The Regge law for heavenly bodies

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It is shown that the angular momentum J of many astronomical objects, from planets to clusters of galaxies, and, possibly, the universe as a whole, can be predicted by simple Regge-like laws from the mass m of the object. It is shown that the spins of the planets and stars are described by the Regge law for a sphere, while the spins of galaxies and clusters of galaxies obey the Regge law for a disk. The cosmic analog of the Chew–Frautschi plot is constructed. Two important cosmological points on it are identified: the Eddington point and the Chandrasekhar point. The coordinates of these points are expressed in terms of certain combinations of classical and quantum-mechanical fundamental constants G, c and $\hbar$, m_p. © *1997 American Institute of Physics.* [S1063-7796(97)00205-2]

INTRODUCTION

The most important physical parameters characterizing a heavenly body are its mass m and its intrinsic angular momentum or spin J. Although all observable cosmic objects evolve in time, owing to conservation laws the values of m and J for each are apparently conserved and their present-day values are the same as they were at the time of formation. Therefore, study of the dependence of J on m for various classes of astronomical objects can shed light on the origin of these objects. In other words, it should be possible to assume that the rotation of heavenly bodies gives us a key to solving the cosmogonical problem. It is well known that the main goal of astronomy and of the natural sciences, in general, is to understand the origins of the observed Universe and its components: galaxies, stars, and planets.

All earlier cosmogonical theories have either ignored the problem of the origin of spin, or have attempted to solve it using artificial auxiliary hypotheses. Many of the cosmogonical theories which have been constructed have been found to be incorrect due to contradictions with the law of angular-momentum conservation.

The progress made in elementary-particle physics allows the problem of the origin of rotation at astrophysical scales to be studied in a new light. We recall that in the early 1960s, on the basis of work by Regge,[1] Chew and Frautschi introduced the concept of a linear trajectory which revealed a fundamental relation of the form $J\sim m^2$ between the mass and spin of strongly interacting elementary particles (hadrons).[2] The Regge theory proved to be very influential in the development of elementary-particle physics, first in the development of dual resonance models and Veneziano amplitudes, and later in generating the idea of relativistic strings.

In this review we show how the application of Regge ideas to astrophysics allows solution of the problem of the origin of rotation of heavenly bodies, which has so far proved intractable to the methods of classical physics.

Section 2 is introductory and contains historical information.

In Sec. 3 we discuss the generalized Regge formula for n-dimensional hadrons. It is shown that there are two universal laws describing the mass dependence of the spin for a large class of astronomical objects:

1. The dependence $J\sim m^{3/2}$ for galaxies and clusters of galaxies [see Eq. (4)];
2. The dependence $J\sim m^{4/3}$ for planets and stars [see Eq. (5)].

In contrast to earlier semiphenomenological approaches, our expressions contain only fundamental constants as parameters and are independent of any fitted, empirical quantities.

Section 4 is devoted to comparison of the theoretical predictions and the observed data for a large class of astronomical objects. The cosmic Chew–Frautschi plots, Figs. 1–3, constructed on the basis of the observed data and theoretical expressions, reveal two important cosmological points whose coordinates can be expressed in terms of the fundamental constants $\hbar$, m_p, G, and c and are related to the *limiting* values of the parameters of heavenly bodies [see Eqs. (26)–(29)]. Using the Planck mass

$$m_{\rm Pl}=\left(\frac{\hbar c}{G}\right)^{1/2}\equiv m_p\left(\frac{\hbar c}{Gm_p^2}\right)^{1/2},$$

we can represent the coordinates of these limit points in compact form

$$\text{Eddington point}\Rightarrow\left\{m_{\rm Universe}=m_p\left(\frac{m_{\rm Pl}}{m_p}\right)^4,\quad J_{\rm Universe}=\hbar\left(\frac{m_{\rm Pl}}{m_p}\right)^6\right\}$$

$$\text{Chandrasekhar point}\Rightarrow\left\{m_{\rm star}=m_p\left(\frac{m_{\rm Pl}}{m_p}\right)^3,\quad J_{\rm star}=\hbar\left(\frac{m_{\rm Pl}}{m_p}\right)^4\right\}.$$

These limiting relations for the angular momenta $J_{\rm star}$ and $J_{\rm Universe}$ are the main result of our approach and supplement the well-known Chandrasekhar limit $m_{\rm star}$ and Eddington limit $m_{\rm Universe}$.

Finally, in the Appendix we show that the Regge trajectories that we use are the *leading* or *yrast* trajectories.

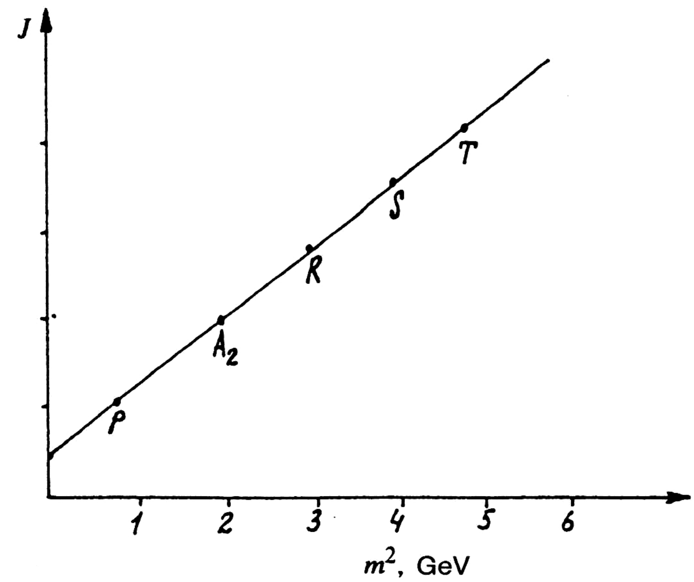

FIG. 1. The Chew–Frautschi plot in the (J, m^2) plane for the $\rho - a_2(1320)$ meson trajectory.

2. ROTATION: THE ROSETTA STONE OF ASTRONOMY

Most heavenly bodies, from asteroids, planets, and stars to galaxies and clusters of galaxies, possess rotational motion. The rotation of the Sun was observed by Galileo, who attributed the shift of the sunspots to it. Immanuel Kant was the first to suggest that the Milky Way rotates, and this was indeed confirmed at the beginning of our century.

In modern astrophysics, rotation plays an important role in explaining the emission mechanism of pulsars, which are apparently rotating neutron stars. It has been hypothesized that rapidly rotating dense objects lie at the centers of galaxies and quasars. Finally, indications have recently been found that the entire Universe as a whole may also rotate.

How did the heavenly bodies acquire rotational motion? There are grounds for believing that the nature of the rotation of most heavenly bodies has not changed significantly since the time they were formed. It can therefore be hoped that the correct explanation of the origin of the conserved rotational angular momentum will provide a key to solving the cosmogonical problem, playing the role of a Rosetta stone in unraveling the mysteries of the origin of heavenly bodies.

2.1. From the Primeval Atom to the Primeval Hadron

In the history of science there has been no lack of cosmogonical and cosmological ideas. However, they often contradicted the observed data or known physical laws and were therefore discarded. And only a few of them contained true and deep intuitive guesses of enduring value.

