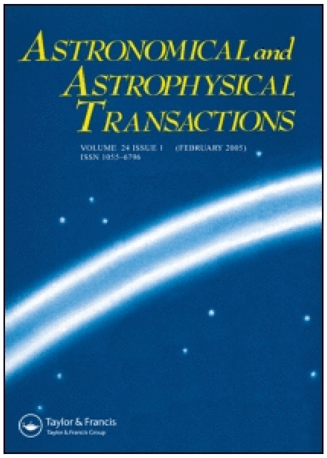

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A. V. Tutukov [a]
[a] Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya Str. 48, 109017 Moscow, Russia.

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STAR FORMATION IN GALAXIES

A. V. TUTUKOV

Institute of Astronomy, Russian Academy of Sciences, Pyatnitskaya Str. 48,
109017 Moscow, Russia

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A model of dynamical and chemical evolution of spherical and disk galaxies are discussed. The star formation rate in the model is regulated through ionization of the interstellar hydrogen by massive O,B stars. The volume of a galaxy is determined by the condition of equilibrium between collisional dissipation of turbulent energy of interstellar gas and turbulisation of the gas by supernovae. The modern theory of stellar evolution helps to describe evolution of the stellar component of a galaxy in time and to estimate the current frequency of supernovae. This model reproduces some basic observed parameters of spherical and disk galaxies and their evolution on the Hubble timescale. The role of external factors in evolution of galaxies and possible reasons of a nonstationary star formation in galaxies and their nuclei are shortly discussed.

Keywords: Galaxies; Star formation

INTRODUCTION

Most of galaxies are members of clusters with the average mass $10^{15}\,\mathrm{M}_\odot$ and the radius 1–3 Mpc (Girardi *et al.*, 1998). These clusters are probably largest elements of the Universe structure, separated by distances $\sim$100 Mpc (Ronkema *et al.*, 2001). The last means, that in limits of cosmological horizon ($\sim 4\times 10^9$ pc) there are $\sim 10^5$ clusters of galaxies. This number is close to the number of quasars (Richard *et al.*, 2001), which are usually nuclei of supermassive spheroidal central galaxies placed near centers of dense clusters (Djorgovski *et al.*, 1999). The volume of a cluster is filled by the hot virial gas with mass comparable to the mass of a cluster. Many central galaxies display a high star formation rate, up to $1000\,\mathrm{M}_\odot$/yr (Schwartz *et al.*, 1991), supported by the accretion of the intracluster gas (cooling flows) and by the fast astration of own gas, induced probably by close passages (collisions) of field galaxies (Taniguchi, 1999). Observations displayed, that the most part of galactic clusters really have cooling flows in their nuclei (Pierre and Starck, 1998).

The power like luminosity (mass) function of galaxies according to observations has a break at luminosity $L = 10^{10}\,\mathrm{L}_\odot$ ($M = 2\times 10^{11}\,\mathrm{M}_\odot$) (Anderson *et al.*, 2000; Allen, 1973). As a result, galaxies like our Galaxy contain the most part of stellar matter, which makes the study of their evolution of a special interest. Galaxies, moving in a cluster, experience the tidal friction. Numerical estimates display, that galaxies with masses above $\sim 10^{11}\,\mathrm{M}_\odot$, moving with an average speed, lose their kinetic energy in the Hubble time and go down

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to the center of a parent cluster. This phenomenon, probably, helps to understand a reason and the position of the break of the luminosity function and the origin of central supermassive cD galaxies. Cooling flows feed central galaxies and nuclei of latters, what are supermassive (up to $10^{10}\,M_\odot$) black holes (quasars). To support the observed stellar luminosity of supermassive galaxies the star formation rate $100–1000\,M_\odot/yr$ is necessary (Neumann, 1999; Puy *et al.*, 1999). Masses of cD galaxies grow in Hubble time by cooling flows and by collisions with other galaxies of the parent cluster up to current values $\sim 10^{13}\,M_\odot$ (Koopman and Tren, 2002). High gas and dust abundances (Dietrich and Wilhelm-Erkerns, 2000) transform these galaxies into powerful sources of infrared radiation $L_{IR} \sim 10^{12}\,L_\odot$ (*e.g.* Firmani and Tutukov, 1994).

