THE PHYSICOCHEMICAL MECHANISM OF THE FORMATION OF PLANETARY SYSTEMS

GEORGY GLADYSHEV
Institute of Chemical Physics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

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Abstract. The planets and their satellites are formed in accordance with similar mechanisms as a result of spatially periodic condensation of gaseous matter during the formation of the central body.

Using the diffusion theory one can calculate the age of the planets and explain the nature of the Titius-Bode law.

1. Introduction

There exist several elaborate hypotheses of the formation of planetary systems, in particular the solar system, in which the decisive role is played by gravitational, magnetic and other forces (references 1, 2, 3 and 4), but there are no quantitative hypotheses taking into account the peculiarities of the kinetics and mechanism of physico-chemical phenomena in the formation of planets and their satellites.

In this paper we present the fundamentals of a diffusion hypothesis, according to which the regular structure of planetary systems can be quantitatively explained as a consequence of spatially periodic condensation of gaseous matter during the formation of the central body.

It will be shown that the planets and their satellites are formed in accordance with similar mechanisms. The present paper is a first attempt to use diffusion theory to explain the solar system's formation. The theory gives the possibility of calculating the time of formation of primary rings of condensed matter and the ages of the planets and the solar system as a whole and then of explaining the nature of the Titius-Bode law.

2. Model Considerations

Let us consider one of the simplest models. Following well-known concepts, let us assume that the Sun began to take shape from a rotating nebula consisting of gaseous matter and fine-grain dust. Gravitational compression led to the formation of a protosun, surrounded by a nebula (disk) of rarefied matter. Later, matter from the Sun began to escape in the equatorial plane. Owing to subsequent diffusion of the ejected hot matter into the relatively cold nebula consisting of matter in a gaseous state, there occurred a spatially periodic condensation of the rarefied gas, leading to the formation of condensed matter from which protoplanets took shape.

Protoplanets experienced gravitational compression and then, as in the case of the

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Sun, lost their gaseous envelopes. Rings were formed, followed by the accumulation of particles and formation of regular satellites.

It can be shown that during diffusion (reference 5) of matter from the protosun or protoplanet into their corresponding nebula (disks) there should form, under certain conditions, periodically condensed rings due to proceeding chemical reactions of formation of nonvolatile compounds. Minute particles of cosmic dust may have served as centers of such a condensation.

A confirmation of the hypothesis under consideration should be the correspondence of the arrangement of the rings being formed to the Titius-Bode rule (references 1, 2, 4 and 6), which can be represented in the form

$$r_n = r_0 \beta^n, \tag{1}$$

where r_n is the major semi-axis of the nth orbit, r_0 is a constant and β is a constant for the solar system close to 1.7.

Let us consider the mechanism of periodic condensation accompanying chemical processes. Assume that the periodic condensation on cosmic scales is similar to the Liesegang phenomenon (references 5, 7, 8 and 9), which although interpreted variously lead in all models to the same basic result.

We shall consider that matter escaping from the protosun or protoplanet is hotter than the nebula's matter. We shall also assume that, after matter from the central body and nebula has mixed, the multi-component gas exists for a certain time in a supersaturated state. For simplicity, we shall designate the concentration of the escaping reactive multi-component diffusing matter by c_s and the concentration of the nebula's reactive matter by c_n.

The interaction of matter s and n yields condensed matter. The magnitude of supersaturation may be represented by the product $(c_s^{n'} c_n^{m'})$ where n' and m' are averaged stoichiometric coefficients. Condensation begins when the value of $(c_s^{n'} c_n^{m'})$ exceeds a certain critical value. After the formation of condensate, the value of c_s and c_n decrease abruptly, so that close to the critical distance r_{cr} (references 6, 7, 8 and 9) the value of $(c_s^{n'} c_n^{m'})$ is reduced practically to zero. With increasing distance from the central body, the process described is repeated periodically (references 7, 8 and 9).

In considering the posed problem, let us assume that for a certain value of $r_n' \ll r_1, r_2, \ldots, r_n$ the motion of particles of matter obey the Fick relation

$$\partial c_{s,n}/\partial t = \operatorname{div} D_{s,n} \operatorname{grad} c_{s,n}, \tag{2}$$

where t is time and $D_{s,n}$ is the coefficient of diffusion.

The approximate theory does not make it possible to obtain the value of r_n but, if it is known, one can determine r_{n+1}, which is proportional to r_n

$$r_{n+1} = a r_n, \tag{3}$$

where a is a constant.

Thus we come to the conclusion that rings of condensed matter are arranged in geometrical progression, i.e. as required by the Titius-Bode rule.

Using the simplified one-dimensional model of Liesegang rings formation (reference 9), one can write

$$\frac{\xi}{r} = \frac{H}{\gamma_1^2}\left(\frac{K}{c_{n_0}^{\alpha}}\right)^{\beta'} \tag{4}$$

for $c_{s_0} \gg s_{n_0}$, where ξ is the distance between the rings, $\alpha = \nu_s + \nu_n$, $\beta' = 1/(2\nu_s + \nu_n)$, $H = f(\nu_s, \nu_n, D_{s,n}, \ldots)$, K is the constant of supersaturation, ν_s and ν_n being coefficients of condensed matter, γ_1 is a dimensionless constant determined (for $D_s = D_n$) by the ration of initial concentrations

$$c_{n_0}/c_{s_0} = (1 - erf(\gamma_1))/(1 + erf(\gamma_1)) .$$

From Equation (4) it follows that ξ/r = constant and is determined by the types of chemical processes and peculiarities of condensation.