Modern cosmology begins with one of these ideas, first expressed in the 1930s by Georges Lemaître, a prominent authority on the general theory of relativity, professor of mathematics and the history of mathematics and physics at the Catholic University in Louvain, Belgium. In 1927 he

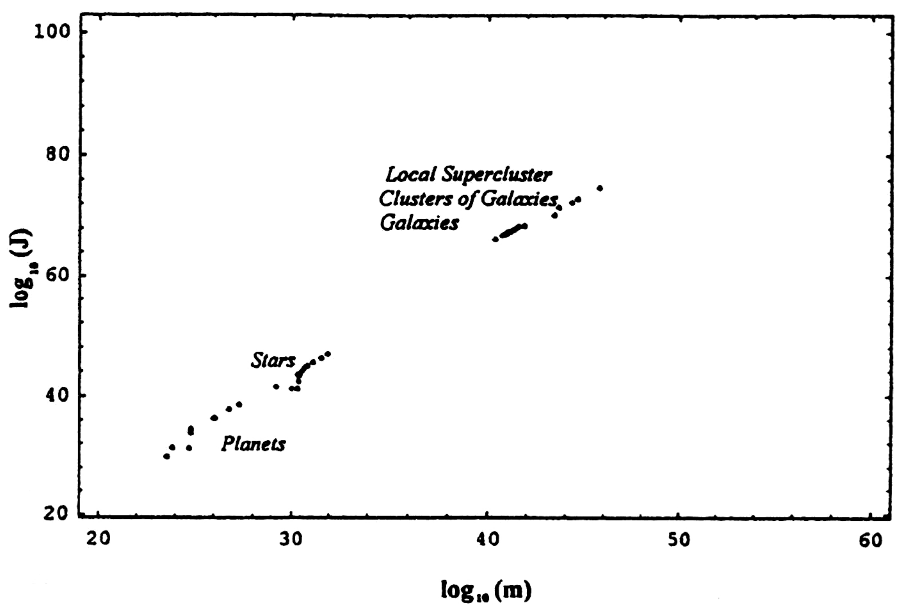

FIG. 2. Observational data on the masses and spins of heavenly bodies in the doubly logarithmic plane using the values of m and J (obs.) from Tables I and II.

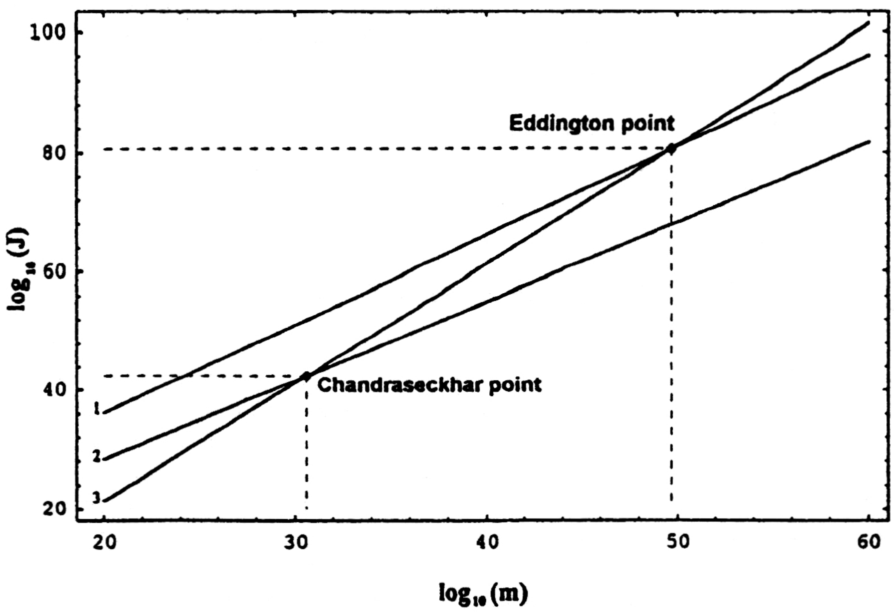

FIG. 3. Theoretical lines corresponding to the Regge trajectories for the disk and the sphere and the Kerr gravitational angular momentum in the doubly logarithmic plane: for the disk $J^{(2)}=\hbar(m/m_p)^{3/2}$ [see (4)]; for the sphere $J^{(3)}=\hbar(m/m_p)^{4/3}$ [see (5)]; for the Kerr angular momentum $J^{\mathrm{Kerr}}= Gm^2/c\equiv\hbar(m/m_{\mathrm{Pl}})^2$ [see (7)]. The Eddington point corresponds to the equation $J^{(2)}=J^{\mathrm{Kerr}}$, and at the Chandrasekhar point $J^{(3)}=J^{\mathrm{Kerr}}$.

found dynamical solutions of the Einstein equations and used them as the basis for the first realistic model of the Universe, combining the theoretical results of relativistic cosmology with the new observational data of Hubble on the redshift of extragalactic objects. While giving due notice to the contribution of Friedmann, we note that it was Lemaître who first succeeded in finding the correct theoretical interpretation of the expansion of the Universe, and so he deserves to be viewed as the father of the theory of the expanding Universe.

Lemaître's dream was to construct a theory which would allow a description of the present Universe with all its diversity starting from very simple initial conditions. He thought that it was possible to construct a unified cosmological theory capable of describing the evolution of the Universe starting from a hypothetically simple initial state to the presently observed diversity of processes and structures.

Accordingly, in 1931 Lemaître produced the hypothesis of the *primeval atom*,[3,4] in which the entire mass of the Universe was initially concentrated. After the discovery of the neutron, Lemaître immediately suggested that the initial state was not an atom, but a neutronic nucleus.

Study of the laws of rotation of heavenly bodies—stars, galaxies, and clusters of galaxies—has led the present author to conclude that the initial state of the Universe was not the primeval atom of Lemaître or the primeval nucleus, but the primeval hadron, having the mass of the Universe and the corresponding Regge spin. We shall see that this assumption leads to a natural explanation of the observed regularities in the angular-momentum distribution of heavenly bodies, the first such explanation in the entire history of astronomy and physics.

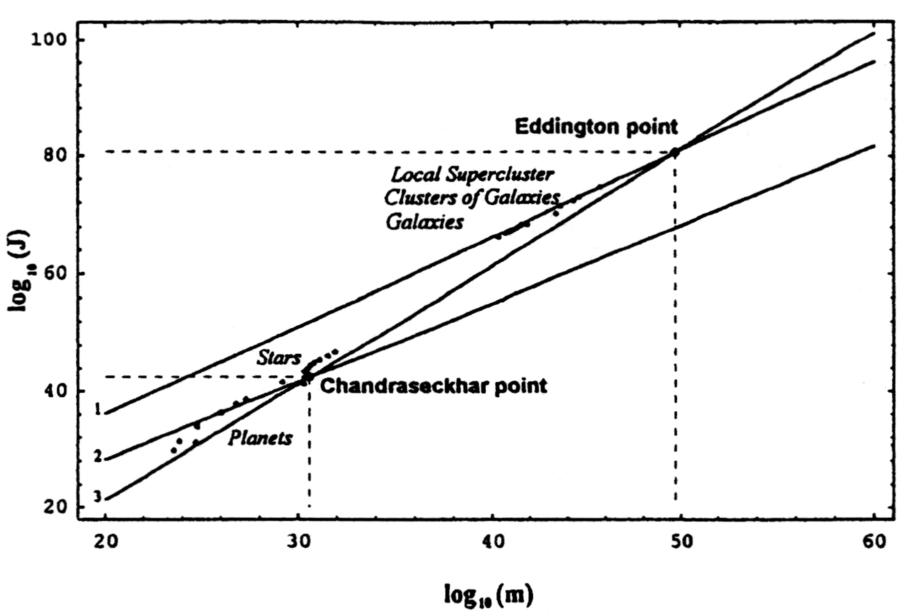

FIG. 4. Generalized Chew–Frautschi plot in the doubly logarithmic plane resulting from combining Figs. 2 and 3.

