SOME INSIGHTS INTO THE PHOTOMETRIC EVOLUTION OF GALAXIES

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The photometric (spectral) evolution is but one aspect of a more universal central question in modern astrophysics — the complex problem of formation and evolution of galaxies. The method used to follow the photometric evolution is straightforward, consisting in computing on the basis of adopted prescriptions for star formation the stellar populations present at various moments and summing up the contributions of all the multitude of stars of different ages and evolutionary stages. The usual strategy is to neglect the dynamics and chemical changes of matter, although during the initial collapse of a galaxy and rapid enrichment of its matter both processes should be important contributors shaping the forming stellar populations. Other widely used simplifications are the rejection of interstellar absorption and the restriction of models to the volume element with constant star formation time scale in its borders (so-called "one-zone models", they stricly apply to the infinitely narrow ellipsoidal shells in real galaxies). An additional postulate that the region considered is closed and isolated, having not been subjected to interactions or mass exchange with the surroundings, is introduced in the simpliest closed "classical" or "canonical" models (Traat 1988), computed e.g. by Tinsley (1972), Searle *et al.* (1973), Traat and Einasto (1979), and others. Such assumption, however, is not always valid and some objects need to be modelled by burst models or more universal accretion models.

Star formation is the key process determining all structural (like the bulge-disk and stellar mass to gas ratios) and photometric properties of galaxies, but the factors governing the star formation on a global scale are still largely unknown. The widely used Schmidt law, $\mathcal{R}(t) = \gamma\rho_g^s/\rho_0$ (ρ_g — gas volume density, γ and n — constants, $t_0 = (\gamma\rho_0^{s-1})^{-1}$ — the characteristic time of star formation) what in fact states just that one needs matter to make stars and this is the easier, the more matter is available, is up to now the best parametrization for star formation rate (SFR). The observational values of n obtained from surface densities are between $1 \div 2$ with some tendency to cluster around ~ 1.5, but the actual value of index for volume density depends on density distribution. In a closed region a condition $\rho_g + \rho_s = \rho_0$ holds, by abandoning mass loss from evolved stars and integration of Schmidt law one gets for SFR the functional form

$$\mathcal{R}(t) = \begin{cases} e^{-\tau}/t_0 \quad , \quad s = 1, \\ \frac{1}{t_0}\left[1 + (s-1)\tau\right]^{\frac{-s}{s-1}} \quad , \quad s \neq 1, \end{cases}$$

with $\tau = t/t_0$ as dimensionless time. This means that the time evolution of a closed system is fixed by a single parameter — the star formation time-scale t_0. In the physically most plausible case $s > 0$ the resulting SFR is monotonically decreasing, with gas density and SFR being highest at the initial moment $t = 0$; in the absence of correlation ($s = 0$) the resulting SFR is constant.

The colors of canonical models, computed relative to V, start from a blue initial value and evolve monotonously redder. The luminosity curve of classical models is

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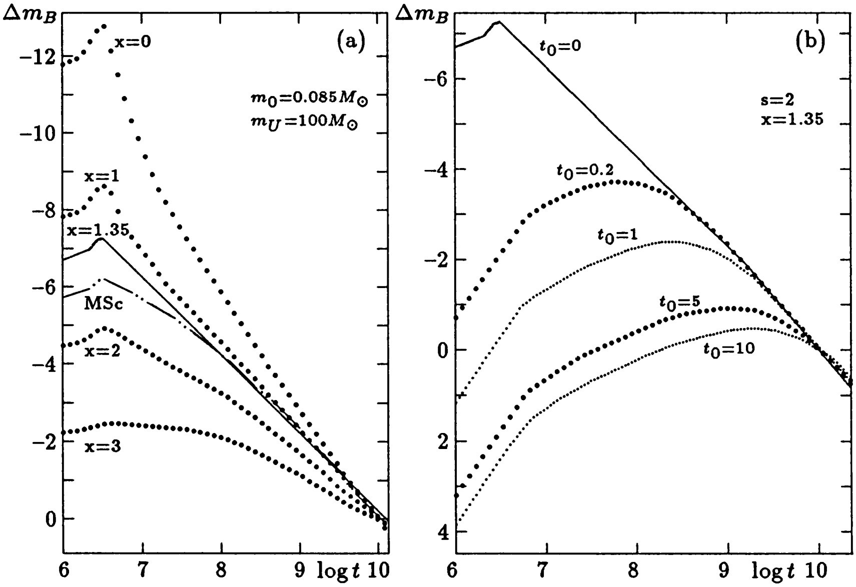

