A MODEL FOR THE CHEMICAL EVOLUTION OF GALACTIC DISKS.

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Introduction

In this paper we discuss a simple model for the chemical evolution of galactic disks, aiming at understanding the observed metallicity gradients in spiral galaxies. The model incorporates both the recent results of Talbot and Arnett (1975), who proposed a rate of star formation driven by the surface mass density, and those of Lynden-Bell (1975), who investigated the consequences of significant infall of gas into the system. A similar attempt was made by Chiosi (1977) for the solar neighbourhood. The result was that the metallicity distribution of nearby stars can be easily interpreted if the time scale for accretion of gas into the solar pool, or in other words the duration of the disk formation phase, is of the order of 2-3 10^9 ys. Such a result is qualitatively in agreement with the models of Larson (1972), Ostricker and Thuan (1975), and also is implicit in the collapse models for the formation of disk galaxies, Larson (1976).

The model that we describe here rests on the following assumptions:

i) the disk is represented by several independent circular rings (no exchange of matter among them);

ii) the surface mass density in each ring is supposed to depend on both the distance from the galactic centre and time. The latter is thought to simulate both a rapid accretion phase (collapse) and a continuous slow accretion of primordial matter (infall);

iii) the adoption of a prescription for the star formation rate and the use of the istantaneous recycling approximation.

1. Basic Equations and Assumptions.

Let $\sigma(r,t)$, $\sigma_g(r,t)$ and $\sigma_s(r,t)$ be the surface mass densities of a ring and of its gaseous and stellar components re

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spectively. Moreover we define $Z\,\sigma_g(r,t)$ to be the mass of gas in form of heavy elements (heavier than He) and $f(r,t)$ the fraction of unastrated matter. The well known conservation equations are:

$$\dot{\sigma}_g(r,t) = -\alpha\,\dot{\sigma}_s(r,t) + \dot{\sigma}(r,t) \tag{1}$$

$$\dot{Z}(r,t) = -\frac{Z(r,t)}{\sigma_g(r,t)}\,\dot{\sigma}_g(r,t) + \alpha\left[p^* - Z(r,t)\right]\frac{\dot{\sigma}_s(r,t)}{\sigma_g(r,t)} \tag{2}$$

$$\dot{f}(r,t) = \frac{1-f(r,t)}{\sigma_g(r,t)}\,\dot{\sigma}(r,t) - \frac{f(r,t)}{\sigma_g(r,t)}\,(1-\alpha)\,\dot{\sigma}_s(r,t) \tag{3}$$

In the above equations: $p^* = p_z/\alpha$, p_z is the stellar yield of heavy elements, α is the proportion of mass in each generation of stars that remains locked in long lived stars or remnants. It is also implicitly assumed that inflowing matter has primordial metal abundance, and Deuterium is destroyed when passes through a star.

Stellar birth rate: We have adopted for the stellar birth rate $\dot{\sigma}_s(r,t)$ the supersonic case of Talbot and Arnett (1975), given by the following relationship

$$\dot{\sigma}_s = \nu_{\odot}\left[\frac{\sigma(r)\sigma_g(r)}{\sigma_{\odot}^2}\right]^{x-1}\sigma_g(r) \quad , \tag{4}$$

where $\nu_{\odot}$ is an adjustable parameter and $\sigma_{\odot}$ is the surface mass density in the solar vicinity. In their formulation, $\sigma(r)$ and $\sigma_{\odot}$ are assumed to be time independent quantities. To take into account temporal dependence, we assume here that relation (4) is valid at any time and all quantities, except $\nu_{\odot}$, are functions of it.

Accretion rate: The term of mass accretion in eq. (1) is split into two contributions, collapse and slow infall. Their temporal and spatial behaviour is

$$\dot{\sigma}(r,t) = A(r)\,e^{-t/\tau_1} + B(r)\,e^{-t/\tau_2} \quad , \tag{5}$$

where τ_1 and τ_2 represent the characteristic time scales of collapse and infall respectively. A(r) and B(r) are two suitable functions of the galactocentric distance, which must be determined by means of two additional constraints, such as the surface mass density and infall rate distributions across the disk at the present epoch.