2.2. The cosmic vortex of Anaxagoras

One of the earliest cosmogonical theories, in which rotation plays an important role, was developed in the fifth century B.C. by Anaxagoras of Clazomenae (500–428 B.C.), who is considered intermediate between the ancient Ionic school of philosophy and the new Greek school. In 480 B.C. he settled in Athens, where he lived for 30 years and was the first teacher of philosophy among the Athenians. Like Socrates, he was eventually accused of heresy, but in contrast to his famous follower he chose exile and moved to Ionia, where he worked happily for another 20 years. Anaxagoras, called by Marx the "most physical of physicists," developed an evolutionary model of the world in which rotation plays the decisive role. Owing to some special factor, the primordial mixture of all matter was set into strong rotational motion. According to Anaxagoras, the speed of this rotation was colossal and incomparable to the speeds familiar to humans. All the further course of evolution of the cosmos was predetermined by the rotation of the cosmic matter.

2.3. The vortices of Descartes

Two thousand years later, the ideas of Anaxagoras about the cosmic matter vortex were revived by Kepler and developed further in the cosmogony of Descartes. The words of Poincaré, author of the comprehensive study *Lecons sur les Hypotheses Cosmogoniques* (1911), resonate today: "Despite the many objections to it, despite the remarkable discoveries in astronomy which can excite wonder in astronomers, vortical cosmogony is still with us."

Even in our own era Jeans suggested that galactic rotation is a consequence of the primeval vortical motion of protogalactic clouds, and Weizsäcker and Gamow developed vortical cosmogony further using new results from the theory of turbulence.

Mention should also be made of the tidal theory of the origin of galactic angular momentum, proposed by Hoyle and developed by Peebles,[39,40] which is the only quantitative theory that has been worked out. Unfortunately, it proved incapable of explaining even the order of magnitude of the observed angular momenta.

This brief summary makes it clear that rotation is not some sort of accidental property of heavenly bodies, but plays a fundamental role in the system of the Universe. However, in all the approaches we have mentioned the question of the origin of primeval vortices remains obscure and is considered the most difficult unsolved problem of cosmogony.

The difficulties that arise in this area are indicated by the fact that even the great Newton, in severely criticizing the vortices of Descartes, was forced to give up on the search for the origin of rotation of heavenly bodies, declaring it to be a result of the labor of an "intelligent and powerful Being." He thereby violated his own well-known maxim: *Hypotheses non fingo*.

We also note that the system of Copernicus, described in his study *De Revolutionibus*, is essentially based on a new kinematical interpretation of rotational motions within the solar system.

There is no question of the importance of solving the problem of the origin of the rotation of heavenly bodies.[19–35]

Today it seems obvious that all the possibilities of classical mechanics for solving this problem have been exhausted, making it necessary to borrow ideas and concepts from other disciplines, in particular, from elementary-particle physics.

3. HADRON SPINS AND THE REGGE LAW

One of the most interesting properties of elementary particles is their capability of possessing intrinsic angular momentum or spin. In a rather simplistic sense, an elementary particle resembles a spinning top. However, this representation is only a convention, because the rotation rate at the edge can exceed the speed of light, which is untenable according to the special theory of relativity. It is therefore said that the spin of elementary particles, including hadrons, has no classical analog and can be described only within the laws of quantum mechanics.

To make this clearer, as an example let us consider the simplest elementary particle, the electron. It is well known that the electron possesses a spin equal to $\hbar/2$. An elementary classical calculation shows that for the electron to possess such a spin its mass must be distributed within a sphere of radius of the order of the Compton wavelength of the electron, 10^{-13} m. However, according to direct experimental data, the electron size is less than 10^{-17} m. In courses on quantum mechanics it is briefly and clearly stated that spin is an intrinsically quantum effect which has no classical interpretation. It is thus meaningless to try to represent the intrinsic angular momentum of an elementary particle as the result of simple mechanical rotation about its axis.

3.1. The generalized Regge law

In the 1960s, following the studies by Regge, Chew, and Frautschi, it became clear that there is a deep relation between the spin and mass of hadrons. The experimentally discovered correlation between spin and mass shows that the heavier the hadron, the larger its spin, and that the spin grows with increasing mass more rapidly than a simple linear proportionality. Clearly, heavy hadrons rotate more rapidly than light ones, and as the hadron mass increases, the hadron spins faster and faster. As a macroscopic analog, we can compare the rotations of the Earth and Jupiter: Jupiter is 300 times heavier than Earth and rotates about its axis 2.5 times more quickly than does Earth.

The main stages in the development of the Regge theory are the following:

1. In proving the validity of the Mandelstam double spectral representation in nonrelativistic quantum mechanics, Regge[1] introduced the concept of moving poles in the complex angular momentum plane.

2. Chew and Frautschi[2] applied the Regge idea to relativistic hadron physics for grouping hadronic particles with different masses and spins into certain families, called Regge trajectories. Chew and Frautschi established the remarkable quadratic dependence of spin on mass for hadrons and hadronic resonances. For sufficiently large values of the masses

it can be written as the following *Regge law* involving only fundamental constants:

$$J^{(1)}=\hbar\left(\frac{m}{m_p}\right)^2, \tag{1}$$

where $m_p=1.673\times10^{-27}$ kg is the proton mass, and $\hbar=1.055\times10^{-34}$ J·sec is the Planck constant.

Before the appearance of this expression, the mass and spin of a particle were usually viewed as independent parameters, with the spin generally regarded as an unimportant "kinematical" complication. Now it is clear that there is a close dynamical relationship between the spin and mass of a hadron. Since m and J are independent Casimir invariants of the Poincaré group, it would be nice to have a group-theoretical understanding of how particles with fixed values of the mass and spin are grouped into families lying on Regge trajectories. As noted in Ref. 5, the realization of Regge trajectories in Nature suggests the existence of a certain functional relationship between the two Casimir invariants and may be related to the existence of a symmetry higher than the Poincaré symmetry.[1)]

In our previous studies[6–13] devoted to solving the problem of the origin of the angular momentum of heavenly bodies, we proposed a generalization of the Regge law for n-dimensional hadrons:

$$J^{(n)}=\hbar\left(\frac{m}{m_p}\right)^{1+1/n}. \tag{2}$$

The number $n=1,2,3$ characterizes the geometrical form of the hadron:

$n=1$ is a string:

$$J^{(1)}=\hbar\left(\frac{m}{m_p}\right)^2, \tag{3}$$

$n=2$ is a disk:

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

$n=3$ is a sphere:

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

Equation (3) can be obtained semiclassically from simple dimensional arguments and scaling. Actually, let us use the classical expression for the angular momentum, $J=mvr$. For constant velocity $v=\text{const}$ we have $J\sim mr$. On the other hand, for an n-dimensional object with constant density the mass $m\sim r^n$, and so $r\sim m^{1/n}$. It then follows that

$$J\sim mr\sim mm^{1/n}\sim m^{1+1/n}.$$

The requirement of scaling of the relation $J\sim m^{1+1/n}$ with the Regge law (1) for a one-dimensional string-like hadron leads to the generalized Regge law (2).

Equation (3) is discussed in more detail in the Appendix. There it is shown that (3) corresponds to the *leading* Regge trajectory. The leading or, as is conventional in nuclear physics, *yrast* trajectory corresponds to the maximum angular momentum for a given mass or, equivalently, the minimum mass for fixed angular momentum. This implies that the entire mass (energy) of a hadron is related to the rotational motion, and so the contribution of vibrational and oscillatory degrees of freedom to the energy is negligible.

It is well known and obvious that the Regge trajectory for a *string* $J\sim m^2$ is a line in the (J,m^2) plane. For a disk $J\sim m^{3/2}$ and a line is observed in the (J^2,m^3) plane, while for a sphere $J\sim m^{4/3}$ and a line is observed in the (J^3,m^4) plane.

