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STAR FORMATION IN DISK AND SPHEROIDAL GALAXIES

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RESUMEN

Se analiza un modelo de evolución dinámica y química para galaxias esféricas y de disco. La tasa de formación estelar se considera regulada por la ionización por estrellas masivas O,B del hidrógeno inter-estelar. El volumen de una galaxia se determina por la condición de equilibrio entre disipación colisional de la energía turbulenta del gas y su agitamiento por supernovas. La teoría moderna de evolución estelar permite describir la evolución de la componente estelar de una galaxia y estimar la frecuencia actual de supernovas. El modelo reproduce algunos parámetros observacionales básicos de las galaxias así como su evolución en escalas de tiempo de Hubble. Se analizan brevemente el rol de factores externos y posibles razones de formación estelar no estacionaria en las galaxias y sus núcleos.

ABSTRACT

A model of dynamical and chemical evolution for spheroidal and disk galaxies is discussed. The star formation rate in the model is regulated by 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 spheroidal 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.

Key Words: **GALAXIES: DISK — GALAXIES: ELLIPTICALS — GALAXIES: EVOLUTION**

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1. INTRODUCTION

A significant part of galaxies are members of clusters with average mass of $10^{15} M_{\odot}$ and radius of 1-3 Mpc (Girardi et al 1998). These clusters are probably the largest elements of the Universe structure, separated by distances ~ 100 Mpc (Ronkema et al 2001). The last means, that within the limit of cosmological horizon ($\sim 4 \cdot 10^9$ pc) there are $\sim 10^5$ clusters of galaxies. This number is close to the number of quasars (Richard et al 2001), which are usual nuclei of supermassive spheroidal cD 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 cD galaxies display a high star formation rate, up to 1000 $M_{\odot}$/yr (Schwartz et al 1991), supported by the accretion of the intracluster gas (cooling flows) and by the fast astration of their own gas, induced probably by close passages (collisions) of field galaxies (Taniguchi 1999). Observations displayed that for the most part, 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 $L = 10^{10} L_{\odot} (M = 2 \cdot 10^{11} M_{\odot})$ (Anderson et al. 2000; Allen 1973). As the result, galaxies like our Galaxy contain for the most part stellar matter, which makes the study of their evolution of special interest. Galaxies moving in a cluster experience tidal friction. Numerical estimates display that galaxies with masses above $\sim 10^{11} M\odot$, moving with an average speed, lose their kinetic energy in a Hubble time and go down 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 cD galaxies and nuclei of latters, what are supermassive (up to $10^{10} M_{\odot}$) black holes (quasars). To support the observed stellar luminosity of cD galaxies a star formation rate of 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, Wilhelm-Erkerns 2000) transform these galaxies into powerful sources of infrared radiation $L_{IR} \sim 10^{12} L_\odot$ (e.g., Firmani & Tutukov 1994).

Masses of even very young distant quasars with age $\sim 7 \cdot 10^8$ yrs (reionization, the redshift z$\sim$6.2) consist of $\sim 10^{10} M_\odot$ (Kaspi 2000). If initial (at the very begin 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, massive BHs could be formed only at an age $\sim 2 \cdot 10^9$ 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, Veron 1993). A more deep study of the role of the Eddington limit in the process of accretion is necessary to clarify 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 precursor of the BH in that case. Such star can be formed in the very center of a young massive galaxy in the process of accretion of gas. The lifetime of a supermassive star independently of its mass is $\sim 10^6$ yrs, so the mass of a supermassive star to the moment of collapse will be $\sim \mu \cdot 10^6 M_\odot$, 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 flows 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 appearence of 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, $\beta \sim 3 \cdot 10^{-5}$, what explain the mass of the BH in the center of our Galaxy (Melia 2001). But for quasars $\beta \sim 0.001$ (McLure & Dunlop 2002), which means that only a small part of massive galaxies can give birth to supermassive BHs in their nuclei and provide for a proper accretion rate for quasars.

The study of galactic evolution is branch of the 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. Surveys of the most distant galaxies provide information about early phases of evolution of the 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 information about evolution of stars of different masses, begining from their birth up to formation of final remnants: white dwarfs, neutron stars and black holes. Supernova explosions are an important evolutionary factor for the dynamical and chemical evolution of galaxies. Formation of white dwarfs is an important source of gas, supporting the star formation process in disks, and a hot wind in spheroidal galaxies.

