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FUTURE STAR FORMATION DYNAMICS REVISITED

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Abstract. The duration of the current stelliferous era is re-examined in the context of our improved understanding of global star formation in disk galaxies. Important constraints come from the controversial existence of star-formation thresholds, as well as recycling, so-called Schmidts law, and the past star formation history. The question to what extent global infall could influence the duration of the stelliferous era is addressed. Additional mechanisms of non-conventional star formation, such as constructive brown dwarf collisions and cumulative brown dwarf accretion are briefly considered.

1. INTRODUCTION

Star formation histories of disk galaxies are determined by the interplay between incorporation of baryons into collapsed objects and return of baryons into diffuse state. The latter process can be two–fold: **(i)** mass return from stars to the interstellar medium (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). Recycling of gas through stars is a well-known and firmly established part of the standard stellar evolution lore (e.g. Chiosi and Maeder 1986), 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. It is easy to show (Kennicutt 1983; Kennicutt et al. 1995) that the proces **(i)** is insufficient to support continuous star formation for a time interval similar to the Hubble time. Therefore, in investigation how long can the present *stelliferous epoch* (Adams and Laughlin 1997) 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. Some of the conclusions of this preliminary report are further developed in Ćirković and Damjanov (2011, submitted).

In a seminal study, Larson, Tinsley, and Caldwell (1980) considered the timescale for gas exhaustion from spiral disks due to star formation, in an attempt to justify the bold hypothesis that S0 galaxies may be disk galaxies that lost their gas-rich envelopes at an early stage and consumed their remaining gas by star formation (see also Caldwell, Kennicutt, and Schommer 1994). They found that the appropriate Roberts' (1963) timescales

$$\tau_R = \frac{M_{\rm gas}}{\psi_0}, \tag{1}$$

(ψ_0 being the present-day star formation rate) are quite short in comparison to the Hubble time (Fig. 1a, b). This problem becomes more aggravated when we pass from the global, integrated values to he surface densities of both gas and star formation averaged over the optical disk radius (Fig. 1c). The Milky Way version of it is as follows. To the best of present knowledge (Mezger 1988; Young 1988), the star formation rate (hereafter SFR) in the Milky Way today is

$$\psi_0 \sim 5.1 \; M_\odot \; \mathrm{yr}^{-1}. \tag{2}$$

On the other hand, the return fraction of gas to the galactic ISM through mass-loss and supernovae, integrated over the classical Miller-Scalo (Miller and Scalo 1979) Initial Mass Function (henceforth IMF) is $r = 0.42$. This value gives the lockup rate (i.e. the rate at which ISM transformed into stars is permanently locked up in low mass and dead stars) as

$$\frac{dM_{\mathrm{star}}}{dt} = (1-r)\psi(t) \sim 3.0 \; M_\odot \; \mathrm{yr}^{-1}. \tag{3}$$

As the Galaxy is $\sim 10^{10}$ years old, it should have used up $\sim 3 \times 10^{10} \; M_\odot$ of interstellar gas during its history. Today's gaseous content of the galactic *disk* is estimated to several times $10^9 \; M_\odot$ (Imamura and Sofue 1997). It is obvious that the present gas supply is going to be exhausted on the timescale short compared to the lifetime of the galaxy, as first pointed out by Tinsley and Danly (1980) and Larson, et al. (1980). Similar situation applies to disks of other spiral galaxies. thus, in a Gyr from now—only a small fraction of the present age of the Galaxy—star formation will cease in the Milky Way.

This is what is sometimes dubbed the *gas consumption problem* (or puzzle): the timescale for gas consumption is much smaller than the Hubble time and galaxies' ages. Should we, therefore, observe changes in global properties of galaxies (e.g., their colors) on timescales of ~ 1 Gyr? How comes that we live in so "special" time—just before the end of the epoch of star formation, while there is still so many young stars?

2. GAUSSIAN INFALL

Since it seems that recycling and Schmidt's law alone cannot account for the short Roberts' timescales, an often invoked option includes baryonic infall from the halo and/or debris from the Local Group formation. As a prototype of the infall models popular in the literature (e.g. Basu 1993; Prantzos and Silk 1998) we consider the impact of Gaussian infall on the duration of the stelliferous era. We take the infall rate in the general form:

$$I(t) = \frac{\mathcal{M}}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(t-t_0)^2}{2\sigma^2} \right]. \tag{4}$$

Here, $\mathcal{M}$ is the normalizing mass scale for the infall, and σ and t_0 are infall temporal width and characteristic epoch, both with dimensions of time. Prantzos and Silk (1998) use values for these parameters $\sigma = t_0 = 5$ Gyr. These are linked with the present-day infall as

$$\mathcal{M} = I_0 \sqrt{2\pi}\sigma \exp\left[-\frac{(t-t_0)^2}{2\sigma^2} \right], \tag{5}$$

where I_0 is the magnitude of the infall at present time.

