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CHEMICAL EVOLUTION OF DISK GALAXIES: SELF-CONSISTENT STRUCTURE OF THE DISK

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RESUMEN. Suponiendo que la tasa de formación estelar y que la dispersión de velocidades del gas en una galaxia de disco están reguladas por la inyección de energía estelar, se construye un modelo autoconsistente de evolución química. La tasa de formación estelar y el grosor del disco dejan de ser parametros libres y sus valores son controlados por mecanismos de retroalimentación entre el gas y las estrellas. Como la presión del gas es función del campo gravitacional del disco, la retroalimentación hace que la tasa de formación estelar sea dependiente de la densidad superficial de masa. Aqui presentamos resultados preliminares, para la Vía Láctea, suponiendo que la masa galáctica aumenta por la acreción de material primigenio y que el gas puede relajarse a un disco isotérmico en equilibrio hidrostático. Los parámetros usados en la nucleosíntesis de elementos y en la tasa de acreción son tomados de Matteucci y François (1989). La tasa de formación estelar es adaptada del modelo de auto regulación descrito por Franco y Shore (1984) y la función inicial de masa es tomada de Scalo (1986). Los gradientes químicos observados, la relación edad-metalicidad en estrellas de la vecindad solar, la evolución química observada en estrellas tipo G y la distribución actual del gas en el disco galáctico, están bien reproducidos por el modelo.

ABSTRACT. Assuming that both the star formation rate and the gas velocity dispersion in a disk galaxy are regulated by the stellar energy injection, a self-consistent chemical evolution model can be constructed. The star formation rate and the disk thickness are no longer free parameters, but they are controlled by the feedback between gas and stars. Given that the gas pressure is a function of the gravitational field, such a feedback results in a star formation rate that is also dependent on the total mass surface density. Here we present preliminary results, for the Milky Way, assuming that the galactic mass grows by primordial infall and that the gas relaxes to an isothermal disk in hydrostatic equilibrium. The nucleosynthesis parameters and the infall rates are taken as in Matteucci and François (1989). The star formation rate is adapted from the self-regulated model discussed by Franco and Shore (1984), and the initial mass function is taken from Scalo (1986). The observed elemental gradients, the age-metallicity relation for the solar neighborhood, the G-dwarf chemical distribution, and the present day disk surface gas density distribution, are reasonably well reproduced by the model.

Key words: **INTERSTELLAR-ABUNDANCES — STAR-FORMATION**

I. INTRODUCTION.

One of the most important input parameters in chemical evolution is the stellar birthrate function. Given that the details of the star formation process are not well understood, the star formation rate is usually assumed to be

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proportional to some power of the surface gas density. The exponent and the proportionality constant (which defines the efficiency of gas conversion) are free parameters, and they are chosen to give the best agreement with observational constraints. This formulation is based on Schmidt's (1959) original suggestion that the star formation rate per unit volume can be proportional to a power of the average gas volume density. In principle, and as long as the gas scale height is constant with galactocentric radius, the formulations with the surface gas density and with the volume gas density are equivalent. The obvious advantage of the surface density formulation is that one does not have to deal with the scale height, and Talbot and Arnett (1975) derived an adequate parametrization to follow the evolution of isothermal disk galaxies with constant total mass.

The dependence of the star formation rate on the available gas mass, however, can be derived under a variety of circumstances (e.g., Schmidt 1959; Cox 1983; Franco and Cox 1983; Franco and Shore 1984). In particular, the stellar energy input from OB associations disrupts the ambient stellar medium and can regulate the star forming activity at galactic scales (Franco and Shore 1984). The mechanism operates via interacting "supershells "and provides an exponent in the range 1.5 to 2. In this paper we present preliminary results of a chemical evolution model with infall and a self-consistent treatment of the galactic disk. The star formation rate is obtained from this simple but precise formulation: the efficiency of gas conversion and the exponent of the surface gas density are fixes quantities. The chemical evolution model is the one described by Matteucci and François (1989), and the results are compared with the available observational constraints.

II. THE GALACTIC MODEL

II.a. Chemical Evolution.