Masses of even very young distant quasars with age $\sim 7 \times 10^8$ yrs (reionization, the redshift $z \sim 6.2$) consist of $\sim 10^{10}\,M_\odot$ (Kaspi, 2000). If initial (at the very beginning of the cosmological expansion) masses of central black holes (BH) were stellar ($\sim 100\,M_\odot$), and the accretion rate was limited by the Eddington value, so massive BHs could be formed only at the age $\sim 2 \times 10^9$ yrs. The latter corresponds to $z \sim 2.5$, and it is of interest to know that there really is a strong concentration of quasars at $z \sim 2.3$ (Veron-Cetty and Veron, 1993). A deeper study of the role of the Eddington limit in the process of accretion is necessary to clear the reality of this scenario at least for a part of quasars. If the accretion rate by a supermassive BH is really limited by the Eddington limit, massive quasars at $z \sim 6$ have to start their accretional growth with the initial masses above $\sim 10^5–10^6\,M_\odot$. A short living supermassive star can be the precedor of the BH in the case. Such stars can be formed in the very center of a young massive galaxy in the process of accretion of gas (Tutukov, 1989). The lifetime of a supermassive star independently of its mass consists of $\sim 10^6$ yrs, so the mass of a supermassive star to the moment of collapse will be $\sim \mu \times 10^6\,M_\odot$, where μ is the accretion rate in units $M_\odot/yr$. So, $\mu \sim M_\odot/yr$ is enough to form a massive enough seed BH. But since cooling flow can supply up to $10^2–10^3\,M_\odot/yr$ (Neumann, 1999), the accretion of even a small part of this influx is enough to explain the reason of appearance of so massive BHs (quasars) at $z \sim 6$.

The observed input of quasars in the total luminosity is ~ 0.1 (Elvis *et al.*, 2001). That provides for a possibility to estimate the average relative mass β of a central BH of a galaxy. The average luminosity of the accreting BH in the Hubble timescale is $\sim 100\beta \cdot M/M_\odot \cdot L_\odot$, where M is the mass of the galaxy, including this BH. The luminosity of a galaxy can be estimated from the $[M/L] \sim 30$ (Allen, 1973). Thus, $\beta \sim 3 \times 10^{-5}$, what explain the mass of the BH in the center of our Galaxy (Melia, 2001). But for quasars $\beta \sim 0.001$ (McLure and Dunlop, 2002), what means, that only a small part of massive galaxies can give birth a supermassive BHs in their nuclei and provide for a proper for quasars accretion rate.

The study of galactic evolution is an actual branch of modern astrophysics. There are two main factors, inspiring the progress in the field. The observational study of galaxies provides rich information about their main properties: masses, luminosities, stellar and gas contents, chemistry, the star formation pattern, activity of nuclei and so on. Survey of most distant galaxies and study of gamma bursters (Lamb, 2002) provides information about early phases of evolution of brightest galaxies. All that puts the study of galactic evolution on a solid observational base. The second factor, promoting the progress in the field is the high level of the modern theory of stellar evolution. The latter gives the information about evolution of stars of different masses, beginning from their birth up to formation of final remnants: white dwarfs, neutron stars and black holes. Supernova explosions are an important evolutionary factor for dynamical and chemical evolution of galaxies. Formation of white dwarfs is an important source of gas, supporting the star formation process in disk and a hot wind of spheroidal galaxies.