3.2. The Kerr angular momentum

In 1963 Kerr found a solution of the Einstein equations for the gravitational field of a particle with mass m and spin J which for $J=0$ goes into the Schwarzschild solution. Curiously, it took nearly half a century to generalize it (we recall that the Schwarzschild solution was obtained in 1915, nearly simultaneously with the creation of the Einstein theory). The important feature for us now is that the Kerr metric establishes an upper bound on the maximum angular momentum of a black hole. The event horizon is given by the expression (see, for example, Ref. 48)

$$r=r_g+\sqrt{r_g^2-\left(\frac{J}{mc}\right)^2}, \tag{6}$$

where $r_g=Gm/c^2$ is the Schwarzschild radius. The expression inside the square root must be greater than or equal to zero in order for the event horizon to be meaningful. It then follows that the maximum spin in the Einstein theory, sometimes called the Kerr spin, is $J^{\text{Kerr}}=mcr_g$ or

$$J^{\text{Kerr}}=\frac{Gm^2}{c}, \tag{7}$$

where $G=6.673\times10^{-11}$ m^3·kg^{-1}·sec^{-2} is the Newton gravitational constant and $c=2.998\times10^8$ m·sec^{-1} is the speed of light.

The Kerr relation can be cast in a form coinciding with the Regge trajectory for a string, but with different slope. For this we use the expression for the Planck mass:[2)]

$$m_{\text{Pl}}=\left(\frac{\hbar c}{G}\right)^{1/2} \tag{8}$$

and write the Kerr angular momentum as

$$J^{\text{Kerr}}=\hbar\left(\frac{m}{m_{\text{Pl}}}\right)^2. \tag{9}$$

Therefore, *the expression for the Kerr angular momentum coincides with the expression for the Regge angular momentum for a string if in the latter we make the replacement* $m_p\to m_{\text{Pl}}$, i.e., if we change the slope parameter, inversely proportional to the squared mass, by a factor of 10^{38}. Let us show that the Regge law for a string (3) is directly proportional to the Kerr angular momentum and find the proportionality factor. We have the following identity between the Kerr and string Regge angular momenta:

$$J^{\text{Kerr}}=\frac{Gm_p^2}{\hbar c}J^{(1)}, \tag{10}$$

where $J^{(1)}$ is given by Eq. (3), and the dimensionless proportionality factor is

$$\frac{Gm_p^2}{\hbar c}=5.903\times 10^{-39}. \tag{11}$$

For reference, let us give the gravitational angular momentum of an n-dimensional object, making the replacement $m_p \rightarrow m_{\rm Pl}$ in (31):

$$J_{\rm grav}^{(n)}=\hbar\left(\frac{m}{m_{\rm Pl}}\right)^{1+1/n}=\hbar\left(\frac{Gm^2}{\hbar c}\right)^{1/2(1+1/n)}. \tag{12}$$

By definition, $J^{\rm Kerr}\equiv J_{\rm grav}^{(1)}$.

It is interesting to note that beginning in the 1960s, a puzzling analogy was noticed between the behavior of hadrons in strong interactions at large distances and gravitation.[49,50] It has recently been shown[51] that this can be understood on the basis of quantum chromodynamics and arises from the possibility of exchanging colorless combinations of two gluons with spin 2 imitating a graviton. This may explain the string behavior $J\sim m^2$ of both the hadronic Regge trajectories and the Kerr angular momentum.

3.3. The string: $J\sim m^2$

We recall that the parameter $n=1,2,3$ in the generalized Regge law (31) characterizes the geometrical shape of the hadron:

- $n=1$ for one-dimensional objects like strings;
- $n=2$ for two-dimensional planar objects like disks;
- $n=3$ for three-dimensional objects like a sphere.

Equation (3) is valid for ordinary string-like hadrons and corresponds to linear Regge trajectory in the Chew-Frautschi plot in the J,m^2 plane. A striking example is the mesonic $\rho-a_2(1320)$ trajectory, which is linear up to the $a_6(2450)$ meson with spin $6\hbar$ and mass 2450 MeV/c^2 and is shown in Fig. 1.

3.4. The disk: $J\sim m^{3/2}$

The Regge spin of two-dimensional disk-like hadrons with shape exponent $n=2$ is given by Eq. (4). Let us transform it, introducing the parameter N characterizing the number of nucleons of an object of mass m:

$$N=\frac{m}{m_p}. \tag{13}$$

Then Eq. (4) takes the simple form

$$J^{(2)}=\hbar N^{3/2}, \tag{14}$$

i.e., *the angular momentum of the disk is equal to Planck's constant times the number of nucleons raised to the* 3/2 *power*. In SI units, where the mass is measured in kg and the angular momentum in kg·m²/sec, Eq. (4) takes the form[3)]

$$J^{(2)}=1.5\times 10^6 m^{3/2} \quad \text{(SI units)}. \tag{15}$$

In astronomy, the mass of an object is often measured in solar masses $m_\odot=1.98892(25)\times 10^{30}$ kg. Then instead of (4) we can use the equivalent expression

$$J^{(2)}=4.3\times 10^{51}\left(\frac{m}{m_\odot}\right)^{3/2}. \tag{16}$$

For convenience, let us list the various expressions for $J^{(2)}$:

$$J^{(2)}=\hbar\left(\frac{m}{m_p}\right)^{3/2}=\hbar N^{3/2}=1.542\times 10^6 m^{3/2} \quad \text{(SI units)}$$

$$=4.324\times 10^{51}\left(\frac{m}{m_\odot}\right)^{3/2}\frac{\text{kg}\cdot\text{m}^2}{\text{sec}}.$$

Taking the logarithm of the last expression, we find

$$\log_{10}\left(\frac{J^{(2)}}{\frac{\text{Kg}\cdot\text{m}^2}{\text{sec}}}\right)=\frac{3}{2}\log_{10}\left(\frac{m}{m_\odot}\right)+51.6274. \tag{17}$$

This equation can be compared to the semiempirical formula of Genkin and Genkina from Ref. 28:

$$\log_{10}\left(\frac{J}{\frac{\text{Kg}\cdot\text{m}^2}{\text{sec}}}\right)=(1.52\pm 0.05)\log_{10}\left(\frac{m}{m_\odot}\right)+50.11\pm 0.04, \tag{18}$$

which was derived in a completely different way using a large amount of statistical data.

The Regge trajectory $J^{(2)}$ gives a fairly good description of the rotational angular momentum of galaxies. Let us illustrate this by the following examples:

1. *Our galaxy.* The mass of our galaxy is $m_G=3.38\times 10^{41}$ kg, and the observed spin is $J_G=1.92\times 10^{68}$ kg·m²/sec. The theoretical prediction $J_G^{(2)}=3.03\times 10^{68}$kg·m²/sec is clearly in good agreement with the observed spin of the Milky Way.

2. *The M51 galaxy.* For the M51 galaxy the observed values of the mass and spin are $m_{\rm M51}=9.54\times 10^{40}$ kg and $J_{\rm M51}=2.48\times 10^{67}$ kg·m²/sec. The theoretically predicted spin is $J_{\rm M51}^{(2)}=4.54\times 10^{67}$ kg·m²/sec.

3.5. The sphere: $J\sim m^{4/3}$

Equation (5) for three-dimensional spherical objects gives a good description of the rotation of planets and stars.

For practical purposes, it is convenient to perform some identity transformations on it as for (4). Let us list the various expressions for $J^{(3)}$:

$$J^{(3)}=\hbar\left(\frac{m}{m_p}\right)^{4/3}=\hbar N^{4/3}=53.114\times m^{4/3} \quad \text{(SI units)}$$

$$=1.329\times 10^{42}\left(\frac{m}{m_\odot}\right)^{4/3}\frac{\text{Kg}\cdot\text{m}^2}{\text{sec}}.$$

From this we find the rule that *the angular momentum of a sphere is equal to Planck's constant times the number of nucleons raised to the 4/3 power.*

Let us consider some examples of the use of the trajectory $J^{(3)}$ to describe the spins of planets and stars.