2. SPHEROIDAL AND DISK STELLAR POPULATIONS

Now we shall discuss the main global properties of galaxies. Stellar population of galaxies can be divided into two main families: spheroidal and disk ones. The first includes mainly old stars and almost no gas, the last is rich in gas and displays signatures of the current star formation. The spheroidal population is represented by elliptical galaxies, and the disk population- by spiral and irregulal ones. A real galaxy consists of both populations. Spiral galaxies have spheroidal massive stellar bulges and many elliptical galaxies have in their 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 factors. A part of elliptical galaxies are probably a result of a fast loss of their gas component, induced by the initial strong burst of star formation in a slowly rotating gaseous spheroidal protogalaxy. Some of these galaxies can be disrupted altogether after fast loss of more than half of their initial mass (Firmani & Tutukov 1994). Such a phenomenon helps to understand the existence of a significant population of planetary nebulae and red giants in intergalactic space (Ford et al. 2001; Durrel et al. 2002). The observational search for SNe Ia in intergalactic space becomes now actual. Repetitive bursts of star formation in gas rich galactic nuclei can be, in a similar way, generators of the bulge component of disk galaxies (Krugel & Tutukov 1993).

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 the formation of E galaxies in collisions (Naab & 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= $T_H/\tau \cdot M/(\sigma R^2)$. For $T_H/\tau = 10$, $M = 10^{15} M_\odot$, $R = 2$ Mpc, $\sigma = 10^3 M_\odot/\mathrm{pc}^2$ a galaxy in a cluster has to experience several collisions during the Hubble time. This possibly explains, why binary galaxies are so rare: ~ 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 $\sim$ 10 years (Rieger, Mannheim 2000) and quasar 3C 390.3 with the central binary black holes with masses $3 \cdot 10^9 M_\odot$ 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 planing 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 a relic component and accretion, is the mass loss by old low mass stars. The galactic gas is contineously heated by supernovae and forms a some sort of galactic hot wind, cleaning elliptical galaxies of gas almost completely, for a possible exeption of their nuclei. The study of the accretional pattern of windy galaxies is an interesting numerical problem. The wind enrichs the intergalactic hot gas with heavy elements (Dupka & White 2000).

3. STAR FORMATION IN SPHEROIDAL SYSTEMS

Now we shortly discuss the star formation in a spheroidal gas-stars system (Krugel & 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 & Tutukov 1992):

$$\mu = f \cdot 3M^2/(4\pi R^3) \sim 300 {M_{11}}^2 \cdot {R_4}^{-3} M_\odot/yr,$$
$$\tau \sim 3 \cdot 10^8 {R_4}^3 M_{11}^{-1} yrs, \quad (1)$$

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

The star formation is accompaigned by supernovae. The latter 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 spheroidal system (Krugel & Tutukov 1993, 1995). An observed consequence of such bursts can be not only appearence of bright infrared nuclei of galaxies (Blain et al.2002), but holes in the circumnuclear 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 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 the collapse of a spheroidal gas+star system 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 & Tutukov 1993; Firmani & 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 & Tutukov 1993,1995).

4. STAR FORMATION IN DISK GALAXIES

The modelling of different aspects of galactic evolution is a popular branch of the modern astrophysics

(Matteuchi & Chiosi 1983; Tosi 1988; Charlot & Bruzual 1991; Firmani & Tutukov 1992; Hernandez et al. 2001). There are several approaches to describe 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 & Tutukov 1992; Krugel & Tutukov 1993). The latter now is assumed to be uniformely distributed in a cylinder with a constant radius R and variable thickness 2·H. The thickness of the gas cylinder increases by supernovae and decreases 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, despite several poorly known physical and numerical parameters. The model is given by two main equations (Firmani & Tutukov 1992):

$$dM/dt = \mu - f \cdot M^2/(2\pi \cdot H \cdot R^2); dH/dt = H_+ - H_-, \tag{2}$$

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

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

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

The astration time $\tau_a \sim 3 \cdot 10^9 \cdot \sigma_2^{-2/3}$ years is close to the observed one for 180 observed galaxies (Murgia et al. 2002). For dense massive galaxies like ours the initial astration time τ_a is of the order one billion of years with a star formation rate of 100-1000 $M_\odot/yr$ (Vernet & 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 astration times of the order or even larger than the Hubble time (Gallagher et al. 1984). As a result, the gas mass in such galaxies is comparable or even larger 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 of their mass (Schombert et al. 2001). Observations strongly support the model proportionality between the star formation rate (luminosity) and the total mass of gas in the galaxy over a very wide range ($10^7 - 10^{12} M_\odot$) of gas masses (Firmani & Tutukov 1992, 1994).