The main assumptions for the chemical evolution model are taken from Matteucci and François (1989). The galactic disk is approximated by a set of independent rings, 2 Kpc in width, without mass exchange. The disk mass increases by the accretion of gas with primordial composition at a rate

$$\frac{d\sigma_{tot}(r,t)}{dt} = A(r)\, e^{-t/\tau(r)}, \tag{1}$$

where r is the galactocentric radius, t is the evolutionary time scale, σ_{tot} is the total mass surface density, and A(r) is selected to fit the present day mass distribution of the disk. The time scale for gas accretion is assumed to increase linearly with galactocentric radius

$$\tau(r) = 0.464r - 1.59. \tag{2}$$

The initial mass function is assumed constant in time and space and is taken from Scalo (1986). The lower mass is 0.1 $M_\odot$ and the upper mass is 80 $M_\odot$. The instantaneous recycling approximation is relaxed and the evolution of ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, and ^{56}Fe are followed in detail. The nucleosynthesis calculations of Woosley and Weaver (1986) have been used for the massive stars (i.e., the Type II SN progenitors, $8 \leq M/M_\odot \leq 100$). In the mass range 0.8 to 8 solar masses, the enrichment of the galactic medium through quiescent mass loss and planetary nebulae ejection is considered (Renzini and Voli 1981, with $\alpha = 1.5$ and $\eta = 0.33$). The existence of Type II SN originating from the C-deflagration of white dwarfs in binary systems has also been taken into account (this is important in the correct derivation of the Iron evolution). The prescriptions for Type Ia supernovae were taken from Nomoto *et al.* (1984) (model W7). Type Ib, on the other hand, are assumed to produce 0.3 $M_\odot$ of Iron per event and represent ~ 50% of the total type I SNe.

II.b. Star Formation Rate.

Assuming that the bulk of the star formation activity is controlled by the energy injection from massive stars located in OB associations (via interacting "superbubbles "), the star formation rate can be written as a "generalized "Schmidt law (Franco and Shore 1984).

$$SFR \simeq K\rho_g^{\gamma}, \tag{3}$$

where ρ_g is the average gas density, K is a constant dependent on the average properties of the OB associations, and the exponent γ depends on the evolutionary stage of the interacting "superbubbles ". For the case of momentum conserving superbubbles $\gamma = 59/40$.

Assuming that each ring of the gaseous disk is able to withstand the stellar energy input and to relax to hydrostatic equilibrium, the pressure at midplane is

$$P(r) \simeq \pi G \sigma_{tot}(r) \sigma_g(r)/2, \tag{4}$$

and the midplane gas mass density is simply

$$\rho_g(r) = P(r)/c^2(r), \tag{5}$$

where σ_g is the gas surface density, and c(r) is the gas velocity dispersion. This velocity dispersion should be the result of a variety of processes pumping energy and momentum to each one of the disk rings. Two main sources can be associated with infall and star formation (see Tenorio-Tagle and Bodenheimer 1988). To begin with the simplest model, however, we assume an isothermal disk with a constant velocity dispersion. In this case, using equation (5), the star formation rate from Franco and Shore (1984) can be written as

$$\frac{d\sigma_g(r)}{dt} \simeq -0.02\, \sigma_{tot}(r)^{19/40} \sigma_g(r)^{59/40}\, M_\odot\, pc^{-2}\, Gyr^{-1}, \tag{6}$$

where σ_{tot} and σ_g are in units of $M_\odot$ pc^{-2}. The feedback between gas and stars introduces a dependence on the total surface mass density and, for open models with infall, the gas consumption has different rates at different evolutionary stages. For closed models, however, the scheme reduces to the one discussed by Talbot and Arnett (1975) with the main difference that now exponent is fixed by the feedback process.

III. RESULTS

The evolution of several single elements (C, N, O, Ne, Mg, Si, S and Fe) along with the gas surface mass distribution and SN rates, are followed in detail. The present age of the Galactic disk is assumed to be 12 Gyr. Figures 1 to 3 show the model results for the solar neighborhood, and Figures 4 to 9 show the results for the elemental gradients and present day gas distribution. The data were taken from Calberg *et al.* (1985), Lacey and Fall (1985), Bhat *et al.* (1984), Li *et al.* (1982), Nissen *et al.* (1985), Pagel (1989), Shaver *et al.* (1983), Talbot (1980), and Twarog (1980). The present model is labeled with the number 5, and is compared with the cases discussed by Matteucci and François (1989). These cases, labeled with numbers 1 to 4, were obtained with a parametric form for the star formation rate