1. *Jupiter.* The mass and spin of Jupiter are well measured and equal to $m_{\rm Jup}=1.90\times 10^{27}$ kg and

$J_{\rm Jup}=4.32\times 10^{38}$ kg·m²/sec. The theoretically calculated value $J_{\rm Jup}^{\rm theor}=1.25\times 10^{38}$ kg·m²/sec nearly coincides with the observed value.

2. *The Earth and the Earth-Moon system.* The observed mass and spin of the Earth are $m_{\oplus}=5.97\times 10^{24}$ kg and $J_{\oplus}=5.91\times 10^{33}$ kg·m²/sec. The theoretical value of the Earth's spin $J_{\oplus}^{\rm theor}=5.74\times 10^{34}$ kg·m²/sec is somewhat larger than the observed value, but closer to the observed spin of the Earth-Moon system.

3. *The Sun and the solar system.* The mass and spin of the Sun are relatively well known from observations and are $m_{\odot}=1.989\times 10^{30}$ kg and $J_{\odot}=1.63\times 10^{41}$ kg·m²/sec. The theoretically predicted value of the solar spin $J_{\odot}^{\rm theor}=1.33\times 10^{42}$ kg·m²/sec lies between the observed values of the solar spin and the total spin of the solar system, $J_{\rm SolarSystem}=3.15\times 10^{43}$ kg·m²/sec.

4. THE COSMIC CHEW–FRAUTSCHI PLOT

In our approach to the problem of the rotation of heavenly bodies a fundamental role is played by the generalized Chew–Frautschi plot[2] for cosmic objects in the doubly logarithmic $\log_{10}(m)-\log_{10}(J)$ plane.

First, we shall construct the plot using the observational data on planets, stars, galaxies, and clusters of galaxies (see Fig. 1 below). Then in Fig. 2 we present the theoretical results. Finally, in order to compare the two we combine the two plots in Fig. 3. Here we see that the agreement between the proposed theoretical approach and observation is rather good.

Two special points are distinguished in the cosmic Chew–Frautschi plot, which we call the Eddington and Chandrasekhar points. Their coordinates are expressed in terms of certain combinations of the fundamental constants G, $\hbar$, c, and m_p. The cosmological interpretation of these points is discussed.

4.1. The observational data on the masses and spins of heavenly bodies

All heavenly bodies — planets, stars, galaxies, and clusters of galaxies — rotate. A critical analysis of the observational data shows that the values given in the literature for the angular momenta of spiral galaxies may involve an error by a factor of 5 or even slightly higher, and that the values of the mass may be uncertain by a factor of 2 or 3.

In the case of elliptical galaxies which are fairly oblate (subtypes E5–E7), it is possible to use information on the rotational data by analogy with the case of spiral galaxies. However, for spherical or nearly spherical systems the rotational velocity is so small that it is difficult to determine from observation. Nevertheless, it is possible to estimate an upper limit on the rotational velocity by two methods: (1) by assuming that it is twice the average error in determining this velocity; (2) by using the fact that the rotation causes the system to become slightly oblate, at the level of subtypes E0–E2. As far as the masses of these systems are concerned, they must be estimated from the velocity spread leading to spectral-line broadening.

The data on clusters and superclusters of galaxies are less precise than those on galaxies. However, even here, as in the case of elliptical galaxies, it is possible to determine an upper limit on the angular momentum using the upper limit on the linear rotational velocity. Only in the case of the Vaucouleurs Local Supercluster, which contains the Virgo cluster and the Local Group, is there a more or less well-defined value of the linear rotational velocity, equal to 400 ± 100 km/sec at a distance of 10 Mpc from the center of the Supercluster. Moreover, there are indirect indications, revealed by correlations of the orientations of the small galactic axes, that the Local Supercluster rotates. Observations indicate that these axes are primarily oriented perpendicularly to the plane in which the Local Supercluster is flattened, i.e., parallel to the possible axis of rotation of the Supercluster as a whole.

Similar indirect data support the hypothesis that other superclusters, for example, those in Pisces and in Ursus Major, rotate.

The cosmogonical significance of the possible rotation of superclusters and the role of the rotation of clusters and superclusters in checking various theories of galactic formation has been analyzed by Ozernoy,[57] who stressed the fact that the observed correlations between the galactic rotation axes at distances of order 100 Mpc indicate a relict origin of rotation and are directly due to the physical conditions under which galaxies were formed. Such correlations appears natural if galaxies and clusters and superclusters of galaxies were formed in the decay of superheavy hadrons with high spin.

A direct indication of the possibility of rotation of the astronomical Universe as a whole has been found by Birch[53,54] using the statistics of the nonuniform distribution of radio galaxies having S and Z shapes.

Below in Tables I and II we give the observational data that we use. These data are shown graphically in Fig. 1, where we represent the entire spectrum of astronomical objects in the $\log_{10}(m)-\log_{10}(J)$ plane (see also Refs. 11 and 13).

4.2. Angular momentum in binary galaxies

The observational data on the distribution of orbital and spin angular momenta in binary galaxies are exceptionally interesting from the viewpoint of the cosmogony of these systems. Estimates of the angular momenta in pairs of galaxies have been made by Gorbachev,[55] who found that the orbital angular momentum of binary galaxies is larger than the sum of their spins by a factor of 1.2–1.6.

It can be shown that a very close theoretical estimate is obtained using our approach. The total angular momentum of a binary system $\vec{J}_{\rm tot}$ is the sum of the orbital angular momentum of the system $\vec{L}$ and the spin angular momenta of the individual galaxies $\vec{J}_1$ and $\vec{J}_2$:

$$\vec{J}_{\rm tot}=\vec{L}+\vec{J}_1+\vec{J}_2. \qquad (19)$$

For simplicity, we assume that the galactic masses are identical and equal to m, and that the spins are expressed using the Regge law for galaxies:

TABLE I. Masses and spins of clusters of galaxies, spiral galaxies, and spherical clusters.*,†

Object	Mass	Spin (obs.)	Spin (theor.)
Clusters of galaxies			
The Local Supercluster	5×10^{45}	6×10^{74}	5.45×10^{74}
A 1656 (Coma)	4×10^{44}	0.9×10^{73}	1.23×10^{73}
A 2199	2×10^{44}	2.2×10^{72}	4.36×10^{72}
Virgo	4×10^{43}	2.6×10^{71}	3.90×10^{71}
Shahbazian I	2.4×10^{43}	1.8×10^{71}	1.81×10^{71}
Spiral galaxies			
Andromeda (M31)	6.78×10^{41}	2.36×10^{68}	8.61×10^{68}
Milky Way	3.38×10^{41}	1.92×10^{68}	3.03×10^{68}
NGC 3031 (M81)	2.78×10^{41}	1.30×10^{68}	2.26×10^{68}
5005	1.98×10^{41}	6.82×10^{67}	1.36×10^{68}
7331	1.86×10^{41}	6.82×10^{67}	1.24×10^{68}
5055 (M63)	1.31×10^{41}	2.91×10^{67}	7.31×10^{67}
1832	1.11×10^{41}	2.85×10^{67}	5.70×10^{67}
1808	9.55×10^{40}	2.11×10^{67}	4.55×10^{67}
5194 (M51)	9.54×10^{40}	2.48×10^{67}	4.54×10^{67}
0681	7.76×10^{40}	1.67×10^{67}	3.33×10^{67}
6574	8.15×10^{40}	1.18×10^{67}	3.59×10^{67}
1084	4.97×10^{40}	7.44×10^{66}	1.71×10^{7}
3504	2.19×10^{40}	1.61×10^{66}	5.00×10^{66}
Spherical clusters			
NGC 104 (47 Tuc)	2.1×10^{36}	1.3×10^{58}	4.69×10^{60}
362	3.6×10^{35}	2.4×10^{57}	3.33×10^{59}

*We use SI units, in which the mass is measured in kg and the spin in kg·m²/sec≡J·sec.

