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DURATION OF THE STELLIFEROUS EPOCH

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Abstract. We investigate the impact of recent advances in research in the gaseous content of the universe on our knowledge of star formation histories of spiral galaxies. The discovery of low-redshift population of Lyα absorbers and first steps made in understanding of the transition between high-redshift intergalactic and low-redshift galactic population of QSO absorption systems, significantly reshape our picture of the gaseous content of the universe. 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 ($z \leq 1$). Such aggregates present a potential reservoir of gas not only for solution of the gas consumption puzzle in spiral disks, but also as a fuel for the future star formation. This baryonic transition from diffuse toward collapsed state, although still hard to establish quantitatively, is a result of several simple physical processes. The resulting increase in the star formation timescales of spiral galaxies has some interesting consequences for the long-term future development of life and intelligent observers in the galactic context. Admittedly highly speculative, this qualitative picture may hopefully provide a motivation for detailed numerical modelling of the physical processes involved.

1. INTRODUCTION: THE STELLIFEROUS EPOCH

Classical cosmological and astrophysical arguments which form the basis of the anthropic principle, like those of Carter, Barrow and Tipler give us *terminus post quem* for emergence of the intelligent observers based on principles known to us (planetary life based on carbon, etc.) in a universe governed by a set of prescribed physical laws. However, it is natural to wonder whether some constraints on *terminus ante quem* for emergence of such observers are built-in in the same physical laws? A natural candidate for such a constraint is the duration of the present stelliferous epoch in spiral galaxies, during which galactic ecology functions efficiently, enabling birth of new generations of stars and slow enrichment of baryonic matter in heavy chemical elements necessary for life. It is clear, however, that matter gradually ends up locked into predominantly inert stellar remnants, and consequently the duration of the stelliferous epoch is finite. Obviously, any form of life as usually specified (carbon-based, planetary, etc.) can not arise after the end of the stelliferous epoch (and it is doubtful even whether it can arise in its last phase, when only extremely long-lived dwarf stars remain shining). Thus, any conclusions pertaining to the finite duration of the stelliferous epoch imply also an astrophysical anthropic constraint.

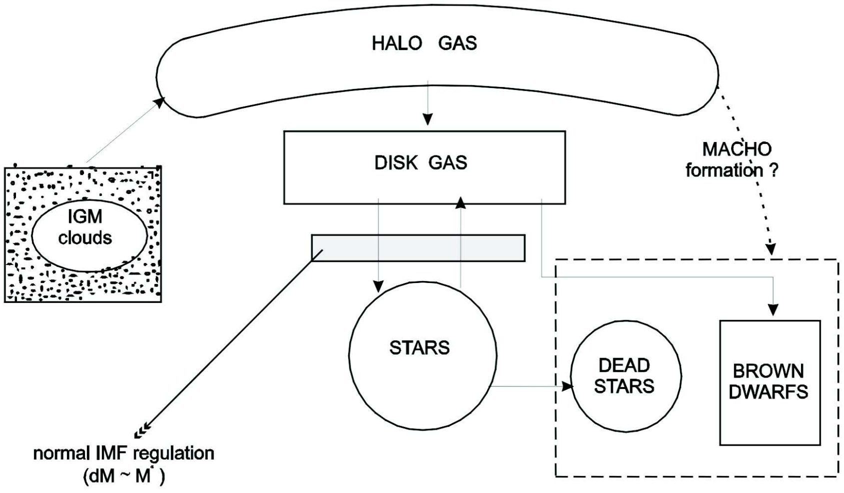

Figure 1: A rather rough scheme of baryonic incorporation. More compact component of the IGM (seen as Lyα clouds) is partially accreted to galactic haloes, where it continues to cool down and fall in galactic gravitational potential. Ultimately it will end up in form of brown dwarfs and stellar remnants. A direct formation route for MACHOs is possible, along the suggestions of Fabian and Nulsen (1994). This need not be regulated through the "normal" IMF which we observe in spiral disks. This is not to claim that baryonic transfer in the opposite direction does not exist – just attempting to clarify this incorporation trend we find more important in the overall cosmological picture.

It is obvious that the present gas supply observed in interstellar medium of the Milky Way as well as external galaxies is going to be exhausted on the timescale short compared to the lifetime of the galaxy, that is sometimes called the gas consumption problem, and represents another instance in which we may regard present state of the universe as somewhat "special". A natural explanation is the baryonic infall from the extended galactic haloes. This is especially appealing, since it helps to solve many other problems (e.g., the nature of baryonic dark matter required by primordial nucleosynthesis), and accounts for several crucial recent observations (e.g., association of a large fraction of low-redshift Lyα clouds with well-defined haloes of normal galaxies). This, however, may be only a part of the much more general process of baryonic incorporation, i.e. gradual accumulation of once diffuse baryonic matter in collapsed structures (galactic disks and other subsystems), for which there is some indication in recent attempts to measure the redshift evolution of the amplitudes of correlation functions of QSO absorption line systems, as well as measurements of both H I and He II Gunn-Peterson effect at high redshift. In this manner, the classical time-scales for degradation of a prototype galaxy could be substantially prolonged in comparison with the naive expectation (following from the gas consumption problem) $\tau \sim 1$ Gyr.