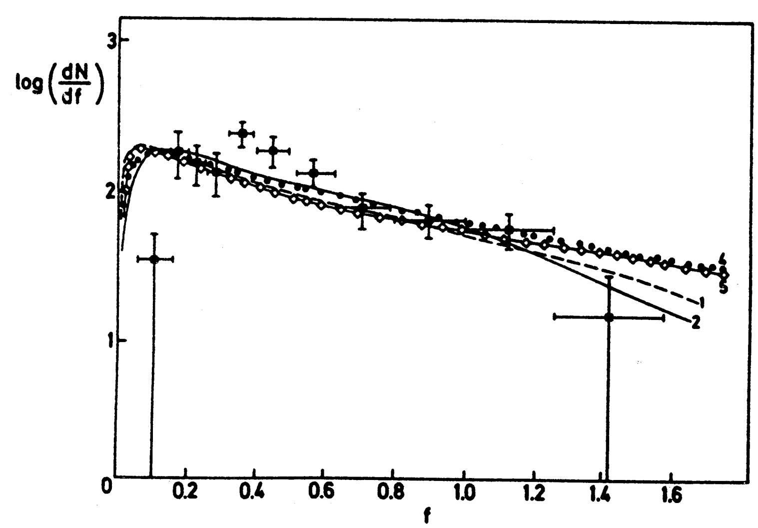

Fig. 1. G-dwarf Iron distribution.

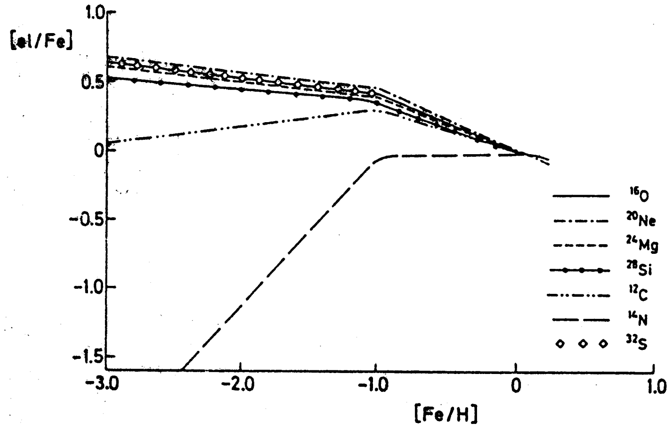

Fig. 2. The [*element*/Fe] - [Fe/H] relation for the solar neighborhood.

$$\frac{d\sigma_g(r)}{dt} = \nu\, \sigma_{tot}(r)^{k_1}\, \sigma_g(r)^{k_2}, \quad (7)$$

where ν, k_1, and k_2 are free parameters, which are chosen to reproduce most of the observational constraints. Model 1 corresponds to $\nu = 0.5$, $k_1 = 0.1$, and $k_2 = 1.1$. Model 2 corresponds to $\nu = 2.7$, $k_1 = 1$, and $k_2 = 2$. Model 3 is equal to model 1 but with enriched infall. Model 4 corresponds to $\nu = 0.25$, $k_1 = 0$, and $k_2 = 1.1$.

Figure 1 shows the observed and predicted G-dwarf distributions as a function of the relative abundance of Iron. The data points are from Pagel (1989). The differences between models are small and for abundances greater than one tenth of the solar iron abundance, all models are equivalent. The fraction of dwarfs with Iron abundances lower than 1/10 of the solar value are in all cases ~ 10%. This predicted value is greater than the observational results, of about 3%, reported by Pagel (1989). The observational results discussed by Beers (1987), however, have casted some doubts on this reported paucity of G-dwarf stars.

Figure 2 shows the relative abundances with respect to Iron. These abundance ratios, which are mostly dependent on the nucleosynthesis prescriptions and the stellar lifetimes, are similar to the ones obtained with model 1 (see discussion in Matteucci and François 1989).

The predicted age-metallicity relation is shown in Figure 3. The model gives results close to the ones from model 4, although models 1 and 2 seem to give a better agreement with the observational data, it should be stressed that the error on the age has been largely underestimated (the use of different evolutionary tracks may lead to differences in the age of 3-4 Gyrs, Buonanno 1987).