Mass distribution: Following Freeman (1970), we adopte an exponential law for the mass distribution through most of the disk. However, as this approximation is not certainly valid in the very central and outer parts of the disk, we instead use the following representation:

$$\sigma(r,t^*) = \frac{\sigma_N}{(r+R_N)^2} \qquad 0 \leq r \leq r_B \tag{6}$$

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$$\sigma(r,t^*) = \sigma_D\, e^{-r/R_D} \qquad r_B < r \le r_M \quad , \qquad (7)$$

where t^* is the age of the galaxy, σ_N, σ_D, R_N and R_D are scale factors that can be easily determined. In addition, r_B and r_M give the radius of the central bulge and the maximum radius of the disk respectively. Rather arbitrarely, we also assume that r_B and r_M are 2 and 20 Kpc respectively.

Infall rate: To derive a plausible guess for the radial variation of the infall rate at the present time, we follow the theoretical analysis of Hunt (1975). To simplify things Hunt's results are approximated by an exponential law, $a_o \exp(-r/R_I)$, where a_o and R_I are two easily determinable scale factors. Under these circumstances B(r) assumes the following expression

$$B(r) = a_o\, e^{-r/R_I}\, e^{t^*/\tau_2} \qquad (8)$$

which is valid as long as in eq. (4) the second term is small compared to the first one at the present age. With some algebric manipulations, after integrating eq. (1) with respect of time, we assigne A(r) to the following relationships:

$$A(r) = \left[\frac{\sigma_N}{(r+R_N)^2} + \tau_2 a_o e^{-r/R_I}\left(1-e^{t^*/\tau_2}\right)\right]\tau_1^{-1}\left(1-e^{-t^*/\tau_1}\right)^{-1} \qquad (9)$$

for $r \le r_B$, and

$$A(r) = \left[\sigma_D\, e^{-r/R_D} + \tau_2 a_o e^{-r/R_I}\left(1-e^{t^*/\tau_2}\right)\right]\tau_1^{-1}\left(1-e^{-t^*/\tau_1}\right)^{-1} \qquad (10)$$

for $r > r_B$.

2. Input parameters.

Basic input parameters of this problem are:

i) the surface mass densities, at the centre and solar vicinity, (σ_c and $\sigma_\odot$) at the present age;

ii) the infall rates, at the centre and solar vicinity ($\dot\sigma_{ic}$ and $\dot\sigma_{i\odot}$) at the present age ;

iii) the characteristic time scales of the collapse and slow infall, τ_1 and τ_2 respectively;

iv) $\nu_\odot$ and x in the stellar birth rate, the age of the galaxy t^*, the stellar yield p_z, and the fraction α of locked mass in each stellar generation.

A few of them however can be considered known with some accuracy, and therefore they will be kept constant. They are summarized in Table 1.

TABLE 1

t^*	$\sigma_\odot$	$\dot\sigma_{i\odot}$	p_z	α	x
13	100	1	0.012	0.8	2

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t^* is in units of 10^9 ys, $\sigma_{\odot}$ is in units of $M_{\odot}/pc^2$, $\dot{\sigma}_{i\odot}$ is in units of $M_{\odot}/pc^2/10^9$ ys. The remaining parameters are free.

3. Results.

As we have not many detailed observations for other regions than the solar neighbourhood, we extend to the whole galaxy only those solutions in Chiosi (1977), which showed a good agreement for the solar vicinity. However, for purposes of comparison some solutions, which do not satisfactorily represent the solar vicinity, are also shown. To this aim, Fig. 1 indicates the distribution of metallicity among stars at several different distances from the galactic centre for four solutions, whose input parameters are summarized in Table 2.

TABLE 2

cases	σ_c	$\sigma_{\odot}$	$\dot{\sigma}_c$	$\dot{\sigma}_{\odot}$	τ_1	τ_2	ν_o
a	10^4	10^2	-	-	0.5	-	2.7
b	10^4	10^2	-	-	3.0	-	2.7
c	10^4	10^2	10^2	1	0.5	15	2.7
d	10^4	10^2	10^2	1	3.0	15	2.7