Figure 1: Past luminosity evolution: *a)* coeval stellar population with different IMF slopes; x=1.35 is Salpeter's original value, MSc denotes the lognormal solar neighbourhood IMF from Miller and Scalo (1979); *b)* stellar populations differing in characteristic formation time-scales, t_0=0 in the case of an coeval stellar population. In both cases *a)* and *b)* the curves are normalized at $t = 10$ Gy, and $Z = 0.03, X = 0.70$.

rising rapidly to an early maximum, caused by the arrival of massive luminous stars to the main sequence and followed by a continuous decrease. With the growth of t_0 this luminosity maximum shifts to the lower absolute values and progressively later ages (*cf* Fig. 1*b*). At the standard value, $x = 1.35$, of the slope of the power-law IMF $\psi(m) \sim m^{-(1+x)}$ and minimum stellar mass taken equal to $m_0 = 0.085 M_\odot$ (the smallest mass of a normal composition star igniting the hydrogen on the main sequence), our models with different t_0-s produce at the age 12 Gy M/L_B ratios between 4 and 10, which is just the right range observed for galaxies of different morphological types.

The left panel of Fig. 1 depicts the past luminosity behaviour of closed models depending on the value of slope x of the power-law IMF under the assumption of star formation in a single initial burst. The amplitude of luminosity is the larger the smaller is x, since with its decrease the fraction of high-luminosity massive stars in IMF is progressively growing. As evident from panel *b)*, some time dilution of star formation will substantially reduce these top amplitudes. The shortest time-scale for primeval ellipticals to make most of their stars equals to the free-fall time ($\sim$ 0.2 Gy), probably some additional time dilution will be caused also by the rising SFR during these initial dynamical stages. Therefore the model with $t_0 = 0.2$ Gy, what in the illustrated $s = 2$ case makes half of all its stars during these first 0.2 Gy, seems to be a reasonable upper limit to the top luminosity of the rapidly star-forming bright massive ellipticals. Since the absorption is ignored in our models, the primeval galaxies are probably dimmer yet, but even this adoption of a small duration of star formation reduces the past luminosity amplitude of galaxies about twice relative to the $t_0 = 0$

case ($\sim$ 30 times in absolute units), to less than 4 magnitudes in B. It is clear that since the initial-burst models enormously overestimate top luminosities of primeval galaxies, one should correct the widespread practice to use them in comparisons with young objects, using instead the models with non-zero t_0.

While the present properties of "normal" galaxies are in a crude general accordance with the results on classical, closed models, a bulk of galaxies is deviating in their properties, most notably by peculiar colors. Some galaxies reveal the ongoing star formation on the level which cannot be sustained by the available matter for no more than but a fraction of a galaxy's lifetime, others indicate just more modest deviations from the monotonic behaviour of the SF process. A tendency prevails that most of these active galaxies are members of systems and interacting with another near-by galaxy or a gas cloud, although the isolated objects are not rare.

Their evolution is described by composite models, first discussed by Larson and Tinsley (1978), in which an extra burst of star formation with small duration is added to an old canonical model to account for the intense young component. The path of these models on the two-color diagram is, as a rule, an almost closed loop, the length of which depends on the burst intensity and its duration. Any such galaxy with a constant SFR during the burst has the bluest colors at the end of the burst, if it is short; in the case of a long and low-intensity burst the bluest point is reached earlier and after that the colors will turn slowly redder. When the SFR differs from constant, the bluest colors occur after the maximum of the burst if it is short, but an increase in burst length makes them first to coincide with maximal SFR and then to precede it. When the burst is over, the original colors will be approximately restored after about $0.5 \div 1$ Gy.

On Fig. 2*a* the evolution of a starburst galaxy is plotted. The underlying old red galaxy is having an age of 12 Gy, it develops star formation bursts with different strengths b, which equals to the mass fraction converted to the stars. Since the original galaxy is extremely void of young blue massive stars, only a little amount of matter has to be processed into stars to cause significant changes of integrated colors.

The burst models do not specify openly where the matter for extra star formation comes from. One of likely sources is its accumulation by infall from a near-by galaxy/gas cloud or intergalactic space. Short accretion will leave no lasting imprint on a galaxy, but in the case of open systems with a continuous exchange of matter with ambience it will become key factor driving their evolution.