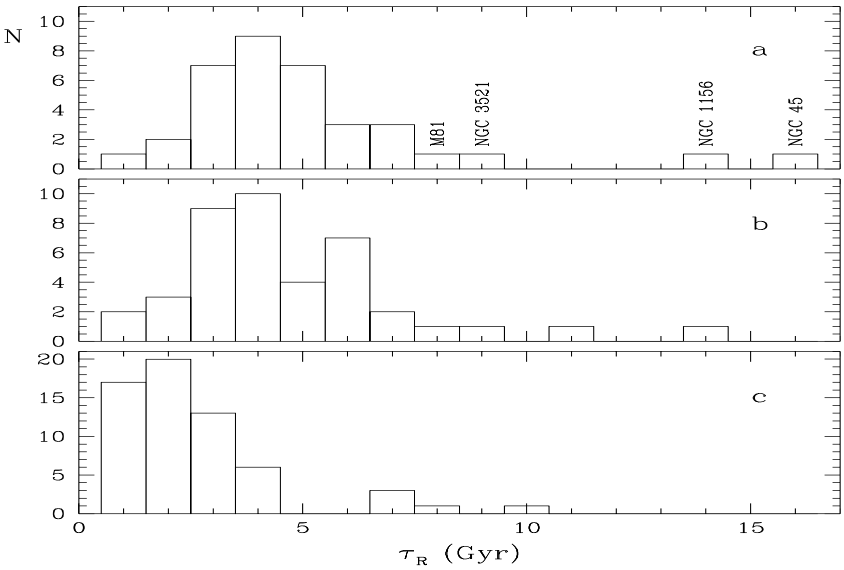

Figure 1: The classical gas consumption puzzle: (a) the distribution of Roberts' times for the original sample of Larson et al. (1980); (b) the same calculated for the sample of 42 normal galaxies for which the total gas masses are given by Kennicutt et al. (1995); and (c) the same using a slightly different definition of Roberts' time (the ratio of the gaseous surface density and the SFR surface density averaged over the optical disk) for the Kennicutt (1998) total sample of 61 galaxies, including some alleged starbursts. There is no difference between either the median τ_R or the general shape of the distribution for the samples (a) and (b), while the sample (c) is characterized by significantly smaller median.

In Figure 2, we see that the distribution of durations of the conventional star-forming epoch changes in shape, but does not show a substantial increase in the median timescale. Both "early" and "late" infall models show similar behaviour with respect to the duration of future star formation. A significant trend is, however, that the decrease in the value of fixed threshold leads to a moderate increase in τ_R, indicating what may be a loophole in the present argument: if rapid cooling or some other physical process significantly decreases $\Sigma_{\rm crit}$ in the cosmological future, an appreciable decrease in the duration of star formation can be achieved; still it would be rather contrived to conclude that anything approaching very long timescales sometimes quoted in literature (e.g. 10^{12} yrs) can be reached.

3. COMPARISONS AND DISCUSSION

While it seems that the gas consumption puzzle has not been entirely resolved by classical means (recycling and Schmidt's law), the controversial nature of baryonic infall and the star formation thresholds precludes reaching definite conclusions about the duration of the stelliferous era. Two final comments are relevant here. First, the duration of the stelliferous era need not necessarily be limited by a sort of global density

