STAR FORMATION TIMESCALES IN SPIRAL GALAXIES

Ivana Damjanov[*], *Milan M. Ćirković*

Astronomical Observatory, Volgina 7, 11000 Belgrade
Serbia and Montenegro

Abstract.
We investigate the impact of different models of global gaseous infall onto "normal" spiral disks on their gas consumption time scales. The old idea of Spitzer about the infall from gaseous galactic haloes was revived with the discovery of the low-redshift population of Lyα absorbers and first steps made in understanding of the transition between the high-redshift intergalactic and the low-redshift predominantly galactic population of QSO absorption systems, as well as improved understanding of the nature of so-called high-velocity clouds. It turns out that large quantities of gas which has not been astrated or has been astrated only weakly are bound to galaxies at later epochs. Such aggregates present a potential reservoir of gas not only for solution of the classical gas consumption puzzle in spiral disks, but also as a fuel for the future star formation. We present results of analyzes performed on the sample of 61 "normal" spiral galaxies used by Kennicutt (1998) for studying the form of global star formation law. Adopting the Schmidt star formation law with index n   1.3 (the average value of a sample of observational surveys), we compare the consumption time scales of the galaxies from the sample for two scenarios of their evolution: "naive" model with neither recycling of interstellar gas nor gas infall from galactic haloes, and a more realistic one with parameters that control the recycling and infall of gas.

1. Introduction

Star formation histories of spiral galaxies are determined by the interplay between incorporation of baryons into collapsed objects (stars, stellar remnants and smaller objects, like planets, comets or dust grains) and return of baryons into diffuse state (gaseous clouds and intercloud medium). The latter process can be two-fold: (i) mass return from stars to the interstellar medium (henceforth ISM) through stellar winds, planetary nebulae, novae and supernovae, which happens at the local level; and (ii) net global infall of baryons from outside of the disk (if any). The former process is a well-known and firmly established part of the standard stellar evolution

[*] Corresponding author: idamjanov@aob.bg.ac.yu.

lore (e.g. [1]), and although details of mass-loss in a particular stellar type may still be controversial, there is nothing controversial in the basic physics of this process. The latter process—global baryonic infall—is, however, far more controversial. Although the infall in the disk is visible through 21cm, optical recombination emission or absorption against high latitude stars, the compensating outflow is mainly hidden, being presumably very hot, rarefied, X-ray emitting gas expelled from the disk by Galactic supernovae (e.g. [2,3]), and, possibly, central nuclear source. It is easy to show [4] that the process (i) is insufficient to support continuous star formation in future for a time interval similar to the Hubble time.

Therefore, in investigation how long can the present stelliferous epoch [5] in the history of the universe last, we have to take into account both of these processes. The availability of fresh gas for fueling the star formation must also be considered as a limiting factor for the length of this epoch (sometimes in literature dubbed Roberts' time; see [6]). Two factors are crucial in this regard: (1) dependence of the rate of star formation on the gas density (encompassed by the empirical Schmidt law), and (2) empirically discovered star formation thresholds. While it is still unclear whether observed thresholds will continue to be valid at later epochs, when the overall star formation rate decreases, and ISM generally becomes colder (Fred C. Adams, private communication), we use the observed values as the working hypotheses. In addition, we apply the simplest ("toy") models to a previously studied sample of galaxies in order to get a better hold on the dependence of Roberts' time on the index of Schmidt law and thresholds.

2. Data

Sample used in our analysis contains 61 "normal" disk galaxies used by Kennicutt ([7], Table 1) with their mean gas and star formation rate (SFR) surface densities. When considering the sample properties, the main criterion was availability of CO and H_I maps. CO emission was used as a tracer for molecular hydrogen, the mean surface densities were averaged within the optical radius of the disk and average surface densities of the gas were obtained by summing H_I and H_2 surface densities. Integrated SFRs were derived from measurements of the H_α emission-line flux and then divided by deprojected area within the optical radius of the disk to derive mean SFR surface densities.