†For clusters of galaxies and spherical clusters the observed spins are estimated from the data on the spread in velocities and linear sizes. For clusters of galaxies we use the results of Ref. 24. The masses and spins of spiral galaxies are taken from Ref. 25.

TABLE II. Masses and spins of stars and planets.*,†

Object	Mass	Spin (obs.)	Spin (theor.)
Main-sequence stars			
O5	7.92×10^{31}	7.07×10^{46}	1.81×10^{44}
B0	3.54×10^{31}	1.46×10^{46}	6.17×10^{43}
B5	1.28×10^{31}	3.12×10^{45}	1.59×10^{43}
A0	6.44×10^{30}	8.56×10^{44}	6.36×10^{42}
A5	4.16×10^{30}	3.01×10^{44}	3.55×10^{42}
F0	3.38×10^{30}	1.27×10^{44}	2.69×10^{42}
F5	2.56×10^{30}	2.57×10^{43}	1.86×10^{42}
G0	2.18×10^{30}	2.54×10^{42}	1.50×10^{42}
Solar system	1.99×10^{30}	3.15×10^{43}	1.33×10^{42}
Sun (G2)	1.99×10^{30}	1.63×10^{41}	1.33×10^{42}
K0	1.54×10^{29}	$<3.65\times10^{41}$	4.38×10^{40}
M0	9.31×10^{28}	$<1.63\times10^{41}$	2.24×10^{40}
Planets			
Jupiter	1.90×10^{27}	4.32×10^{38}	1.25×10^{38}
Saturn	5.68×10^{26}	7.68×10^{37}	2.50×10^{37}
Uranus	8.72×10^{25}	2.09×10^{36}	2.05×10^{36}
Neptune	1.02×10^{26}	2.10×10^{36}	2.53×10^{36}
Earth-Moon	5.97×10^{24}	2.81×10^{34}	5.75×10^{34}
Earth	5.97×10^{24}	5.91×10^{33}	5.75×10^{34}
Pluto	6.6×10^{23}	2.3×10^{31}	3.05×10^{33}
Venus	4.87×10^{24}	1.8×10^{31}	4.38×10^{34}
Mercury	3.33×10^{23}	6.5×10^{29}	1.23×10^{33}

*We use SI units, in which the mass is measured in kg and the spin in kg·m²/sec≡J·sec.

†The observational data are from Refs. protect 26 and 27. The total angular momentum of the satellites in the Jupiter, Saturn, and Uranus systems is much smaller than the spin of the central planet. In the Jupiter system the total angular momentum of the moons is 4.24×10^{36} kg·m²/sec, in the Saturn system it is 9.6×10^{35} kg·m²/sec, and in the Uranus system it is 0.7×10^{34} kg·m²/sec.

$$J_1=J_2=J=\hbar\left(\frac{m}{m_p}\right)^{3/2}. \tag{20}$$

If the pair of galaxies was formed by the decay of a protohadron with mass $2m$, the total angular momentum of the system must be

$$J_{\text{tot}}=\hbar\left(\frac{2m}{m_p}\right)^{3/2}=\sqrt{2}\,2J. \tag{21}$$

The minimum and maximum orbital angular momenta are

$$L_{\min}=J_{\text{tot}}-2J=(\sqrt{2}-1)2J, \tag{22}$$

$$L_{\max}=J_{\text{tot}}+2J=(\sqrt{2}+1)2J. \tag{23}$$

The average orbital angular momentum is half the sum

$$\frac{L_{\min}+L_{\max}}{2}=J_{\text{tot}}=\sqrt{2}\,2J, \tag{24}$$

which is consistent with the number obtained by Gorbachev from the observational data:

$$\frac{L_{\min}+L_{\max}}{2}=(1.2-1.6)2J\approx1.42\,J. \tag{25}$$

4.3. Theory

In Fig. 2 we show three straight lines corresponding to the two Regge trajectories $J^{(2)}$ and $J^{(3)}$ and the Kerr trajectory J^{Kerr} in the doubly logarithmic $\log_{10}(m)-\log_{10}(J)$ plane. We recall that the Regge trajectory $J^{(2)}$ from Eq. (4) corresponds to flat, disk-like objects, the trajectory $J^{(3)}$ from (5) describes three-dimensional spherical objects, and the gravitational trajectory J^{Kerr} from (7) characterizes one-dimensional string-like objects.

Two important points can be distinguished in this plot:

• The *Eddington point* corresponding to the intersection of the Regge trajectory for a disk (4) with the Kerr angular momentum (7). At this point, we must have $J^{(2)}=J^{\text{Kerr}}$, i.e., the equation

$$\hbar\left(\frac{m}{m_p}\right)^{3/2}=\frac{Gm^2}{c},$$

when solved for m, gives the Eddington expression for the mass of the Universe, expressed as a combination of fundamental constants. Substituting the resulting value of the mass into (4) or (7), we find the coordinate of the intersection point on the $J^{(2)}$ axis. Therefore, the Eddington point has the coordinates

$$m_{\text{Universe}}=m_p\left(\frac{\hbar c}{Gm_p^2}\right)^2, \tag{26}$$

$$J_{\text{Universe}}=\hbar\left(\frac{\hbar c}{Gm_p^2}\right)^3. \tag{27}$$

• The *Chandrasekhar point* corresponds to the intersection of the Regge trajectory for a sphere $J^{(3)}$ with the Kerr trajectory J^{Kerr} at the point where $J^{(3)}=J^{\text{Kerr}}$ or

$$\hbar\left(\frac{m}{m_p}\right)^{4/3}=\frac{Gm^2}{c}.$$

Solving this equation, we find the coordinates of the Chandrasekhar point:

$$m_{\text{star}}=m_p\left(\frac{\hbar c}{Gm_p^2}\right)^{3/2}, \tag{28}$$

$$J_{\text{star}}=\hbar\left(\frac{\hbar c}{Gm_p^2}\right)^{2}. \tag{29}$$

These results can be written compactly using the intersection condition written in the general form

$$\hbar\left(\frac{m}{m_p}\right)^{1+1/n}=\frac{Gm^2}{c}.$$

The solutions of this equation for arbitrary n have the form

$$m(n)=m_p\left(\frac{\hbar c}{Gm_p^2}\right)^{n/n-1}, \tag{30}$$

$$J(n)=\hbar\left(\frac{\hbar c}{Gm_p^2}\right)^{n+1/n-1}. \tag{31}$$

For $n=2$ this solution corresponds to the Eddington point, and for $n=3$ it corresponds to the Chandrasekhar point.

Using the Planck mass, we can rewrite (30) and (31) as

$$m(n)=m_p\left(\frac{m_{\text{Pl}}}{m_p}\right)^{(2n/n-1)}, \tag{32}$$

$$J(n)=\hbar\left(\frac{m_{\text{Pl}}}{m_p}\right)^{2(n+1)/n-1}. \tag{33}$$

4.4. The canonical derivation of the limiting masses

In 1931 Chandrasekhar discovered an upper limit on the mass of a degenerate configuration. Soon afterwards, in 1932, a few months after the discovery of the neutron, Landau gave a simple derivation of Eq. (28) for the limiting mass of a star.

It is useful to recall the canonical derivation of the expressions for the limiting masses (26) and (28) without using the Regge theory.[4)]

First, we consider the general case of an n-dimensional degenerate configuration. We assume that a self-gravitating object with mass m and radius r is supported in equilibrium owing to the relativistic Fermi energy. Then for each nucleon we must have

$$\text{Gravitational energy}=\text{Fermi energy}\ \frac{Gmm_p}{r}=p_F c. \tag{34}$$

If the distance between the nucleons is d, according to the Heisenberg uncertainty relation the Fermi momentum is

$$p_F=\frac{\hbar}{d},$$

and from the requirement of constant density we find the following relation between r and d:

$$r=\left(\frac{m}{m_p}\right)^{1/n} d.$$

Substitution of these values into (34) leads to an equation which does not involve the distance d:

$$\frac{Gmm_p}{\left(\frac{m}{m_p}\right)^{1/n}}=\hbar c$$

and whose solution for m takes the form

$$m=m_p\left(\frac{\hbar c}{Gm_p^2}\right)^{n/n-1},$$

which coincides with Eq. (30) derived above.