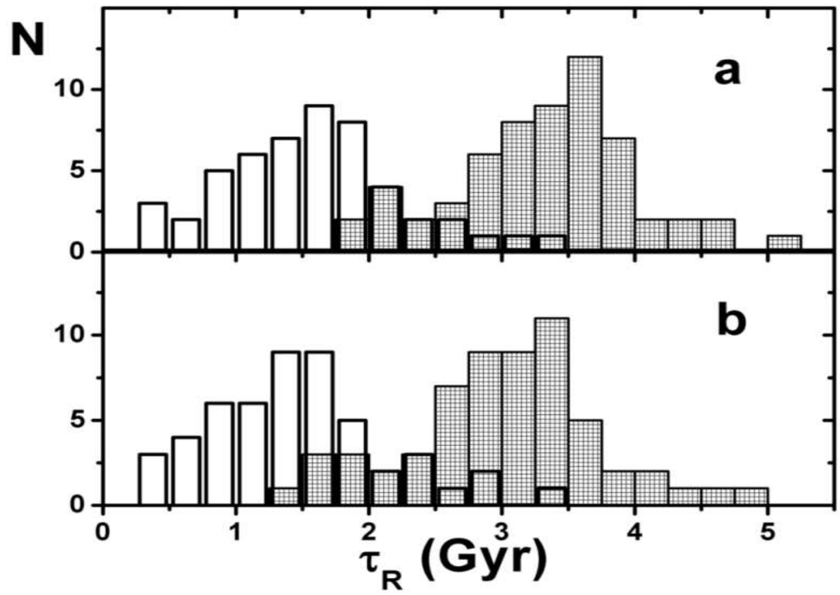

Figure 2: The predictions for the duration of the stelliferous era with Schmidt law, recycling and the Gaussian infall taken into account. Two characteristic timescales for infall are considered: (a) the "early" $t_0 = 5.5$ Gyr infall (following the example of Prantzos & Silk 1998); and (b) the "late" $t_0 = 8.5$ Gyr model (Heavens et al. 2004). The present-day fiducial net infall is taken to be $I_0 \simeq 1 M_\odot$ yr^{-1} in both cases.

threshold as the inferred from observations and considered here. It is reasonable to assume that the present-day thresholds are function of the actual physical conditions in ISM today, notably of its temperature and chemical composition. Both are likely to be significantly changed in epoch more than $\sim 10^{10}$ years distant from the present (Adams & Laughlin 1997). Thus, some form of conventional star formation may persist for significantly longer periods than those discussed above; to this, one may add non-conventional modes of star formation characteristic for very long timescales available in the cosmological future, most notably brown dwarf collisions and accretion of ISM by brown dwarfs. However, this does not resolve the gas consumption puzzle in the form posed by Larson et al. (1980).

Second, our treatment of gaseous infall here is cursory at best. We have considered only the Gaussian form of infall often used as an *ansatz* in literature in order to illustrate the general argument. In the course of future detailed study, we shall investigate the structure of infall in more detail, which can be fruitfully connected with the wealth of observational data obtained recently on both Lyα absorption in galaxy haloes and HVCs as infalling remnants of the epoch of the Local Group formation. Interconnection and prospective synthesis of these seemingly diverse topics promise significant advances in our general understanding of the evolution of the baryonic content of the universe, both past and future.

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References

Adams, F. C. and Laughlin, G.: 1997, *Rev. Mod. Phys.*, **69**, 337.
Basu, S.: 1993, *Bull. Astr. Soc. India*, **21**, 583.
Caldwell, N., Kennicutt, R., & Schommer, R.: 1994, *Astron. J.*, **108**, 1186.
Chiosi, C. and Maeder, A.: 1986, *Ann. Rev. Astron. Astrophys.*, **24**, 329.
Ćirković, M. M. and Damjanov, I.: 2011, *Mon. Not. R. astron. Soc.*, submitted.
Heavens, A., Panther, B., Jimenez, R., & Dunlop, J.: 2004, *Nature*, **428**, 625.
Imamura, K. and Sofue, Y.: 1997, *Astron. Astrophys.*, **319**, 1.
Kennicutt, R. C. Jr.: 1983, *Astrophys. J.*, **244**, 685.
Kennicutt, R. C. Jr.: 1998, *Astrophys. J.*, **498**, 541.
Kennicutt, R. C., Tamblyn, P. and Congdon, C. W.: 1995, *Astrophys. J.*, **435**, 22.
Larson, R. B., Tinsley, B. M. and Caldwell, C. N.: 1980, *Astrophys. J.*, **237**, 692.
Mezger, P. G.: 1988, in Galactic and Extragalactic Star Formation, ed. R. E. Pudritz & M. Fich (Kluwer, Dordrecht), 227.
Miller, G. E. & Scalo, J. M.: 1979, *Astrophys. J. Supp.*, **41**, 513.
Prantzos, N. and Silk, J.: 1998, *Astrophys. J.*, **507**, 229.
Roberts, M. S.: 1963, *Ann. Rev. Astron. Astrophys.*, **1**, 149.
Tinsley, B. M. and Danly, L.: 1980, *Astrophys. J.*, **242**, 435.
Young, J. S.: 1988, in *Galactic and Extragalactic Star Formation*, ed. R. E. Pudritz & M. Fich (Dordrecht: Kluwer), 579.