SPHERICAL AND DISK STELLAR POPULATION

Now we shortly discuss main global properties of galaxies. Stellar population of galaxies can be, commonly speaking, divided into two main families: spheroidal and disk ones. The first includes mainly old stars and almost no gas, the last is rich with gas and displays signatures of the current star formation. The spheroidal population presented by elliptical galaxies, and the disk population- by spiral and irregular ones. A real galaxy consists, commonly speaking, of both populations. Spiral galaxies have spheroidal massive stellar bulges and many elliptical galaxies have in circumnuclear regions star-gas disks. It is clear, that disk galaxies are products of dissipative evolution of rotating gas protogalaxies (*e.g.* Wiebe *et al.*, 1998). The spheroidal component is a product of several reasons. A part of compact elliptical galaxies are a probable result of a fast loss of their gas component, induced by the initial strong burst of star formation in a slowly rotating gas spheroidal protogalaxy. Some of these galaxies can be disrupted at all after fast loss more than a half of their initial mass (Firmani and Tutukov, 1994). Such phenomenon helps to understand the reason of existence of a significant population of planetary nebulae and red giants in the intergalactic space (Ford *et al.*, 2001; Durrel *et al.*, 2002). The observational search of SNe Ia in intergalactic space becomes now actual. Repetitive bursts of star formation in gas rich galactic nuclei can be by the similar way generators of the bulge component in disk galaxies (Krugel and Tutukov, 1993). Dissolution of globular clusters with their massive (10^3–10^7 m central black holes (Gebhardt et al., 2002) can help to form the central supermassive black hole and bulge of a galaxy simultaneously.

Two other known possibilities to form bulges of galaxies and to populate intergalactic space by old stars are galactic collisions and mergings of their supermassive BH nuclei. Numerical models have demonstrated formation of E galaxies in collisions (Naab and Burkert, 2001). The number of collisions N during the Hubble time T_{H} per a galaxy with the surface density σ in a cluster of galaxies with the total mass M, radius R and the dynamical timescale τ is $N = T_{\mathrm{H}}/\tau \cdot M/(\sigma R^2)$. For $T_{\mathrm{H}}/\tau = 10$, $M = 10^{15}\,\mathrm{M}_\odot$, $R = 2\,\mathrm{Mpc}$, $\sigma = 10^3\,\mathrm{M}_\odot/\mathrm{pc}^2$ a galaxy in a cluster has to experience several collisions during the Hubble time. This possibly explains, why binary galaxies are so rare: $\sim$0.03 (Patton *et al.*, 2001). It is natural, that collisions are more frequent in dense clusters, and observations show, that masses of bulges are really higher in such clusters (Tran, 2000). Dense clusters have also a larger fraction of E galaxies. Secular growth of galactic masses was displayed by Drory *et al.* (2002). The reality of merging of central supermassive BHs demonstrate galaxy Markarian 501 with the orbital period of the central binary BH ~ 10 years (Rieger and Mannheim, 2000) and quasar 3C 390.3 with the central binary black holes with masses $3 \times 10^9\,\mathrm{M}_\odot$ and the orbital period $\sim$300 years (Gaskell, 1996). The merging of nuclei has to consist of two stages. Initially the separation between nuclei decreases by the dynamical friction of BHs in the dense stellar field of the galactic core. The latter expands, forming a stellar bulge and partly evaporating. Finally, components merge under radiation of gravitational waves, which possibly can be found in current and planning programs of their search.

The disk component of galaxies is mainly a result of the dissipative evolution of a rotating gas protogalaxy. A high density of the gas component and a low efficiency of supernovae in the heating of a relatively thin galactic gas disk, opened in polar directions, provide for conditions for conservation of gas in these galaxies. The main source of gas, apart of relic component and accretion, is the mass loss by old low mass stars. The galactic gas is continuously heated by supernovae and forms some sort of galactic hot wind, cleaning elliptical galaxies of gas almost completely, for a possible exception of their nuclei. The study of the accretional pattern of windy galaxies is an interesting problem. The wind enriches the intergalactic hot gas with heavy elements (Dupka and White, 2000).

STAR FORMATION IN SPHERICAL SYSTEMS

Now we shortly discuss the star formation in a spherical gas-stars system (Krugel and Tutukov, 1993; 1995). It can be an elliptical galaxy or a galactic spheroidal core. For analytical numerical estimates we take a one-zone model and assume that the star formation rate μ and the astration time τ are determined by the condition of complete ionization of the interstellar uniform gas (Firmani and Tutukov, 1992):

$$\mu = f\frac{3M^2}{4\pi R^3} \sim 300 M_{11}^2 R_4^{-3}\ \mathrm{M}_\odot/\mathrm{yr}, \quad \tau \sim 3 \times 10^8 R_4^3 M_{11}^{-1}\ \mathrm{yrs} \tag{1}$$

where M is the gas mass, $f = 5 \times 10^7\ \mathrm{cm}^3/\mathrm{g/s}$ (Tutukov and Krugel, 1980), R is the radius of the galaxy, M_{11} is the gas mass in units $10^{11}\ \mathrm{M}_\odot$ and R_4 is the radius of the galaxy in units 10^4 pc. If $R_4 \leq 2M_{11}^{1/3}$ the astration time will be shorter $\sim 10^9$ yrs, which agrees with observational estimates for E galaxies (Totani and Takeuchi, 2002; Peebles, 2002).