3. Different evolutionary models

a) Gas Consumption Timescale

Gas consumption timescale is defined as

$$\tau_g \equiv \left| \frac{M_{gas}}{\dot{M}_{gas}} \right| , \qquad (1)$$

where M_{gas} denotes available gas mass in the interstellar medium (ISM), and

$$\dot{M}_{gas} = \frac{dM_{gas}}{dt} \qquad (2)$$

presents the star formation rate (SFR in $M_{\odot}$ yr^{-1}) defined as the mass of stars formed out of gas in ISM per unit time. If we consider it constant for all cosmic times and equal to the observed value for each galaxy, the resulting timescales for subsample of 42 "normal" spiral galaxies, presented in a histogram in Figure 1, show almost no difference when comparing to a histogram of Larson et al. [4] sample in Figure 2.

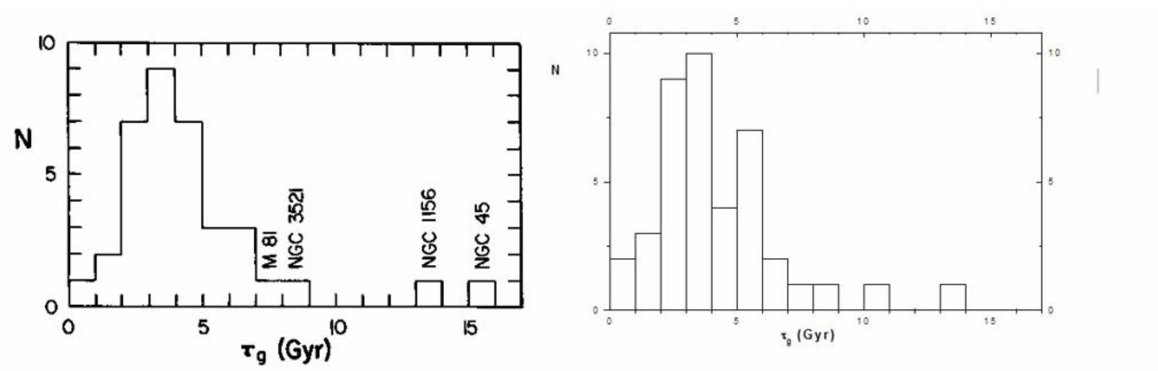

Fig. 1. – *left:* Histogram of gas consumption timescales for a sample of "normal" galaxies. Galaxies with long timescales are labeled (Larson et al. 1980); *right:* Histogram of gas consumption timescales for a sample of 42 spiral galaxies. The largest values are for late-type spirals. Used data from Kennicutt, Tamblyn and Congdon [8].

b) Star Forming Era I

We used the galaxy sample from [7] to compare the impacts that three different scenarios of their evolution:

(i) “naïve” one, with closed-box galactic disk,
(ii) one which takes recycling of gas into account, and
(iii) more realistic one with parameters that control the recycling and infall of gas

have on the length of era of continuous star formation from interstellar gas in the disk of normal spiral galaxies. The term in the equation for the evolution of ISM that is present in all of these scenarios is Schmidt law [9]. In the case of “naïve” model, that is the only term:

$$\frac{d\Sigma_{\rm gas}}{dt} = -\mathrm{A}\Sigma_{\rm gas}^{1.3}\ , \tag{3}$$

where $\Sigma_{\rm gas}$ is mean gas surface density (units $M_\odot$ pc^{-2}), while A = 0.48 Gyr^{-1} denotes star formation efficiency (value taken from [7]). Integrating this equation over time interval $\tau_{\rm R}$ that corresponds to the duration of star forming era, we obtain

$$\tau_{\rm R} = \frac{\Sigma_{\rm gas}^{-0.3}(\tau_{\rm R}) - \Sigma_{\rm gas}^{-0.3}(\tau_{\rm i})}{0.3\mathrm{A}}, \tag{4}$$

using $\Sigma_{\rm gas}(\tau_{\rm i})$ for the present value of mean gas surface density and $\Sigma_{\rm gas}(\tau_{\rm R})$ = 6 $M_\odot$ pc^{-2} for the threshold value, i.e. the minimum mean gas surface density required for continuing star formation process. This constant value was taken from [10]. Histogram of estimated duration of star forming era for Kennicutt sample of “normal” spiral galaxies [7] is shown in Figure 2*a*.