2. SIMPLEST ESTIMATES FOR THE DURATION OF THE STELLIFEROUS EPOCH

In the present discourse, we adopt the following notation:

M_{gas} (t) – gaseous mass in the disk at epoch t
M_{star} (t) – stellar mass in the disk at epoch t
σ_{gas} (t) – surface density of gas in the disk at epoch t
ψ(t) – star formation rate at epoch t
τ– duration of the stelliferous epoch
t_0 – present epoch

Let us consider the star formation rate (henceforth SFR) in the disk of a typical spiral galaxy. Integrating over the entire disk, we obtain the following Schmidt (1959) law for the global SFR:

$$\psi(t) = pM^n_{\rm gas}(t), \tag{1}$$

where p is the proportionality constant, for n =1 in units of $\rm yr^{-1}$. For $n = 1$ model, and if the Milky Way is typical, we have $p \approx 10^{-9}\ \rm yr^{-1} = 1\ Gyr^{-1}$.

In this case, we have for the duration of the stelliferous epoch

$$\tau = \frac{1}{p(1-r)} \ln \frac{M_0}{M_f}, \tag{2}$$

where M_0 and M_f are the initial and the final gas mass, and r is the return fraction of gas to the galactic ISM through mass-loss and supernovae. Integrated over the classical Miller-Scalo (Miller and Scalo 1979) IMF it is r =0.42.

This may increase τ to 120-350 Gyr (Adams & Laughlin 1997).

However, this is just the beginning of the story, since the galactic disk *in toto* is not a closed system. We expect intergalactic gas to be infalling into galactic disks and contribute to the star-formation material. The scenario sketched above gives a natural source of the infalling gas, and further numerical work may show whether the quantification of this proposition is realistic enough. It is consequent to assume that the gaseous halo is such a gas reservoir, rather than diffuse IGM or satellite systems (which tend to be gas-poor in general). However, the origin of the halo gas is not altogether clear. As has been repeatedly shown (White and Rees 1978; Mo and Miralda-Escude 1996), the hierarchical structure formation scenarios leave large quantities of baryons in the virialized state within dark (presumably CDM) haloes. Slow cooling of this gas (which becomes slower and slower, as the density of hot gas decreases) leads to formation of condensations of gas cold enough to be ionized mainly by photoionization. These halo clouds, slowly infalling toward the bottom of the gravitational well created by dark matter, could be the same objects as at least fraction of the QSO absorption-line systems (Chiba and Nath 1997).

Various infall profiles (Gaussian, exponential, bimodal, etc.) will tend to give various time scales for the duration of the stelliferous, and they should be compared with existing observational constraints (e.g. chemical abundance gradients) and with one another. In addition, models for the formation and distribution of MACHOs are relevant for any considerations of the Galactic ecology.

The true equation of global ISM evolution to be integrated is

$$\frac{dM_{\mathrm{gas}}}{dt} = -\frac{dM_{\mathrm{star}}}{dt} + I(t) = -\psi(t) + I(t), \tag{3}$$

where $I(t)$ is the infall function:

$$I(t) = \Delta_{\mathrm{in}}(t) - \Delta_{\mathrm{out}}(t), \quad (\text{all in units of } M\odot \ \mathrm{yr}^{-1}). \tag{4}$$

Solving (3) for temporal evolution of the gaseous mass of the disk gives:

$$M_{\mathrm{gas}}(t) = e^{-p(1-r)t}\left[M_0 + \int_0^t I(t) e^{p(1-r)t} dt\right], \tag{5}$$

whose boundary condition $M_{\mathrm{gas}}\ (\tau) = M_f$ gives the duration of the stelliferous epoch.

The value of M_f is related to the issue of **star-formation thresholds**. Currently favored fixed threshold is $\sigma_{th} \ \sim 6 \ M\odot \ \mathrm{pc}^{-2}$. However, the mechanisms leading to the existence of thresholds are not well-understood. Their magnitude may be variable at long timescales!

3. TOY MODELS OF INFALL

Let us consider some of the simplest ("toy") models of infall. Obviously, the most tractable is the unrealistic case of constant infall:

$$I(t) = \begin{cases} I_0, \ t \leq t_w \\ 0, \ t > t_w \end{cases}, \tag{6}$$

where t_w is the characteristic timescale for the infall (obviously $t_w < t_0$, if we perceived the present-day infall). The resulting timescale, according to (5) is

$$\tau = t_w + \frac{1}{p(1-r)} \ln\left[\frac{M_0 e^{-p(1-r)t_w} + \frac{I_0}{p(1-r)}}{M_f}\right] \tag{7}$$

