{m_p} \right)^{1+\frac{1}{n}} \tag{3}$$

Here the exponent $n=1, 2, 3$ characterizes the spatial shape of a spinning object.

– The choice $n=1$ brings to the previous one-dimensional *rotating string-like* case (2), connected with the usual hadronic Chew-Frautschi plot;

– $n=2$ corresponds to the *rotating disk-like* (two-dimensional) configuration

$$J = \hbar \left(\frac{m}{m_p} \right)^{\frac{3}{2}} \tag{4}$$

and describes observational data for galaxies, their clusters and superclusters, and ultimately the universe itself;

– $n=3$ corresponds to the *rotating spherical* (three-dimensional) objects

$$J = \hbar \left(\frac{m}{m_p} \right)^{\frac{4}{3}} \tag{5}$$

and well describes spin-mass relation for planets and stars.

The comparison of relations (4) and (5) with observations can be seen in [1] and in other works, cited there. The observational data are fitted well by theoretical formulas maintaining only fundamental constants, without invoking any phenomenological fitting parameters.

Gravitational (Kerr) Angular Momentum

Gravitational or Kerr angular momentum $J_{Kerr} = Gm^2/c$ is a maximal angular momentum of rotating black hole with mass m. Here c is the speed of light and G the gravitational constant. Using Planck mass $m_{Pl} = \sqrt{\hbar c/G}$, where $\hbar$ is Planck's constant, it is possible to rewrite Kerr angular momentum in *string-like* form

$$J_{Kerr} = \hbar \left(\frac{m}{m_{Pl}} \right)^{2} \tag{6}$$

This formula formally resembles relation (2) after substitution of proton mass with Planck's one $m_p \to m_{Planck}$. The huge difference is only in the slope of the trajectory, which is obvious from identity

$$J = \hbar\left(\frac{m}{m_p}\right)^2 \equiv \frac{\hbar c}{G m_p^{\,2}} \frac{G m^2}{c} = \frac{\hbar c}{G m_p^{\,2}} J_{Kerr} \tag{7}$$

The dimensionless combination $\hbar c / G m_p^{\,2} = 1.7 \times 10^{38}$ expose the difference of slopes amid hadronic and gravitational strings.

Two Important Points

Equating Kerr momentum with (4) and (5) gives two equations, from which coordinates of intersection points can be deduced (see details in [1]):

$$Chandrasekhar\ mass = m_p\left(\frac{\hbar c}{G m_p^{\,2}}\right)^{\frac{3}{2}} \qquad spin = \hbar\left(\frac{\hbar c}{G m_p^{\,2}}\right)^2 \tag{8}$$

$$Eddington\ mass = m_p\left(\frac{\hbar c}{G m_p^{\,2}}\right)^2 \qquad spin = \hbar\left(\frac{\hbar c}{G m_p^{\,2}}\right)^3 \tag{9}$$

The Chandrasekhar and Eddington masses are one of the most remarkable numbers in all of physics. The corresponding spin expressions were obtained by the author [2].

It is interesting to note, that that all these relations can be represented in terms of Planck mass as follows

$$Chandrasekhar\ mass = m_{Pl}\left(\frac{m_{Pl}}{m_p}\right)^2 \qquad spin = \hbar\left(\frac{m_{Pl}}{m_p}\right)^3 \tag{10}$$

$$Eddington\ mass = m_{Pl}\left(\frac{m_{Pl}}{m_p}\right)^3 \qquad spin = \hbar\left(\frac{m_{Pl}}{m_p}\right)^4 \tag{11}$$

Oort, Ambartsumian, E. Burbige, Hoyle and the Rotation Problem

In April 1970 the Pontifical Academy of Sciences organized a *Study Week on Nuclei of Galaxies* [8] with the participation of the prominent astronomers of the time. Among other things, they debated the talk of Soviet-Armenian astronomer Victor Ambartsumian about the possible origin and formation of galaxies due to the activity of their nuclei. This view is completely different from the classical one, according to which galaxies condensed from primeval nebulae.