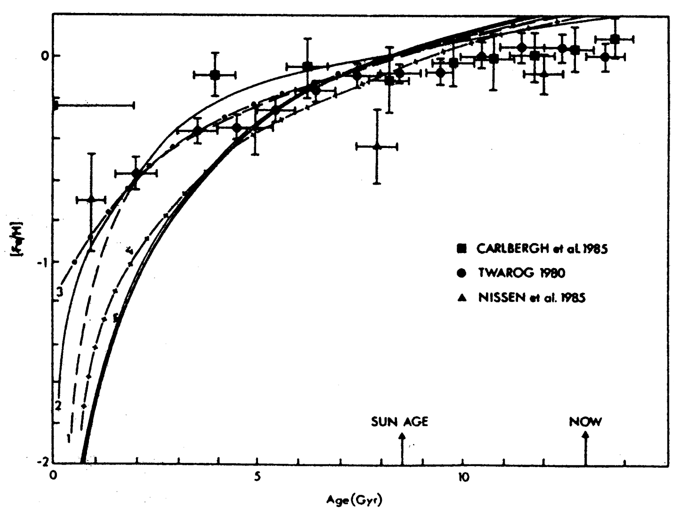

Fig. 3. Age-Fe relationship for the solar neighborhood.

Figures 4 to 8 give the predicted gradients for Nitrogen, Oxygen, Neon, Sulphur, and Iron, respectively. In Figures 4 to 7, we have plotted the results derived from H II regions by Shaver *et al.* (1983). One can notice that, except for model 4, the models predict correct gradients but the absolute abundance values are higher than the observed ones at any given galactocentric radius. The reasons for this apparent discrepancy have been discussed by several authors (e.g., Peimbert 1986; Rubin *et al.* 1988), and they may be associated with systematical errors and with the presence of dust grains.

Figure 9 displays the observed total surface gas density distribution (dashed and dotted lines) along with the model predictions. Model 4 provides a reasonably good approximation to the observational gas data but, as said before, it predicts shallow abundance gradients. Models 1, 3 and 5, give good abundance gradients and gas distributions close to the data of Bhat *et al.* (1984), Li *et al.* (1982), and Talbot (1980). Overall, one could say that model 1 fits better the observed gas trends. As can be noticed from the uncertainties in the observational data, however, the values for the gas mass distribution in the inner Galaxy seem to be known within a factor of about 3. As a consequence, one cannot draw definitive conclusions about these models. Nonetheless, model 2 does not fit any of the observed gas distributions

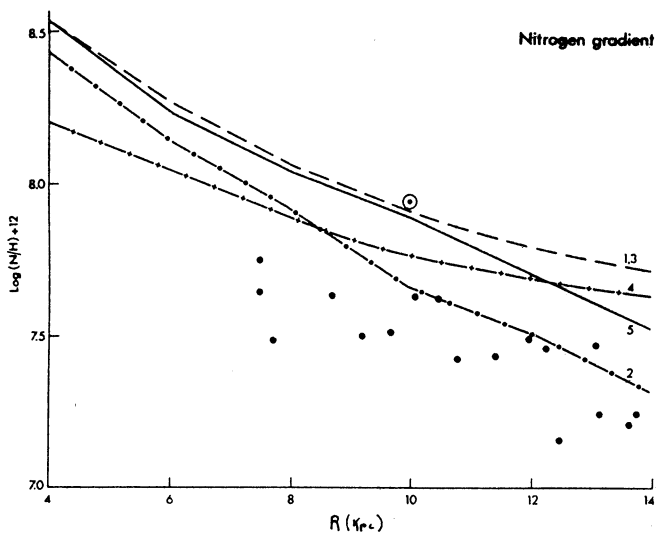

Fig. 4. Galactic gradient of Nitrogen.

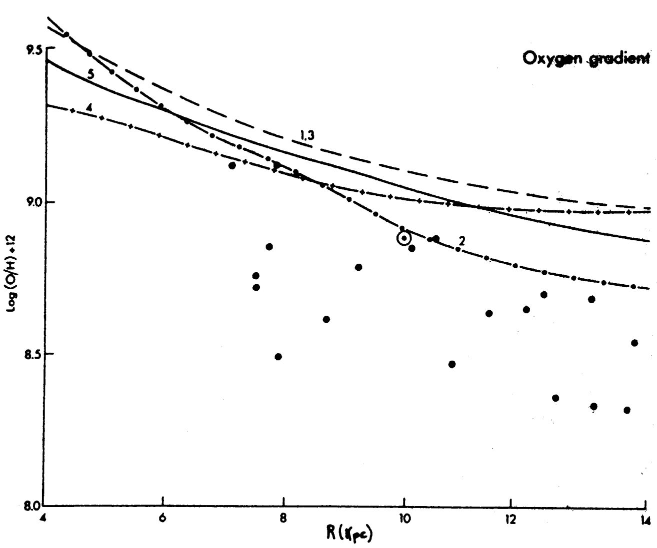

Fig. 5. Galactic gradient of Oxygen.