The star formation is accompanied by supernovae. Latters can change the contraction of the gas component of a galaxy on the expansion. The decrease of the gas density decreases the star formation and supernova rate. As the result, under certain conditions arises a bursting mode of star formation in a spherical system (Krugel and Tutukov, 1993; 1995). An observed consequence of such bursts can be not only the appearance of bright infrared nuclei of galaxies (Blain *et al.*, 2002), but holes in the gas component of a galaxy, like in PKS 2354-35 (Heinz *et al.*, 2002). It is possible, as well, that the initial astration can be so powerful, that the galaxy can be clean of gas at all. Consequent explosions of SNIa heat gas, support the galactic wind, removing gas lost by old stars and excluding, thus, the further star formation. This is one of possible scenarios of formation of elliptical galaxies. And, finally, the dissipation of the gas turbulent motion can be so efficient, that supernovae can not supply enough energy to prevent a spherical gas + star system collapsing into a supermassive BH. The actual scenario is entirely predetermined by the ratio between astration, dissipation and presupernovae times as well as by the ratio between gravitational and supernovae energies (Krugel and Tutukov, 1993; Firmani and Tutukov, 1994). The dense gas in nuclei of massive E and cD galaxies efficiently cooling and can therefore survive and support the star formation there. The accretion of gas by nuclei are more efficient in interacting galaxies (Boris *et al.*, 2002). The star formation in a compact nuclear gas + star system can be in form of powerful repetitive bursts of star formation (Krugel and Tutukov, 1993; 1995).

STAR FORMATION IN DISK GALAXIES

The modelling of different aspects of galactic evolution is a popular branch of modern astrophysics (Matteuchi and Chiosi, 1983; Tosi, 1988; Charlot and Bruzual, 1991; Firmani and Tutukov, 1992; Hernandez *et al.*, 2001). There are several approaches to description of the history of star formation and chemical evolution of disk galaxies. We now present a simple model, where the star formation rate is determined by the condition of complete ionization of the interstellar gas (Firmani and Tutukov, 1992; Krugel and Tutukov, 1993). The latter now is assumed uniformely distributed in a cylinder with a constant radius R and variable thickness

$2H$. The thickness of the gas cylinder is increasing by supernovae and decreasing because of dissipation of the turbulent motion of gas clouds by collisions. The advantage of this simple one-zone model consists of a clear physical nature, inspite of remaining, as usually, several poorly known physical and numerical parameters. The model is given by two main equations (Firmani and Tutukov, 1992):

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \mu - f\frac{M^2}{2\pi HR^2}; \quad \frac{\mathrm{d}H}{\mathrm{d}t} = H_+ - H_-; \tag{2}$$

H_+ here is the rate of the expansion of gas disk supported by supernovae explosions, and H_- is the rate of contraction of the gas disk because of dissipation of energy of the gas turbulent motion. The first equation controls gas mass, and the second-controls the gravitational energy of the gas disk in the field of gravity. A simple algebra provides for estimates of some global parameters of the star formation process in disk galaxies (Firmani and Tutukov, 1992):

$$H_0 = 500\sigma_2^{-1/3}\,\mathrm{pc}, \quad M_9 = R_4^2\sigma_2^{1/3}, \quad \mu = 0.4M_9\sigma_2^{2/3}\,\mathrm{M_\odot/yr}, \tag{3}$$

where σ_2 is the total surface density of the galaxy in units $10^2\,\mathrm{M_\odot/pc^2}$, R_4 is the radius of the disk in units 10^4 parsecs, M_9 is the gas mass in units $10^9\,\mathrm{M_\odot}$. These estimates are close to observed values of corresponding parameters of disk galaxies (Firmani and Tutukov, 1992).