Somewhat more realistic is the case of Gaussian infall (e.g., Prantzos and Silk 1998):

$$I(t) = \frac{\Im}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(t-t_w)^2}{2\sigma^2}\right], \tag{8}$$

where $\Im$ is the normalizing mass scale for the infall, and t_w and σ are temporal width and characteristic epoch. Prantzos and Silk (1998) suggest $\sigma = t_w = 5$ Gyr. Resulting timescale for the Gaussian infall model is impossible to give in a closed analytical form, since the integral in Eq. (5) now becomes:

$$\frac{\Im}{\sqrt{2\pi}\sigma}\int_0^t \exp\left[-\frac{(t-t_0)^2}{2\sigma^2} + p(1-r)t\right] dt =$$
$$= \frac{\Im}{2}\exp\left(k^2 - \frac{t_0^2}{2\sigma^2}\right) \times \left[\mathrm{erf}\left(\frac{t}{\sqrt{2}\sigma} - k\right) - \mathrm{erf}(k)\right]. \tag{9}$$

Here, k is a dimensionless constant given as

$$k \equiv \frac{\sigma}{\sqrt{2}} \left[\frac{t_0}{\sigma^2} + p(1-r) \right], \tag{10}$$

and we use the standard definition of the error function:

$$\mathrm{erf}(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2)dt. \tag{11}$$

For the abovementioned numerical values of t_0 and σ, the constant k takes value $k \cong 1.73$. We postpone a detailed discussion of these results to a subsequent study.

Finally, we consider the exponential infall (e.g., Chiappini et al. 1997), which can also turn out to be a realistic description, since the cooling process becomes very inefficient at low densities, and evacuation of the hot halo phase necessary leaves densities $\sim 10^{-4}$ cm^{-3}. It is described as:

$$I(t) = I_0 \exp \frac{t}{t_w}, \tag{12}$$

where t_w is the characteristic timescale for the infall. Combining Eqs. (5) and (12), we obtain an expression for the mass of star-forming gaseous disk at any epoch t as

$$M_{\mathrm{gas}}(t) = e^{-p(1-r)t} \left[M_0 + \frac{I_0}{k_e}(1 - e^{-k_e t}) \right], \tag{13}$$

where k_e is a constant of dimension (time)$^{-1}$:

$$k_e \equiv p(1-r) + \frac{1}{t_0}. \tag{14}$$

The corresponding value of τ_R is obtained, as above, by solving the transcendent equation (13) for the same boundary conditions $M_{\mathrm{gas}}\ (\tau) = M_f$. More detailed treatment of these (and other, more realistic) cases will be given in the subsequent work.

4. DIRECTIONS FOR THE FUTURE STUDIES

Apart from putting tighter constraints on the parameters of IGM accretion by galactic haloes and halo gas accretion by galactic disks, we shall, in the course of future work, investigate the consequences of this extension of star formation timescale for intelligent beings and their evolution in the Galaxy. One of the effects sorely needing more elaborate treatment is the presence of star formation thresholds mentioned above, through which the stelliferous timescale is shortened. It is conceivable that topology of the star formation regions and variation in the galactic gravitational potential may considerably change the average values we have discussed above. Another problem is the accretion of the disk gas by stars (pioneered by Hoyle and Lyttleton 1940), the effect which is usually considered negligible in astrophysical discussions except for exceptional cases of chemical anomalies (see, for instance, Yoshii 1981). However, we can not be certain that this remains so over the vast timescales discussed in physical eschatology, particularly after realization that significant amounts of gas will be left in the galaxy even after the normal star formation ceases. Finally, as pointed out by Adams and Laughlin (1997), non-conventional modes of star formation, like merging of sub-stellar objects (brown dwarfs, giant planets), can play some role on these very long timescales. These also should find place in a unified model.

On the other hand, the major problem remains the determination of the incorporation rate of intergalactic baryons. In a project currently under way, we shall use a large sample of recent low-z data (e.g., Jannuzi et al. 1998) to measure the TPCF amplitudes at low redshift. This should give us a better hold on the rate of transition from intergalactic to galactic regime, and thus the relevant timescales. In a related work, we shall try to estimate the rate of cooling and infall of the gas from the halo within a specific, weakly non-adiabatic quasi-hydrostatic model of the galactic gaseous haloes.

In any case, it seems that we could approach the problem of future star formation histories (which our descendants will have, hopefully, to face in the far future) with somewhat greater optimism than it was the case until recently.

It must be emphasized that in all discussions of physical eschatology, it is necessary to consider the fate of intelligent life, since all other life forms will almost certainly be extinguished on shorter timescales by local processes (e.g. their sun's leaving the main sequence). Only highly organized intelligent beings could intentionally manipulate the galactic resources as long as there is available free energy. This leads directly to a crucial point emphasized by Dyson in his seminal 1979. paper. Rare discussions of the future of Galactic physical processes existing so far, lack exactly the same ingredient which makes the analogy with terrestrial ecology fail. This is the potential presence of negentropy sources of the similar scale as the system under consideration, the role played in Earth's ecology by the entire biosphere of our planet. Perceiving the key role played by lifeforms in terrestrial ecology, it is only natural to wonder whether life could ultimately play a similar role in the Galactic system as well. Particularly this is to be expected if one accepts the generic relation between parts of a "nested hierarchy of self-organized systems that begins with our local ecologies and extends upwards at least to the galaxy". (Smolin 1997) Ultimately, this question is tightly connected with the problem of growth of complexity in the universe, and attempts at finding laws applicable to this growth.

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