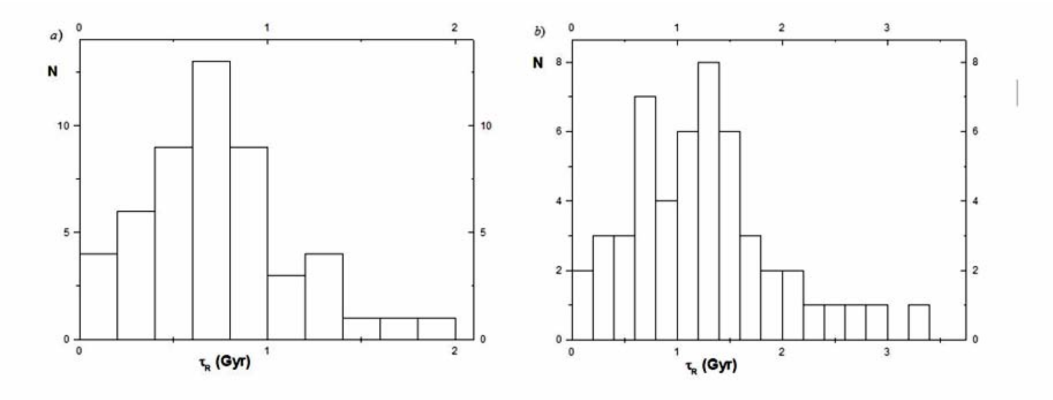

Fig. 2. –Histograms of star forming timescales in case that evolutionary model
contains *a)* pure Schmidt law; *b)* Schmidt law with recycling.

The next step is to take into account recycling of gas, i.e. mass return from stars to ISM through stellar winds, planetary nebulae, novae and supernovae. The equation for the evolution of ISM now takes the following form:

$$\frac{d\Sigma_{\text{gas}}}{dt} = -(1-r)\mathrm{A}\Sigma_{\text{gas}}^{1.3}\,. \tag{5}$$

Factor 1 - r denotes the lockup rate, i.e. the rate at which ISM transformed into stars is permanently locked up in low mass and dead stars. The return fraction of gas to the galactic ISM through mass-loss and supernovae, integrated over the classical Miller-Scalo [11] Initial Mass Function (IMF) is r = 0.42. In this way the duration of star forming era is prolonged for a factor of ~ 2, as presented in the Figure 2*b*.

The final step in this analysis would be adding to the right side of eq. (5) a term that corresponds to the net global infall of baryons from outside of the disk.

c) Infall of baryons into the disk

Arguments for taking into account the baryonic infall from galactic halo onto the disk can be divided into two major groups: theoretical reasons and observational constrains. In the former, ones of great importance are:

(i) Galaxy formation theories imply prolonged baryonic cooling and infall (e.g. [12,13]);
(ii) Infall is necessary to solve G-dwarf problem and other problems of chemical evolution of the Galaxy;
(iii) Morphological evolution along the spiral sequence in the sense Sd $\rightarrow$ Sa requires that at least a part of the dark matter must be gaseous;
(iv) Cooling flow-type phenomena seem to be generic in the best theoretical models.

Among observational constrains we should emphasize the following:

(i) High-velocity clouds as observed primordial infall (e.g. [14]); [unsolved problem: how big fraction of the observed infall is part of the Galactic fountain, i.e. already processed in the disk?]
(ii) QSO absorption lines in the low-redshift regime are often located in haloes of normal luminous galaxies (e.g. [15]);
(iii) In observations of merging galaxies, it has been noted for some time that quantity of visible gas in such events is larger than coadded

estimates for each galaxy (as judged by luminosity and morphology) before merger occurred.

d) *Star Forming Era II*
The true equation of global ISM to be integrated is

$$\frac{d\Sigma_{\mathrm{gas}}}{dt} = -(1-r)\Psi(t) + \mathrm{I}(t), \tag{6}$$

where $\Psi(t)$ represents the SFR surface density at epoch t and, according to Schmidt law [9], can be rewritten as

$$\Psi(t) = \mathrm{A}\Sigma_{\mathrm{gas}}^{1.3}, \tag{7}$$

while the term $\mathrm{I}(t)$ is the infall function, i.e. denotes the net exchange rate of gaseous matter of the spiral disk with its environment:

$$\mathrm{I}(t) = \Delta_{\mathrm{in}}(t) - \Delta_{\mathrm{out}}(t) \tag{8}$$

with $\Delta_{\mathrm{in}}(t)$ and $\Delta_{\mathrm{out}}(t)$ as infall and outfall rates of gas. Following the arguments given in Prantzos and Silk [16] we adopted Gaussian form of the infall function:

$$\mathrm{I}(t) = \frac{\mu}{\sqrt{2\pi}\sigma} e^{-\frac{(t-t_0)^2}{2\sigma^2}} \quad \text{and} \quad \mu = \mathrm{I}_0\sqrt{2\pi}\sigma e^{\frac{(\mathrm{T}-t_0)^2}{2\sigma^2}}, \tag{9}$$

where μ is the normalizing mass scale for the infall, I_0 present-day infall and T the age of the Milky Way, with the value of T =13.5 Gyr [17]. The characteristic epoch of infall peak t_0 and temporal width σ are assumed to be equal, according to [16]. In the course of modeling, we have been changing the values of Gaussian parameters I_0, t_0 and σ. Resulting timescale is impossible to give in a closed analytical form and numerical methods had to be used. Histogram presented in the Figure 3, obtained for the values of $t_0 = \sigma = 8$ Gyr, shows that the duration of star forming era is prolonged for a factor of ~ 2, 3, 4, or even 12, depending on the used value for present-day infall I_0. Finally, Figure 4 ilustrates the dependence of the mean value for duration of star forming era $<\tau_R>$ on the value of present-day infall.

4. Instead of conclusions

We have investigated a broad range of models of the evolution of the

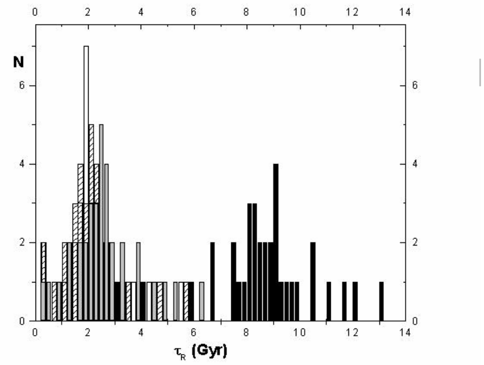

Fig. 3. – Star forming timescales for the Kennicutt sample of “normal” spiral galaxies [7] if the baryonic infall is taken into account. The form of infall function is Gaussian, with the values of characteristic epoch of infall peak t_0 and temporal width σ equal to 8 Gyr and the value of present-day infall I_0 equal to: *white bars* $-1/\sqrt{10^3}$ $M_\odot$ yr^{-1}, *slashed bars* - $1/10$ $M_\odot$ yr^{-1}, *grey bars* $-1/\sqrt{10}$ $M_\odot$ yr^{-1} and *black bars* - 1 $M_\odot$ yr^{-1}.

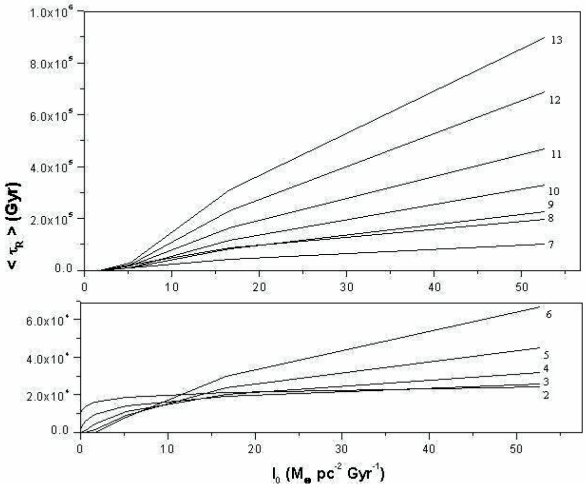

Fig. 4. – Predictions for duration of star forming era in the Gaussian infall model, as a function of present-day infall I_0, for different values of the infall peak (characteristic) epoch t_0. Numbers at the ends of the curves corespond to different values of t_0 (in Gyr).

global star formation rate in spiral disks with fixed threshold applied to Kennicutt's sample of disk galaxies. Recycling and application of Schmidt's law do not significantly change the duration of the stelliferous era for all models considered. This – contrary to previous claims – does not solve the "anthropic" part of the classical gas consumption puzzle: we seemingly live near the end of the stelliferous era. True solution has to be found in the baryonic infall into the disk. The magnitude of the present-day infall and, especially, the value of the star formation threshold do significantly impact the resulting values for τ_R. Fixed threshold with the Gaussian infall prolongs the duration of the stelliferous era for a factor of ~3, at least, in comparison to the "naive" values. In the course of the future work, we shall investigate the case of spatially varying threshold, as well as influence of the infall on other global galactic properties, like color and metallicity.

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