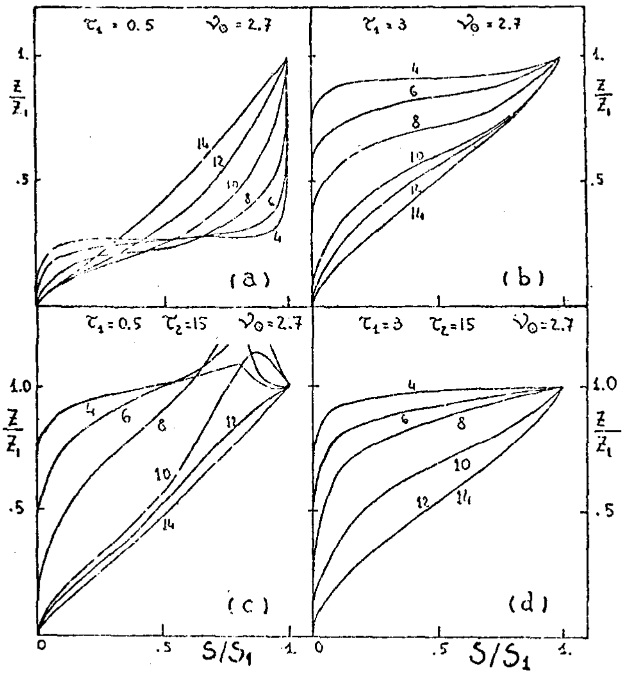

Fig. 1: Metallicity distribution in stars at different distances from the galactic centre.

Table 3 summarises the radial variations of gas metallicity Z, the surface mass density of the gas, and the fractionary abundance f_D of unastrated matter (Deuterium). Of particular interest is the variation of the metallicity with the position in the disk. In all models, moving from the external regions of the disk, the gas surface mass density σ_g and metallicity Z first increase to

TABLE 3 (Gradients)

Case	R	0	2	4	6	8	10	12	14	16	18	20
a	σ_g	0.02	0.05	0.10	0.21	0.46	1.00	1.97	2.49	1.66	0.77	0.33
	Z	4.25	4.42	4.58	4.67	4.58	3.75	2.08	0.73	0.16	0.03	0.01
	f	0.45	0.44	0.43	0.42	0.43	0.48	0.66	0.86	0.97	0.99	1.00
b	σ_g	0.65	0.66	0.68	0.72	0.82	1.00	1.30	1.34	0.81	0.37	0.16
	Z	1.27	1.30	1.37	1.49	1.70	1.88	1.48	0.58	0.13	0.03	0.00
	f	0.79	0.79	0.78	0.77	0.74	0.71	0.75	0.89	0.97	0.99	1.00
c	σ_g	0.91	1.02	0.99	0.97	0.96	1.00	1.22	1.33	0.85	0.40	0.17
	Z	1.25	1.26	1.27	1.28	1.36	1.77	1.63	0.67	0.15	0.03	0.00
	f	0.80	0.80	0.79	0.79	0.79	0.74	0.73	0.87	0.97	0.99	1.00
d	σ_g	0.84	0.90	0.90	0.90	0.92	1.00	1.15	1.12	0.67	0.30	0.13
	Z	1.25	1.26	1.28	1.33	1.43	1.58	1.33	0.55	0.13	0.03	0.01
	f	0.80	0.80	0.79	0.79	0.77	0.76	0.77	0.89	0.97	0.99	1.00

Units: R (Kpc), σ_g ($\sigma_{g\odot}$), Z (p_z).

a peak, then both decrease again. The Z peak is always inside the one of the gas component. This result is in agreement with a similar behaviour in Talbot and Arnett (1975). According to this,the central regions of the galaxy are expected to be metal deficient with respect of the solar vicinity. The comparison of these results with Larson's (1976) models of spiral galaxies leads to a number of conclusions. Models with short time scale of collapse τ_1 and no occurrence of infall of primordial matter at the present time can be ruled out as they do not approximate the results from dynamical models. On the other hand, models with either short time scales τ_1 and inclusion of the slow infall term or long time scales τ_1 (2-3 10^9 ys) and no matter of the infall term, give rise to similar results. The most salient difference is the occurrence of the supermetal rich phase in the first category. As the present observations seem to exclude the occurrence of such a supermetal rich phase, Pagel and Patchett (1975), the second type of models should be preferred. In such a case, infall of primordial (or almost primordial) gas on the galactic disk is expected to occur at the present time at rates compatible with the observational data (1∿2 $M_\odot/pc^2/10^9$ ys).

In spite of the crudness of this approach and the adoption of the istantaneous recycling approximation, which can invalidate some solutions, the above results are confirmed by the analysis of Larson and Tinsley (1977), based on collapse models. They in fact obtained results for the gradient of chemical composition across the disk very similar to the ones described here.

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