The astration time $\tau_a \sim 3 \times 10^9 \cdot \sigma_2{}^{-2/3}$ years is close to the observed one for 180 galaxies (Murgia *et al.*, 2002). For dense massive galaxies like ours the initial astration time τ_a consists of the order one billion of years with the star formation rate 100–1000 $\mathrm{M_\odot/yr}$ (Vernet and Cimatti, 2001). Thus, massive disk galaxies had a strong burst of star formation in the beginning of their evolution (Gallagher *et al.*, 1984; Afonso *et al.*, 2001; Massarotti *et al.*, 2001). Low density $\sigma_2 \leq 0.1$ and surface brightness galaxies have the astration time of the order or even larger of the Hubble time (Gallagher *et al.*, 1984). As the result, the gas mass in such galaxies is comparable or even higher than the stellar mass (*e.g.* van den Hoek *et al.*, 2000). The gas content in small low surface density disk galaxies according to observations can reach 0.95 support the model proportionality between the star formation rate (luminosity) and the total mass of gas in the galaxy in a very wide range (10^7–$10^{12}\,\mathrm{M_\odot}$) of gas masses (Firmani and Tutukov, 1992; 1994).

A success of analytical estimates permitted the development of a more detailed numerical model, including the modern presentation of stellar evolution (Shustov *et al.*, 1997; Wiebe *et al.*, 1998). The model is able to reproduce, apart from the observed history of the star formation, the observed distribution of heavy elements with height above the Galactic plane in limits 300–3000 pc ($1 > Z/Z_\odot > 0.05$). The model predicts a strong flash of the star formation during first billions of years of life of massive galaxies. Optical depth of young massive galaxies can get several stellar magnitude, what have to transform these galaxies into bright sources of infrared radiation (Wiebe *et al.*, 1998). Two bright young infrared galaxies at $z \sim 2.7$ was found by Mello *et al.* (2002). A large (3–5^mm) optical depth of young massive galaxies may and probably does limit the application of SNeIa as a standard candle for distant galaxies with $z > 2$. This effect is very important for a proper understanding of cosmology (Sullivan et al., 2002). The model explains as well the observed growth of luminosity of disk galaxies of a fixed mass with radius by the delayed flash of star formation. The model describes also the distribution of circumsolar G dwarfs over their metallicity. A standard introduction of SNe II, enriching the gas component with oxygen and SNe Ia, producing mainly iron, is able to reproduce the observed correlation [O/Fe]–[Fe/H]. The introduction of a galactic wind helps to explain the enrichment of intragalactic hot gas with heavy elements (Arnold *et al.*, 1992; Shustov *et al.*, 1997). Low mass (luminosity) galaxies lose more heavy elements, produced by them. It is a probable reason of the observed growth of metallicity of galaxies with their luminosity (Melbourne and Salzer, 2002; Shustov *et al.*, 1997).

The observed astration time in old disk galaxies is of the order of the Hubble time. But it is well known, that there are bright infrared galaxies with the astration time about 100 times shorter (Firmani and Tutukov, 1994). A very important property of these ultraluminous galaxies is the presence of close or merging companions (Rudnik and Kennikutt, 2000; Pustilnik *et al.*, 2001; Chary *et al.*, 2001). The gravitational interaction of galaxies probably changes the astration time from usual $\sim 10^{10}$ years to the dynamical timescale for a galaxy $\sim 10^8$ years. The latter increases the astration rate and the luminosity of a gas rich galaxy about hundred times, what really was observed for Markarian and luminous ($L_{\mathrm{IR}} \sim 10^{11}$–$10^{12}\,\mathrm{L}_\odot$) infrared galaxies (Firmani and Tutukov, 1994). Most massive galaxies can get during the burst the luminosity 10^{12}–$10^{13}\,\mathrm{L}_\odot$, corresponding to the star formation rate $\sim$100–1000 $\mathrm{M}_\odot$/yr. So intense star formation can lead to the formation of the galactic wind with intensity 10–100 $\mathrm{M}_\odot$/yr (Rupke *et al.*, 2002). It is known, that the supernova rate in interacting galaxies is really higher than an average one (*e.g.* Navasardian *et al.*, 2001). Supernovae support hot galactic wind, what is seen now in the X-ray emission as a halo around disk galaxies with an intense star formation (Wang, 2002).

