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Fuelling Star-Formation - The Fate of Halo Baryons?

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The old idea of Spitzer about the infall from gaseous galactic haloes was revived with the discovery of the low-redshift population of Lyman-alpha 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. Independent results on the cosmological baryon density point in the same direction, indicating that large amounts of "dark" baryons are hidden in haloes of normal luminous galaxies. With this assumption in place, it is only natural to hypothesize about the long-term fate of these baryons which undergo radiative cooling and occasional reheating in mergers throughout the history of galaxies. Ultimately, the baryons are bound to fall in the gravitational potential of the dark halo and coalesce with the rotationally supported disk. Such aggregates present a potential reservoir of gas not only for solution of the classical gas consumption puzzle, but also as a fuel for the future star formation. We investigate the impact of some models of global gaseous infall onto spiral disks on their gas consumption time scales using 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, 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. We conclude that the infall resolves the classical gas consumption puzzle, and that ultimately most of the baryons in the universe will be processed through stars.

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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). While the former process is a well-known and firmly established part of the standard stellar evolution lore, the latter - global baryonic infall - is 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 and, possibly, central nuclear source. It is easy to show [1] 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 [2] 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). 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 ([3], Table 1) with their mean gas and star formation rate (SFR) surface densities. Adopting the Schmidt star formation law [4] 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.

The former gives gas consumption timescales

$$\tau_g \equiv \left| \frac{M_{gas}}{\dot{M}_{gas}} \right|, \quad \dot{M}_{gas} = \frac{dM_{gas}}{dt} = \mathrm{SFR} \tag{1.1}$$

where M_{gas} denotes available gas mass in the interstellar medium (ISM), and SFR (in $M_{\odot}$ yr^{-1}) presents the star formation rate 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 1a), show almost no difference when comparing to a histogram of Larson et al. [1].

3. Analysis

The equation of global ISM to be integrated is

$$\frac{d\Sigma_{gas}}{dt} = -(1-r)\Psi(t) + \mathrm{I}(t) \tag{1.2}$$

where $\Psi(t)$ represents the SFR surface density at epoch t and, according to Schmidt law [4], can be rewritten as

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

while factor $1 - r = 0.58$ 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 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. Following the arguments given in Prantzos and Silk [5] we adopted Gaussian form of the infall function:

$$\mathrm{I}(t) = \frac{\mu}{\sqrt{2\pi}\sigma} e^{-\frac{(t-t_0)^2}{2\sigma^2}}, \tag{1.4}$$

and

$$\mu = \mathrm{I}_0\sqrt{2\pi}\sigma e^{\frac{(\mathrm{T}-t_0)^2}{2\sigma^2}}, \tag{1.5}$$

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 [6]. The characteristic epoch of infall peak t_0 and temporal width σ are assumed to be equal, wtih the value of 5 Gyr [5]. Resulting timescale is impossible to give in a closed analytical form and numerical methods had to be used. These timescales, obtained for the different values of Gaussian parameter $\mathrm{I}_0 \in \{0.1; 1; 10\}$ $M_{\odot} yr^{-1}$are presented in the histograms in Figure 1b), 1c) and 1d), respectively.

We immediately perceive that, contrary to the usual claims, recycling and even infall do not automatically solve the gas consumption puzzle, since Schmidt Law with fixed star formation threshold in fact aggravates the problem. In order to investigate the case of spatially varying threshold, we used data for galaxy NGC 925 from Boissier et al. [6]. Type is SAB(s)d, distance is 9.16 Mpc, and other properties relevant for our analysis are listed in the Table 1.

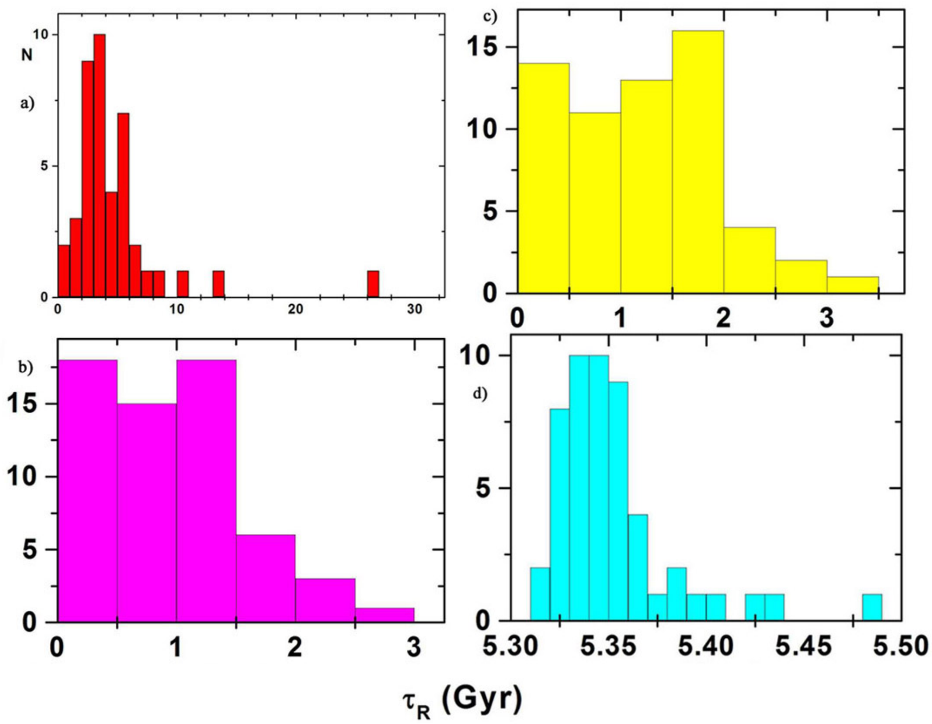

Figure 1. Distribution of Roberts' timescales for the original sample of Larson et al. [1] (the uppermost panel) and subsequently refined models with Schmidt Law, fixed threshold, recycling and Gaussian infall.

