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THE INFLUENCE OF STAR FORMATION THRESHOLDS ON DURATION OF THE STELLIFEROUS ERA

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Abstract. The influence of star formation thresholds on calculations of the duration of the stelliferous era is discussed. Our knowledge on the details of the global star formation processes is still very incomplete, and it is necessary to try to constrain the relevant parameters. The empirical and theoretical considerations of the thresholds for star-formation in disk galaxies are briefly reviewed, and it is shown how their value influences the possible future duration of star formation in the framework of the classical Schmidt law with and without the global gaseous infall. This topic has several important ramifications for the galactic future of intelligent beings and general anthropic considerations.

1. INTRODUCTION: STELLIFEROUS ERA AND GAS CONSUMPTION TIMESCALE

Cyclic motion of gas in disks of spiral galaxies between the interstellar medium (ISM) and the stellar component is well-known and very active field of study (e.g. Samland, Hensler and Theis 1997; Fields, Mathews and Schramm 1997; Kennicutt 1998). However, it is clear that the efficiency of this "galactic ecology" is not perfect, and that, consequently, star formation in spiral disks must cease at some point of cosmic time (Ćirković 1999a). The present epoch, characterized by active star formation, is sometimes called the *stelliferous epoch*, the term we shall use in further text (Adams and Laughlin 1997). It ends with the exhaustion of fresh gas available for the star formation. Characteristic timescale for the total gas exhaustion is in the first approximation given by

$$\tau = \frac{M_{\rm gas}(t_0)}{\psi_0}, \tag{1}$$

where $M_{\rm gas}(t_0)$ is the present-day mass in gas, and ψ_0 is the star formation rate (SFR). As has been noted, this timescale is short in comparison to the Hubble time (characteristic numbers are $M_{\rm gas} \simeq 6 \times 10^9\ M_\odot$ and $\psi_0 \simeq 5.1\ M_\odot\ {\rm yr}^{-1}$; therefore, $\tau \sim 1$ Gyr). Thus, in a billion years from now—only a small fraction of the present age of the Galaxy—star formation will cease in the Milky Way. In fact, it will cease somewhat earlier, due mainly to the existence of star formation threshold at finite disk surface density (Kennicutt *et al.* 1995 and references therein). This is so-called gas consumption problem in spiral galaxies (Larson, Tinsley and Caldwell 1980), which provided motivation for significant improvement in our picture of the global star formation during the last two decades (see a nice review in Kennicutt 1998).

2. RECYCLING AND STAR FORMATION RATE

When we take recycling of gas into account we can write, as a conservative estimate,

$$\tau_R = \frac{M_{\rm gas}}{\dot{M}_{\rm star}} = \frac{M_{\rm gas}}{(1-r)\langle\psi(t)\rangle}. \tag{2}$$

Here, $r = 0.42$ is the return fraction of gas integrated over the classical Miller-Scalo initial mass function (Miller and Scalo 1979; Mezger 1988). The increase thus obtained is a factor of 2–3 (somewhat more conservative than that proposed by Adams and Laughlin). A further step is to assume that the SFR is proportional to the gas surface density (cf. Schmidt 1959; Arimoto, Yoshii and Takahara 1992) and therefore the gass mass at any instant of time:

$$\psi(t) = pM_{\rm gas}(t), \tag{3}$$

where p is the constant of proportionality in units of yr^{-1} (we may assume that other time dependencies, like the global metallicity, etc. are incorporated in value of p). There is some observational evidence that this assumption of biased star formation is correct (Gavazzi and Scodeggio 1996), although the dependence is more like $\propto M_{\rm gas}^{1.3}$ than simple linear law (Kennicut 1989). For this case, the timescale becomes

$$\tau_R = \frac{1}{p(1-r)} \ln \frac{M_0}{M_f}, \tag{4}$$

where M_0 is the initial quantity of gas in the galaxy, and M_f is the final mass of the gas when the star formation ceases. The question of the final mass is intimately connected with the problem of star formation thresholds, and will not be considered here. We only mention that, following the example of Adams and Laughlin (1997), we can obtain absolute upper limit to this timescale by extreme requirement $M_f \sim 1\ M_\odot$.

If we now postulate gaseous infall characterized, over the period of time t_i by the infall rate $I(t)$ (in units of $M_\odot$ yr^{-1}), simple reasoning gives us the gaseous mass of the galaxy at any time t before the infall ceases $(t \leq t_i)$ as

$$M_{\rm gas}(t) = e^{-p(1-r)t} \left[M_0 + \int\limits_0^t I(t) e^{a(1-r)t} dt \right] \tag{5}$$

It is apparent that, after specifying the initial and final gaseous masses, M_0 and M_f, as well as specific form of infall function $I(t)$, by solving this equation we obtain the duration of the star forming epoch τ_R which satisfies the final condition

$$M_{\rm gas}(\tau_R) = M_f. \tag{6}$$

We shall relegate the detailed discussion of the plausible forms of infall rate function $I(t)$ to a later detailed work (Ćirković 1999b), and will instead, concentrate on the more realistic minimal final gaseous mass M_f.