The accretion models have been studied by Traat (1988), he used the accretion function $\alpha(t)$ to fix the mass balance in the area under consideration (the whole system or some part of it). This function was scaled per unit *initial* mass and per 1 Gy. If accretion is present, $\alpha(t) > 0$, in the case of mass loss $\alpha(t) < 0$, if there is no accretion or mass loss, $\alpha(t) = 0$.

In the case of the constant infall to the system $(\alpha > 0, s > 0)$ after some time the equilibrium will develop between gas infall and star formation, with the total mass of gas in a galaxy remaining unchanged and star formation proceeding at the rate $\mathcal{R} = \alpha$ exactly balanced by infall. This state will be reached the earlier the greater α and the smaller t_0 are. Such equilibrium production of stars has long been suspected for a number of galaxies, notably for faint irregulars which have had constant SFR-s during the last $\sim$ 10 Gy (Gallagher *et al.* 1984). Models, exposed to heavy accretion, tend to retain quite high relative gas content. They can finish even with larger mass of gas than was the initial mass of the parent cloud, from which the galaxy formed. In the opposite case when a galaxy is losing mass, its gas supplies will be completely exhausted at some moment, after which $\mathcal{R} \equiv 0$.

The accretion models are illustrated in Fig. 2*b* where the evolution of B–luminosity

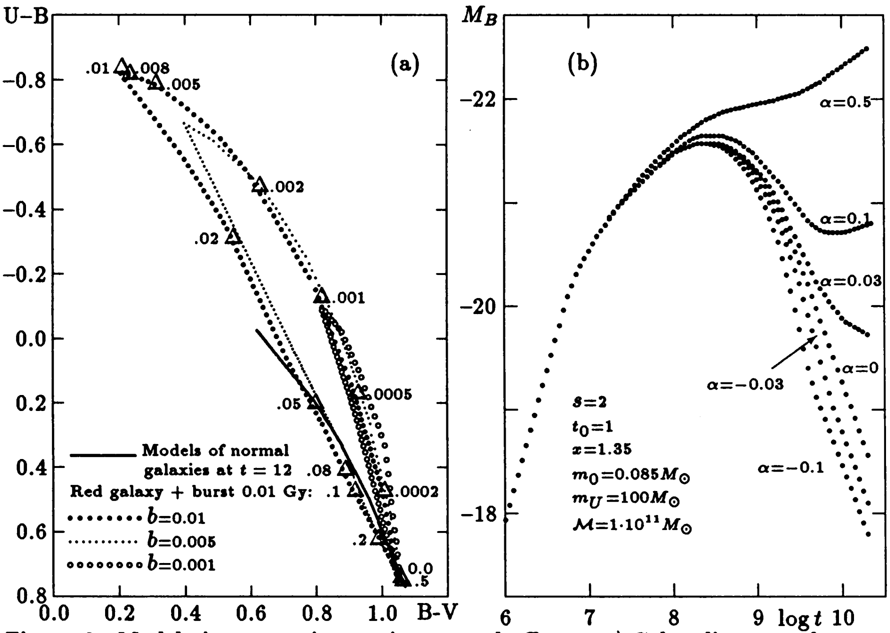

Figure 2: Models incorporating environmental effects: *a)* Color diagram of a very red model galaxy with age 12 Gy, developing a star formation burst with strength b. Triangles mark the burst age in Gy for the $b = 0.01$ case. *b)* Luminosity evolution of an stellar population (homogeneous galaxy) with SF time-scale $t_0 = 1$ and different levels of constant accretion of matter. Model $\alpha = 0$ represents the case without accretion, negative α values indicate mass loss.

of a model with $t_0 = 1$ and a number of accretion rates is plotted. The inclusion of mass exchange in the evolutionary models has the effect that every closed model with a fixed t_0 value will be replaced by a family of models with α as its parameter. Allowing a sufficient range for the accretion parameter, all the range of colors of normal galaxies can be explained with models differing only in accretion rate but having the same internal star formation time-scale. Since in young galaxies the accretion and mass loss are more probable, this can strongly influence any cosmological tests using very faraway and young galaxies. The main point to finish with is to stress that all the photometric evolutionary models of galaxies rely critically on their past SFR-s. Every revision or modification of assumptions involved in the specification of the SFR will typically cause radical changes in the output, what is also evident in the case of models incorporating environmental effects discussed above.

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