Observations display that gas disk of spiral galaxies extends behind their observed zone of star formation (Ferguson *et al.*, 1998; van den Kruit, 2001). The star formation on the galactic edge almost absents for exception of interacting galaxies. A possible reason for this is a too low density of the gas here (Mathews *et al.*, 2001). The inert gas rings around spiral galaxies are a probable result of the viscous expansion of the gas disk. It would explain a rather high observed heavy element abundance in this gas.

CONCLUSION

The application of the simple one zone numerical model of star formation in a spherical and a disk galaxy helps to reproduce some their global characteristics. Now we shall shortly discuss some problems, related to the development of this model. The first one is the nature of the dark matter. It is known, that the $[M/L]$ ratio increases from $\sim$10 for our galaxy to $\sim$170 for clusters of galaxies (Bahcall and Commerford, 2001). The mostly important parameter of the presented model for the $[M/L]$ ratio is the initial mass function of stars (IMF). The usual assumption about it: $f(M) \sim M^{-2.5}$ keeps the most part of the stellar mass in red and brown dwarfs. But two factors possibly limit this hope. The detailed study of the IMF for 0.1–1 $\mathrm{M}_\odot$ stars (*e.g.* Kroupa, 2001) have displayed, that it change its slope from -2.5 to -1.5 near of solar mass stars. This break confines the most part of stellar mass to stars with masses about one solar mass. Gravitational microlensing, apart that, appears an efficient enough to exclude a significant number of brown dwarfs with masses below $\sim 0.1\,\mathrm{M}_\odot$ in globular clusters (Sahu *et al.*, 2001). Thus, the problem of dark matter remains unsolved at least on the level of modern stellar physics (Avila-Reese and Firmani, 2000).

The change of the break mass for example by variation of the dust temperature (Massevich and Tutukov, 1988) can be possibly applyed for explanation of overmetallicity of circumquasar stars. The model displays, that the observed "standard" abundance of heavy elements $\sim$0.01 is equal to the ratio of heavy elements amount, produced by supernovae to the total mass of almost unprocessed matter, returned into interstellar medium by 1–3 $\mathrm{M}_\odot$ stars of the same generation (Wiebe *et al.*, 2001). It is of importance here that the most part of unprocessed gas is lost by stars with masses close to the break mass. The value of the break mass may be, as the result, an efficient instrument to change the equilibrium value of heavy element abundance. It is clear, that the growth of the break value of the stellar mass will increase the heavy element abundance and vice versa. Such possibility can be useful to understand the reason of very high abundance of heavy elements of stars near very young ($\sim 10^9$ years) quasars, where it exceeds the solar value 3–8 times (Dietrich and Wilhelm-Erkens, 2000; Fan *et al.*, 2001; Hamman *et al.*, 2001). The reality of a significant change of the low IMF cut off displays the young globular cluster in M 82, where, according a high $[L/M]$ ratio, it is about 2–3 $M_\odot$ (Smith and Gallagher, 2001). The enrichment of circumquasar stars by a supermassive stars, forming the quasar itself probably impossible, since supermassive stars collapse. The role of a change of the break mass in observed gradient of heavy element abundance for disk galaxies can be studied now, as well, although the necessity of a galactic wind remains evident, at least, for the enrichment of the intergalactic gas with metals.

The efficiency of one zone, ionizationally controlled star formation model for description of common properties of star formation in spheroidal and disk galaxies opens a way to construction multizone models. A necessary element of such models has to be the description of gas mass exchange between zones. An important role for the model plays a proper inclusion of SNe Ia, whose explosions are delayed several billions of years after the star formation process. This can lead under certain circumstances to periodic bursts of star formation. Bursts of star formation in galactic nuclei can due to SNe blow out hourglass shaped holes, like holes, found near nucleus of the disk galaxy NGC 1482 (Veilleux and Rupke, 2002). Bursts of star formation in a galactic nucleus can form a ring like star formation fronts in their disk components. A stochastic star formation in a disk galaxy can appear responsible for origin of some spiral galaxies, where spirals can be a result of a selforganization of the star formation in the differentially rotating gas component of a disk galaxy. A multizone model will help to study in more details interaction of galaxy with intergalactic hot gas, what in some cases may be an important evolutionary factor.

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