The mass of the Sun is expressed in terms of this combination of fundamental constants for $n=3$, and most stars have masses lying in the narrow range from 0.1 to 10 times this value. For $n=2$, as expected, we obtain the Eddington expression for the mass of the Universe.

The dimensionless combination of fundamental constants frequently encountered here has the value

$$\frac{\hbar c}{Gm_p^2}=1.69358\times 10^{38}. \tag{35}$$

Bearing this in mind, from (26), (27), (28), and (29) we find the numerical values for the limiting masses and spins:

$$m_{\text{Universe}}=2.86822\times 10^{76}\ m_p=4.79744\times 10^{49}\ \text{kg} \tag{36}$$

$$J_{\text{Universe}}=4.85756\times 10^{114}\ \hbar=5.12265\times 10^{80}\ \text{J}\cdot\text{sec} \tag{37}$$

$$m_{\text{star}}=2.20399\times 10^{57}\ m_p=3.68644\times 10^{30}\ \text{kg} \tag{38}$$

$$J_{\text{star}}=2.86822\times 10^{76}\ \hbar=3.02474\times 10^{42}\ \text{J}\cdot\text{sec} \tag{39}$$

or, numerically,

Eddington point$\Rightarrow\{4.80\times 10^{49}$ kg,

5.12×10^{80} J·sec$\}$

Chandrasekhar point$\Rightarrow\{3.69\times 10^{30}$ kg,

3.03×10^{42} J·sec$\}$.

5. THE ORIGIN OF COSMIC MAGNETIC FIELDS

Large-scale magnetic fields play an important role in the Universe, and most heavenly bodies—planets, stars, and galaxies—possess magnetic fields. The magnetic fields of many bodies can be approximated by the field of a point dipole located at the center of the object, with the direction of the axis of the equivalent dipole, as a rule, coinciding (or making a small angle) with the axis of rotation of the object. For example, the Earth's magnetic field is approximated well by the field of a point dipole with magnetic moment

$\mu_{\oplus}=8.1\times10^{22}\ A\cdot m^2$. If in the familiar expression for the dipole magnetic moment $\mu=e/mJ$ we replace the charge e by the effective "gravitational charge" [5)]

$$e^*=\sqrt{\epsilon_0 G}m\equiv\sqrt{\frac{G}{\mu_0}}\frac{1}{c}m, \qquad (40)$$

we obtain the Blackett expression[45,46] for the dipole magnetic moment of heavenly bodies:

$$\mu=\sqrt{\frac{G}{\mu_0}}\frac{J}{c}, \qquad (41)$$

which to a good approximation describes the magnetic fields of planets and stars. In particular, for the Earth the Blackett formula gives $\mu_{\oplus}=1.43\times10^{23}\ A\cdot m^2$. For Mercury the observed magnetic moment is $2.4\times10^{19}\ A\cdot m^2$, while the value calculated from the Blackett formula is $5.6\times10^{19}\ A\cdot m^2$. For Jupiter the observed moment is $1.5\times10^{27}\ A\cdot m^2$, and the theoretical value is $1.1\times10^{28}\ A\cdot m^2$.

For the Milky Way the dipole magnetic moment predicted by the Blackett formula (41) is $\mu_G=4.9\times10^{57}\ A\cdot m^2$. The hypothesis that magnetic dipoles exist at the galactic scale was first made in Ref. 47 on the basis of analysis of the observational data on the magnetic field configuration in the active explosive galaxy M82. The structure of the magnetic fields of certain radio sources with "tails," for example, 3C 129 and NGC 1265 moving in clusters of galaxies, also indicates the existence of galactic magnetic dipoles.[52]

The charge $\sqrt{\epsilon_0 G}m$ is extremal in the sense that it plays a special role in the Einstein theory of general relativity, where it is the maximum allowed charge of a black hole in the Kerr–Newman metric, because the mass m, spin J, and charge e of a black hole must satisfy the condition

$$\frac{e^2}{\epsilon_0}Gm^2+J^2c^2\leqslant G^2m^4. \qquad (42)$$

There is also another indirect justification for Eq. (41). According to classical electrodynamics, a magnetized sphere of radius r with dipole moment μ possesses a magnetic energy of order $\mu_0\mu^2/r^3$. The kinetic energy of rotation of this sphere has order of magnitude J^2/mr^2, where m is the mass and J is the angular momentum of the magnetized sphere. The magnetic energy is equal to the kinetic energy of rotation if $\mu=\sqrt{r/\mu_0 m}J$. For a black hole the radius is equal to the gravitational radius $r=Gm/c^2$, which again leads to the Blackett formula (41).

It is interesting to generalize the Blackett formula to higher magnetic and electric moments. By dimensional analysis we find the following expressions for the magnetic multipoles $\mu^{(k)}$:

$$\mu^{(k)}=\sqrt{\frac{G}{\mu_0}}\frac{J}{c}\left(\frac{J}{mc}\right)^{k-1} \quad k=1,3,5,... \qquad (43)$$

and the electric multipoles $\epsilon^{(k)}$:

$$\epsilon^{(k)}=\sqrt{\epsilon_0 G}m\left(\frac{J}{mc}\right)^{k} \quad k=0,2,4,.... \qquad (44)$$

Let us estimate the possible octupole ($k=3$) magnetic moment of our galaxy:

$$\mu^{(3)}=\sqrt{G}\frac{J_G^3}{m_G^2c^3}=2.4\times10^{94}\ A\cdot m^4. \qquad (45)$$

It is easy to see that the octupole moment gives a negligible contribution in the vicinity of the solar system and can be disregarded compared to the dipole contribution. However, the octupole contribution can be compararable to the dipole contribution at distances of order 0.2 kpc. In the immediate neighborhood of the nucleus of the Milky way the field must have a rather complicated structure with higher multipoles contributing.

In concluding this section, we note that, in contrast to angular momentum, which is conserved in the evolutionary process, the magnetic moment of decaying objects is not completely conserved. However, because of the high conductivity and the large self-induction of the evolution products, the primordial magnetic field is weakened only insignificantly, and the relaxation time of order 10^{30} yr significantly exceeds the age of the Milky Way. Therefore, during the lifetime of the Milky Way only insignificant changes of the magnetic field associated with the motion of ionized interstellar matter could have occurred.

Therefore, in some sense we can speak of the quasi-conservation of the magnetic field of the superhadron during the evolution of its decay products.

6. A SCENARIO FOR THE ORIGIN OF THE UNIVERSE FROM THE PRIMEVAL HADRON

The above discussion suggests a possible explanation of the origin of astronomical proto-objects possessing definite mass and spin. The formation of the Universe and its structural components, galaxies and stars, can be represented schematically as follows. First, the entire Universe was a planar superhadron of mass equal to about 10^{80} proton masses and spin equal to 10^{120} in units of the Planck constant. This Primeval Hadron then decayed into objects which were also planar superhadrons: proto-clusters of galaxies. Next, these proto-clusters of galaxies underwent fragmentation into superhadrons with mass of the order of the galactic mass and, finally, into stars. Rotational motion is observed at all levels of organization of the astronomical systems as a result of conservation of the superhadron spin. According to the Peebles classification,[40] our scenario balongs to the top→down class, in contrast to the more commonly encountered bottom→up scenarios. It is interesting that the entire cascade of hierarchial fragmentations occurs from yrast states. It is necessary to assume that in the formation of fragments with mass of the order of the stellar mass, the geometrical shape of the hadrons must change from planar to spherical. A simultaneous phase transition from quark to baryonic (neutronic) matter might also occur.