Moreover, from the same equation it follows that the distance between rings is the greater, the smaller c_{n_0}.

We shall show that from the standpoint of the diffusion laws the proposed hypothesis is quite justified. Let us assume that for very rarefield gas (reference 10)

$$D = 2.63 \times 10^{-3}\sqrt{\frac{T^3}{M}}/p\sigma^2, \tag{5}$$

with D in (cm^2/sec) and T is the temperature (°K), M is the average atomic (molecular) weight of matter, p is the pressure in (atm) and σ is the average diameter of the particles in (Å).

By use of the expression

$$\tau = \frac{r^2}{4\gamma^2 D} , \tag{6}$$

where γ is a dimensionless constant determined in the general case (reference 8) by the ratios

$$D_s/D_n, c_{s_0}/c_{n_0}, (c_s^{n'} c_n^{m'})_{cr}/(c_s^{n'} c_n^{m'}),$$

one obtains

$$p(\text{atm}) = 2.63 \times 10^{-3}\sqrt{\frac{T^3}{M}} \times 4\gamma^2\tau/r^2\sigma^2 . \tag{7}$$

If one assumes that T is sufficiently high (e.g. 100° K and higher, reference 4) and τ, the time of formation of all "primary rings" is commensurable with the age of the solar system ($\approx 1.4 \times 10^{17}$ sec), then p, calculated from Equation (7), turns out to be such that the overall mass of the nebula is commensurable with (or even significantly exceeds) the mass of the planets of the solar system (reference 11).

Another model assumes diffusion of matter from the periphery of the nebula to a relatively rarefield region which could have formed during gravitational compression. From the standpoint of mathematical description this model is analogous to the model discussed above. Therefore, the overall results obtained are applicable, in principle, to both models.

3. Discussion

The detailed theory of diffusion formation of planets should take into account the fact that the original distances and periods of rotation (T_n) around the central body are functions of many parameters

$$r_n(T_n) = f(T, p, c_{s_j}, c_{n_i}, \Delta\bar{H}_j, \Delta\bar{H}_i, \ldots),$$

where $\Delta\bar{H}_j$ and $\Delta\bar{H}_i$ are average heats of condensation and of chemical transformation.

One can believe that a consequence of the functional dependence of r_n should be that Equation (1) is more satisfactorily obeyed for systems of regular satellites of large planets than for the planets of the solar system themselves.

The theory presented in the paper affords making some predictions. In particular, it predicts an effect of separation of chemical substances during the formation of the primordial rings of planetary systems and the existence of rings round the young planets of the solar system, for example, Neptune.

Besides, rings and satellites may be formed around large satellites of planets, etc.

It is interesting to apply the hypothesis under consideration to galactic scales.

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Notes and References

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[4] *Symposium sur l'Origine du Systèmes Solaire* (Symposium on the Origin of Solar systems) Nice, 3–7 Avril, 1972, Reeves, Hubert responsable de la publication, Edition du Centre National de la Recherche Scientifique, Paris, 1972. For some interesting aspects of the solar system formation see for instance the papers by W. McCrea, H. Reeves, G. Arrhenius, R. B. Larson, H. C. Urey, E. Anders, J. Lewis and J. Vedder and by some other authors.

[5] At first we talk about diffusion (in a classical sense) of matter into the nebula (disk). It can be shown that moving matter of the central body exchanges energy with the matter of the

nebula itself which is spread along Keplerian orbits; thus the matter of the central body moves according to the diffusion laws.

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[11] We present a numerical example. Combination of Equations (5) and (6) and $pV = (m/M)RT$ gives

$$\tau = \frac{m R r^2 \sigma^2}{\sqrt{M} V 2.63 \times 10^{-3} 4\gamma^2 \sqrt{T}} .$$

If $m = 1.35 \times 10^{30}$ g, $R = 82.1$ cm^3 atm/mode °K, $r = 6 \times 10^{14}$ cm, $\sigma = 3$Å, $M = 20$, $V = 10^{44}$ cm^3, $\gamma = 6$, $T = 200$ °K, then $\tau = 5 \times 10^9$ yr.

We emphasize that this evaluation is semi-quantitative. The gas diffusion leads to a decrease in the distance from the central body of corresponding masses of the nebula (compressing nebula). But this and other effects not taken into account by us do not change the general picture of the phenomenon. For the time being, we also disregard the presence in the nebula and in the protostar matter of "unreactive" ("uncondensing") substances, such as redundant hydrogen and the like.

A more exact solution of the problem assumes the use of the equation of motion of a partially ionized gas in a velocity field provided that the equation takes into account gravitational, Coriolis and electromagnetic forces, temperature and density gradients and other effects.

According to one of the simplest models, the rings of the germs of primary protoplanets and satellites are formed in general of the iron and silicon compounds. Fe (as other heavy elements) is transported from the central body in the form of the following compounds such as FeH, $FeH_n(CO)_m$ $(SiO)_p$ Hal_r (the sum of n, m, p, r may change from 1 to 5). Then these compounds may react, for example, with H_2O of the protonebula, producing non-volatile compounds.