3. STAR FORMATION THRESHOLDS AND THE FINAL GASEOUS MASS

The final mass of gas for star formation obviously depends on the physics of the process of star formation itself, which is not completely clear to this day. However, a sort of consensus emerged recently on the existence of the *star formation thresholds*, i.e. minimal column density necessary for star formation of about $N_{\rm crit} \simeq 10^{21}$ H atoms $\rm cm^{-2}$ (Skillman 1986; Phillipps, Edmunds and Davies 1990). If we now identify mass in gas of the threshold column density with equilibrium value of the final gass mass (and correct for the presence of helium), we obtain a *maximal* value for M_f

$$M_f \leq 3.3 \times 10^9 \left(\frac{R_d}{10\ \rm kpc}\right)^2 \left(\frac{N_{\rm crit}}{10^{21}\ \rm cm^{-2}}\right) M_\odot, \tag{7}$$

where R_d is the radial size of the galactic disk within which the star formation takes place (and the star formation threshold is valid). This relation is inequality, since the gas consumption can not be treated as uniform process; as is well known, the large "bubbles", "chimneys" and other irregularities are large-scale consequences of the spatial variation in star formation rates throughout the Galaxy. However, it can be used as an overall average for $L \sim L_*$ galaxies, keeping in mind the necessity for further refining.

In the simplest model, given by the equation (4), we can now use the upper limit (7) in order to get the *minimal* duration of the stelliferous epoch. It turns out to be $\tau_R^{\rm min} = 11.5$ Gyr, the value rather low, but consistent with the present situation in the Galaxy, and much easier to bring in agreement with the observational data on galaxy luminosity evolution than the earlier estimates (e.g. Larson *et al.* 1980), which predicted a significant evolution on $\tau \sim 1$ Gyr scales.

Now we are dealing with the real difficulty: estimate of the total column density in various phases of ISM and their phase transition. This question is relevant, since the phase transitions take place depending on the local conditions, and probably, depending on the total column density of various phases present. These data are difficult to obtain with any certainty. The possibility, frequently suggested in the literature, that the SFR is proportional not to the total gas mass, but to H_2 mass (e.g. Talbot 1980), and its consequences for the duration of the stelliferous are considered in the extension of the present work (Ćirković 1999b).

4. CONCLUSION AND PROSPECTS

Investigations of the global star formation histories have been an exceptionally active field of astrophysical research (Kennicutt 1998, and references therein). It offers a syncretic view of both galactic and extragalactic physical and chemical processes. In the continuation of the present reserach, we shall consider impact of large-scale cosmological processes, namely incorporation of baryons into galaxies via intergalactic accretion and merging minihaloes, onto the duration of the stelliferous era in more detail. In addition, various models of infall of fresh gas from the halo will be consider, and predictions of each of model infalls will be discussed. While it is still premature to try to connect partial solutions to this problem with the "first principles" of galactic evolution, it can be envisaged that the flood of new observational data expected during the next decade mainly from X-ray and new optical observatories will enable much less speculative approach.

An interesting extension of research along these lines applies to the anthropic principle and fate of intelligent life in galactic environment of the far future (Barrow and Tipler 1986). One may dare to insist that the survival of such intelligent life (as far as astrophysical processes are concerned) seems assured for the entire duration of the stelliferous era, but this statement becomes unwarranted for the later, *degenerate era* (Adams and Laughlin 1997). This especially applies to intelligent lifeforms, for which the expansion time over galactic length scales are many orders of magnitude smaller than the duration of the stelliferous era (e.g. Hart 1975). Although the end of stelliferous era need not necessary mean extinction of all galactic life forms, it will certainly be a landmark in their evolutionary histories, so its dating (as precise as current level of our ignorance allows) deserves further investigation.

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References

Adams, F.C. and Laughlin, G.: 1997, *Rev. Mod. Phys.*, **69**, 337.
Arimoto, N., Yoshii, and Takahara, F.: 1992, *Astron. Astrophys.*, **253**, 21.
Barrow, J.D. and Tipler, F.J.: 1986, The Anthropic Cosmological Principle (Oxford University Press, New York).
Ćirković, M.M.: 1999a, *Serb. Astron. J.*, in press.
Ćirković, M.M.: 1999b, *Ap and SS*, submitted.
Fields, B.D., Mathews, G.J., and Schramm, D.N.: 1997, *Astrophys. J.*, **4483**, 625.
Gavazzi, G. and Scodeggio, M.: 1996, *Astron. Astrophys.*, **312**, L29.
Hart, M.H.: 1975, *Q. Jl. R. Astr. Soc. 16*, 128.
Kennicutt, R.C.Jr.: 1989, *Astrophys. J.*, **244**, 685.
Kennicutt, R.C.Jr.: 1998, *Ann. Rev. Astron. Astrophys.*, **36**, 189.
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. by R. E. Pudritz and M. Fich (Kluwer Academic Publishers, Dordrecht).
Miller, G.E. and Scalo, J.M.: 1979, *Astrophys. J. Suppl.*, **41**, 513.
Phillipps, S., Edmunds, M.G., and Davies, J.I.: 1990, *MNRAS*, **244**, 168.
Samland, M., Hensler, G., and Theis, Ch.: 1997, *Astrophys. J.*, **476**, 544.
Schmidt, M.: 1959, *Astrophtys. J.*, **129**, 243.
Skillman, E.D.: 1986, in "Star Formation in Galaxies", ed. by C. J. Lonsdale Persson (NASA, Washington), p. 263.
Talbot, R.J.Jr.: 1980, *Astrophys. J.*, **235**, 821.