The most interesting feature is the prediction that the entire astronomical Universe as a whole rotates. Using the numerical value of the spin of the Primeval Hadron, we can estimate the rotational angular velocity of the Universe. It turns out that $\omega_U\approx10^{-13}$ radian/yr, i.e., the time for a single complete revolution of the Universe is roughly 10^{13} yr, which is a thousand times larger than the age of the Universe. Birch[53,54] found indications of possible rotation of the

Universe with this velocity on the basis of study of the geometrical form of the magnetic fields in radio galaxies.

The following estimate of the rotational angular velocity of the Universe seems realistic:

$$\omega_U = 10^{-3\pm 1} \frac{\text{radian}}{\text{age of the Universe}}. \tag{46}$$

This is apparently consistent with the data on the absence of quadrupolar anisotropy of the background microwave radiation.

The expression for the angular momentum of the Universe,

$$J_{\text{Universe}} = \hbar \left(\frac{\hbar c}{G m_p^2} \right)^3,$$

admits an interesting interpretation: *the density of the spin angular momentum of the proton and the Universe are the same*. In fact, from the equation

$$\frac{\hbar}{r_p^3} = \frac{J_{\text{Universe}}}{r_{\text{Universe}}^3},$$

where $r_p = \hbar / m_p c$ is the proton radius and $r_{\text{Universe}} = r_p \hbar c / G m_p^2$, we find the expression derived above for the angular momentum of the Universe.

7. CONCLUSIONS

Any theory of the formation of the Universe which ignores the fact that galaxies, stars, and clusters possess angular momentum cannot be considered complete. Only by carefully studying the spin vectors of galaxies and stars is it possible to find a key to the problem of the origin of the Cosmos.

A correct understanding of the origin of the rotation of cosmic objects is of great value for cosmology, because spin is apparently a parameter which is as intrinsic to heavenly bodies as mass, and so it must give valuable physical information about the initial state.

The approach we have proposed allows a self-consistent theoretical derivation of reasonable numerical values for the angular momenta of cosmic objects, from planets to the astronomical Universe as a whole, in extremely large ranges of mass (30 orders of magnitude) and angular momentum (50 orders of magnitude). It should be stressed that this was achieved without using any arbitrary fitted parameters; the only parameters involved in our expressions are the fundamental constants of nature.

Might there exist a hidden mass and a hidden angular momentum[40,41] in cosmic bodies? Apparently yes, but if this hidden mass participates in gravitational interactions, it could also possess a hidden Regge behavior. It is also possible that the hidden mass is only an effective manifestation of the nonstationarity of astronomical systems and, as noted by Corliss,[42] "The need for a hidden mass disappears if it is assumed that galaxies and clusters of galaxies may also not be in a state of (dynamical) equilibrium."

In this article we have stressed the fact that the idea of the Regge behavior of the angular momenta of cosmic objects and systems of such objects allows the theoretical explanation of the observed rotational motion of heavenly bodies. The fact that the concept of Regge trajectories can be used successfully in astrophysics demonstrates the uniqueness and simplicity of Nature in a huge range of masses and angular momenta from the scale of elementary particles up to the scale of clusters of galaxies and the astronomical Universe as a whole.

The main difference between our approach and other cosmological theories is that our approach uniquely includes the quantum-mechanical constants $\hbar$ and m along with the classical constants G and c, whereas, for example, the standard Big Bang cosmology based on the general theory of relativity is a purely classical theory.

A more detailed description of the origin of the heavenly bodies may be possible after the construction of a unified theory incorporating the strong, electromagnetic, and gravitational interactions. Until then, the expressions obtained here can be viewed as "fragments" of such a theory, analogous to the way the expressions for the Bohr atom are related to the more fundamental derivations of wave mechanics.

Our arguments suggest the possibility that cosmic objects originate in the decay of superhadrons: macroscopic quantum bodies. Galaxy formation via the decay of cosmological hadronic fireballs was first studied by Sisteró[14,15] (see also Refs. 16 and 17). Frankel,[56] starting from other arguments, discusses the possibility that in the distant past the Universe had an extremely anisotropic planar configuration, which is consistent with our results.

Any further development of this approach will help to shed light on the crucial question of whether the astronomical Universe was actually formed as a result of the decay and fragmentation of a planar superheavy hadron. Or, in other words, is the observed Universe with all its diverse structure—galaxies, stars, planets, and diffuse matter—a residue of a single Primeval Hadron with the shape of a disk and having mass of order $10^{80} m_p$ and spin of order $10^{120}\hbar$?

If this is so, it will be amusing to learn that the primeval vortices discussed by the natural philosophers of ancient times have a quantum origin.

APPENDIX: THE LEADING REGGE TRAJECTORY OF AN *n*-DIMENSIONAL HADRON

We shall show that the Regge trajectory (31) corresponds to the minimum of the total hadron mass m for a given spin $J^{(n)}$, i.e., that it is the leading or yrast Regge trajectory. In nuclear physics, states with the minimum mass (energy) for a given spin are called yrast states. In these states the total energy (mass) is the rest energy plus the energy of the rotational motion, and so the contribution to the energy from vibrational motions is zero.

Let us consider an n-dimensional rotating object with total mass m, radius r, constant density ρ, and angular velocity $\omega = c/r$. The total mass m is the sum of the rest mass and the mass due to the rotational energy:

$$m = \rho r^n + m_{\text{rot}} = \rho r^n + \frac{J\omega}{2c^2} = \rho r^n + \frac{J}{2cr}. \tag{47}$$

The leading trajectory corresponds to the minimum m for fixed J. Minimizing m with respect to r,

$$\frac{\partial m}{\partial r}=0=-\frac{J}{2cr^2}+n\rho r^{n-1}, \tag{48}$$

we find the value of r which for a given J leads to the minimum mass:

$$r=\left(\frac{J}{2n\rho c}\right)^{1/n+1}. \tag{49}$$

Substitution of this value of r into (47) leads to the following relation between spin and mass for the leading Regge trajectory:

$$J=m^{1+1/n}\frac{2n\rho^{-1/n}c}{(n+1)^{1+1/n}}. \tag{50}$$

Our basic generalized Regge law (31) follows from (50) if in the latter we substitute the nuclear value for the density ρ:

$$\rho\sim\frac{m_p}{\left(\frac{\hbar}{m_pc}\right)^n}\sim\frac{m_p}{\left(\frac{\hbar}{m_pc}\right)^n}\frac{(2n)^n}{(n+1)^{n+1}}. \tag{51}$$

As Matveev has noted, the same result follows from minimization of the semirelativistic expression for the total mass of a rotating n-dimensinal object:[6)]

$$m=\sqrt{(\rho r^n)^2+\left(\frac{J}{2cr}\right)^2}. \tag{52}$$

[1)]The author would like to thank Prof. A. M. Baldin for interesting discussions of this topic.

[2)]The numerical value of the Planck mass is $m_{Pl}=2.177\times10^{-8}$ kg, which is 1.3×10^{19} times larger than the proton mass, i.e., $m_{Pl}=1.3\times10^{19}m_p$. We also have the identity $m_{Pl}\equiv m_p(\hbar c/Gm_p^2)^{1/2}$.

[3)]In SI units, $kg\cdot m^2/sec\equiv J\cdot sec$.

[4)]More details about the derivation of the Chandrasekhar limit can be found in Ref. 48, along with the dramatic history of the physics of compact objects.

[5)]The dielectric constant ϵ_0 and the magnetic permeability μ_0 of free space should be used in SI units: $\epsilon_0=8.854\times10^{-12}$ F/m and $\mu_0=1.257\times10^{-6}$ H/m.

[6)]The author thanks V. A. Matveev for this remark.

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