The success of analytical estimates permitted us to develop 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, besides of the history of star formation, the observed distribution of heavy elements with height above the Galactic plane between 300-3000 pc ($1 > Z/Z_\odot > 0.05$). The model predicts a strong flash of star formation during the first few billion years of life of massive galaxies. The optical depth of young massive galaxies can reach several stellar magnitudes, which would transform these galaxies into bright sources of infrared radiation (Wiebe et al. 1998). Two bright young infrared galaxies at $z \sim 2.7$ were found by Mello et al. (2002). The model explains also 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 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 most of the heavy elements, produced by them. This is a probable reason of the observed growth of metallicity of galaxies with their luminosity (Melbourne & 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 astration times about 100 times shorter (Firmani & Tutukov 1994). A very important property of these ultraluminous galaxies is the presence of close or merging companions (Rudnik & Kennikutt 2000; Pustilnik et al. 2001; Chary et al. 2001). The gravitational interaction of galaxies probably changes the astration time from the usual $\sim 10^{10}$ years to the dynamical timescale for a galaxy $\sim 10^8$ years. The latter increases the astration rate and

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the luminosity of a gas-rich galaxy about a hundred times, which really was observed for Markarian and luminous ($L_{IR} \sim 10^{11} - 10^{12} L_\odot$) infrared galaxies (Firmani & Tutukov 1994). Most massive galaxies can reach during the burst luminosities of $10^{12} - 10^{13} L_\odot$, corresponding to a star formation rate $\sim 100 - 1000 M_\odot$/yr. Such an intense star formation can lead to the formation of galactic winds with intensity 10-100 $M_\odot$/yr (Rupke et al. 2002). It is known that the supernova rate in interacting galaxies is really higher than average (e.g. Navasardian et al. 2001). Supernovae support hot galactic wind, which is seen now in the X-ray emission as a halo around disk galaxies with intense star formation (Wang 2002).

Obervations display that gas disk of spiral galaxies extends behind their observed zone of star formation (Ferguson et al. 1998; van den Kruit 2001). Star formation on the galactic edge is almost absent except in 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.

5. CONCLUSIONS

The application of the simple one-zone numerical model of star formation in spheroidal and disk galaxies helps to reproduce some of their global characteristics. Now, we shall briefly discuss some problems, related to the development of this model. The first one is the role of the dark matter. It is known that the [M/L] ratio increases from ~ 10 for our galaxy to ~ 170 for clusters of galaxies (Bahcall & Commerford 2001). The most important parameter of the present model for the [M/L] ratio of the stellar component is the initial mass function of stars (IMF). The usual assumption about it: $f(M) \sim M^{-2.5}$ keeps most of the stellar mass in red and brown dwarfs. But two factors possibly limit this hope. The detailed study of the IMF for $0.1 - 1 M_\odot$ stars (e.g. Kroupa 2001) has displayed that it changes its slope from -2.5 to -1.5 near one solar mass stars. This break confines most of the stellar mass to stars with masses of about one solar mass. Besides, gravitational microlensing appears efficient to exclude a significant number of brown dwarfs with masses below $\sim 0.1 M_\odot$ in globular clusters (Sahu et al. 2001). Thus, the problem of dark matter remains unsolved, at least on the stellar level (Avila-Reese et al. 2002).

The change of the break mass, for example by variation of the dust temperature (Massevich & Tutukov 1988), can be possibly applied to explain the overmetallicity of circumquasar stars. The model displays that the observed "standard" abundance of heavy elements ~ 0.01 is equal to the ratio of heavy elements produced by supernovae to the total mass of almost unprocessed matter, returned to the interstellar medium by $1 - 3 M_\odot$ stars of the same generation (Wiebe et al. 2001). It is of importace 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 thus 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 viceversa. Such a possibility can be useful to understand the reason of the 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 & Wilhelm-Erkens 2000; Fan et al. 2001; Hamman et al. 2001). The reality of a significant change of the low IMF cut-off is displayed by the young globular cluster in M 82, where, assuming a high [L/M] ratio, it is about 2-3$M_\odot$ (Smith & Gallagher 2001). The enrichment of circumquasar stars by supermassive stars forming the quasar itself is probably impossible, since supermassive stars collapse. The role of a change of the break mass in the observed gradient of heavy element abundance for disk galaxies can be studed 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 the one-zone, ionizationally controlled star formation model for the description of common properties of star formation in spheroidal and disk galaxies opens a way to construct multi-zone models. A necessary element of such models has to be the description of gas mass exchange between zones. An important role for the model is played by 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. These bursts in galactic nuclei can be due to SNe blowing out hourglass shaped holes, like the holes, found near the nucleus of the disk galaxy NGC 1482 (Veilleux & Rupke 2002). Bursts of star formation in a galactic nucleus can form ring-like star formation fronts in their disk components. Stochastic star formation in a disk galaxy can be responsible for the origin of some spiral galaxies, where the spiral shape can be a result of a self-organization of star formation in the differentially rotating gas component of the disk galaxy. A multizone model will help to study in more detail the interaction of galaxy with intergalactic hot gas, which in some cases may be an important evolutionary factor.

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