R [**kpc**]	***V*(R)** [**km s^{-1}**]	***κ*(R)** [**s^{-1}**] **x 10^{-16}**	$\sum_{\mathbf{crit}}$ **(R)** [**M$_\odot$ pc^{-2}**]	$\sum_{\mathbf{gas}}$ **(R)** [**M$_\odot$ pc^{-2}**]	**Q**
2.45	50	12.5	17.1	12.2	1.4
4.89	81	9.76	13.07	9.1	1.44
7.33	110	7.5	10.26	10.45	0.98
9.77	111.6	6.02	8.23	9.93	0.83

Table 1. Data for NGC 925, a prototype spiral used to assess the importance of dynamical star formation threshold

The first column contains radii **R** for which gas surface densities $\mathbf{\Sigma_{gas}(R)}$ (fifth column) are available. Velocities ***V*(R)** in the second column were derived from the rotation curve approximated with the function

$$V(\mathrm{R}) = 0.5W_c\left(1 - e^{-\frac{\mathrm{R}}{\mathrm{R}_v}}\right), \tag{1.6}$$

where W_c = 260 km s^{-1} denotes the HI line width and $\mathrm{R_v}$ = 5 kpc controls the rise of curve at small radii. Local epicyclic frequencies ***κ*(R)** (third column), given by

$$\kappa = \left[\frac{2V(\mathrm{R})}{\mathrm{R}} \left(\frac{dV}{d\mathrm{R}} + \frac{V(\mathrm{R})}{\mathrm{R}} \right) \right]^{\frac{1}{2}}, \tag{1.7}$$

are used for calculating the critical values of gas surface density $\mathbf{\Sigma_{crit}(R)}$ (forth column),

$$\Sigma_{\mathrm{crit}} = \frac{\kappa \sigma_{\mathrm{gas}}}{\pi \mathrm{G}}, \tag{1.8}$$

with local gas velocity dispersion $\sigma_{gas} = 6$ km s^{-1} [6] and gravitational constant G = 1.33 km^3 M$_{\odot}^{-1}$ s^{-2}. These values, along with gas surface densities $\mathbf{\Sigma_{gas}(R)}$, give (last column) the values of the Toomre parameter **Q(R)** which controls star formation in disk galaxies, i.e. this may occur only if condition

$$\mathrm{Q} = \frac{\Sigma_{\mathrm{crit}}}{\Sigma_{\mathrm{gas}}} < 1 \tag{1.9}$$

is satisfied ([6] and references therein). According to the values in Table 1, star formation in NGC 925 has already ceased for R < 5 kpc, and different scenarios for the future of this process for other two values of R is presented in Figure 2a) and 2b). This could, in perspective, be tested empirically, thus putting strong constraints on the values for Roberts' timescales suggested here.

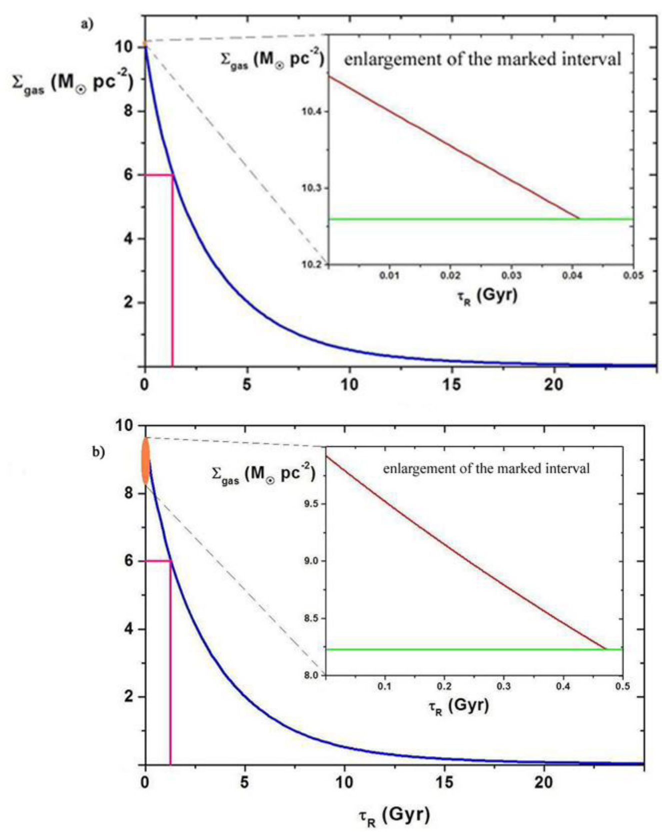

Figure 2. The decrease in gas surface density as exhaustion of the fuel for star formation.

4. Conclusions

We have investigated a broad range of models of the evolution of the 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. In order to investigate the later we have started the analysis of the case with spatially varying threshold by using dynamical one. Preliminary result might be that dynamical threshold reduces the duration of star forming epoch, but this detailed analysis has to be continued. In addition, we shall also investigate influence of the infall on other global galactic properties, like color and metallicity.

References

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