The objection to such a possibility was formulated on the basis of the conservation law of angular momentum. Indeed quite small dense objects could not have sufficient angular momentum to feed the whole galaxy. Let us show a small excerpt from this discussion:

Oort: Prof. Ambartsumian spoke about the possibility of making a whole galaxy from nucleus by eruption. There is one great difficulty, which is to get *angular momentum.* Angular momentum is such a characteristic thing everywhere in the universe, especially for spiral galaxies, that to me this forms a very great difficulty.

Ambartsumian: On the *angular momentum* which Prof. Oort mentioned: of course, I also keep this problem in my mind…I agree that what I have said is not the real explanation. The situation is dark but there many possibilities.

Oort: I agree that often quite unexpectedly things which we cannot imagine have turned up.

The possible solution of this old quandary lies completely out of the scope of classical physics and can be obtained only in the framework of quantum theory.

Epilogue

The difficulty lies, not in the new ideas,
but in escaping the old ones…
(John Maynard Keyns)

We have presented a new, *quantum-mechanical* model for the origin of the angular momentum of celestial bodies. Unlike to the previous classical attempts, our approach gives surprisingly accurate numerical predictions of the angular momentum for all spinning astrophysical objects. This occurs for the first time in the history of astronomy.

The creation of spin (angular momentum) is impossible through any applications of a classical field. Artificial invention (postulation) of torque fields such as shear is a unique way to create spin classically.

Another interesting result from this advance is merely philosophical and bears to witness to the unity and simplicity of Nature in micro and macro scales. An understanding of this cannot be achieved by focusing narrowly on the *classical* side of the subject. Instead an integrated, interdisciplinary, open-minded of *quantum-mechanical* vision of the problem of origin of rotation in astrophysics is necessary.

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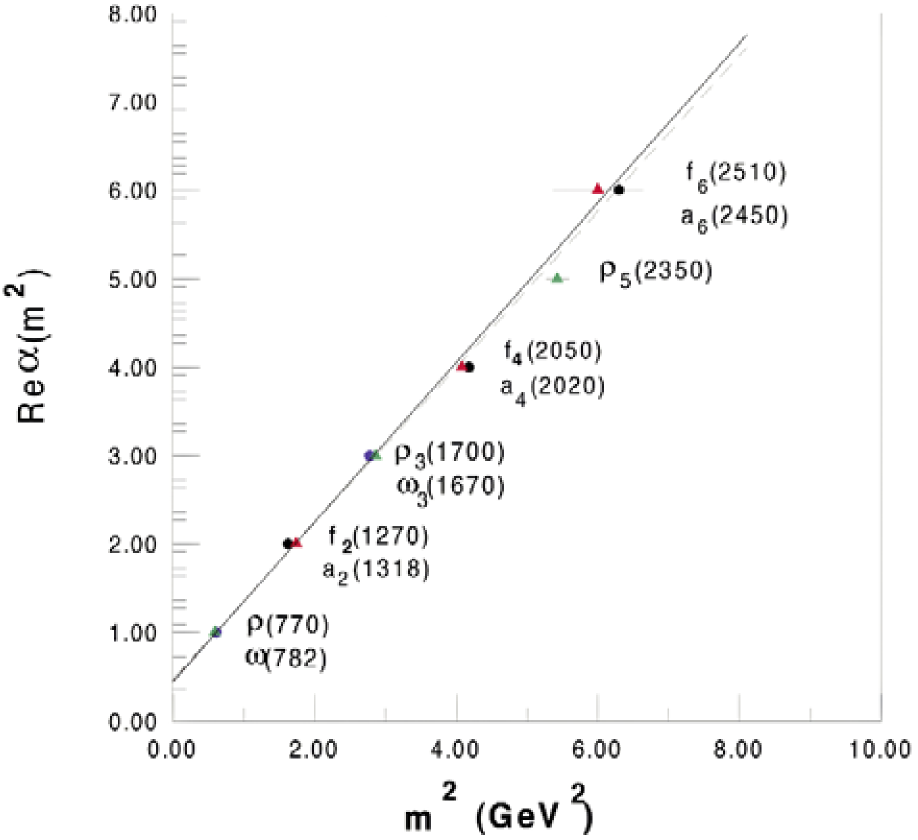

Figure 1. Chew-Frautschi plot (*J* versus m^2) represents almost perfect fit for observed hadrons (mesons) spin-mass relation. Taken from [3].