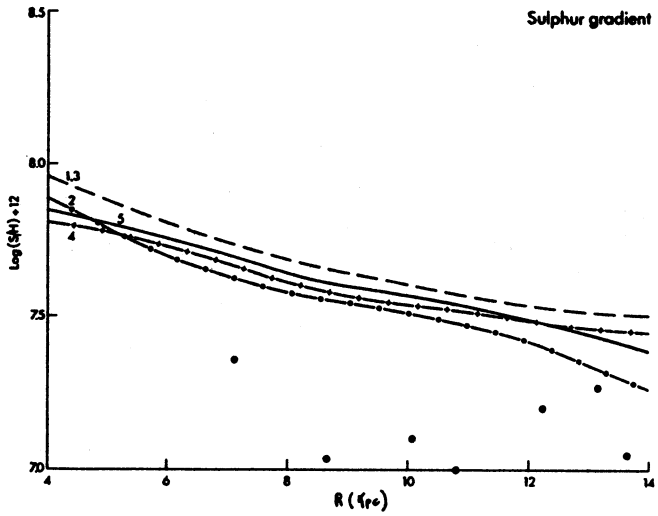

Fig. 6. Galactic gradient of Sulphur.

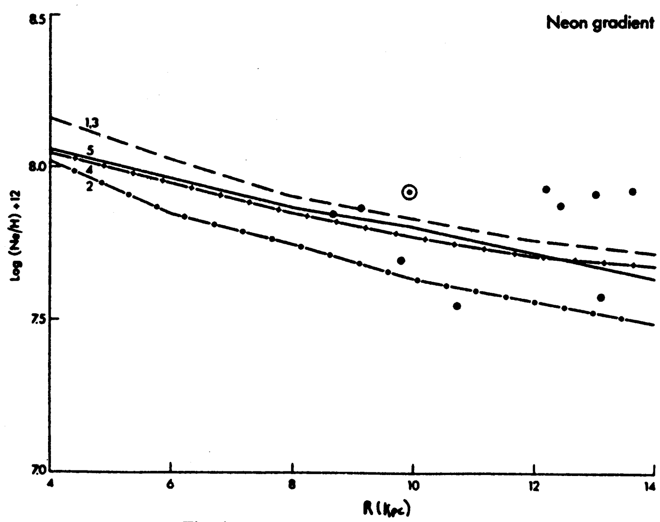

Fig. 7. Galactic gradient of Neon.

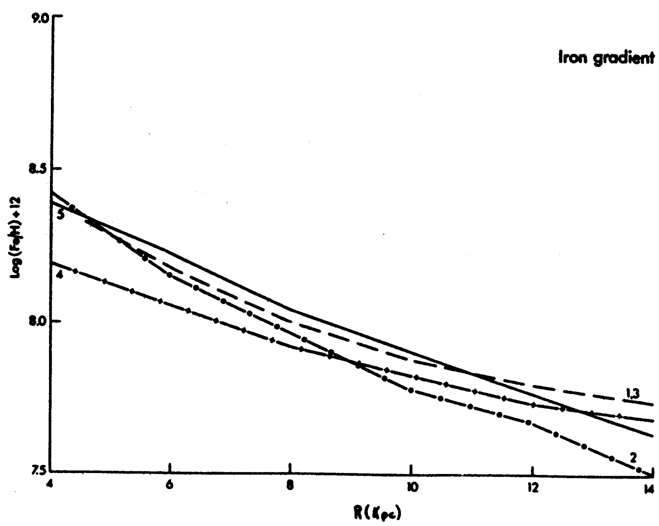

Fig. 8. Galactic gradient of Iron.

and therefore can be rejected. The steep decrease of the surface gas density towards the inner Galaxy predicted by this model, is due to the strong dependence of the star formation rate on the surface gas density. Figure 9 suggests that, as discussed by Lacey and Fall (1985), in the absence of radial inflows the dependence of the star formation rate on the surface gas density should be shallower than σ_g^2.

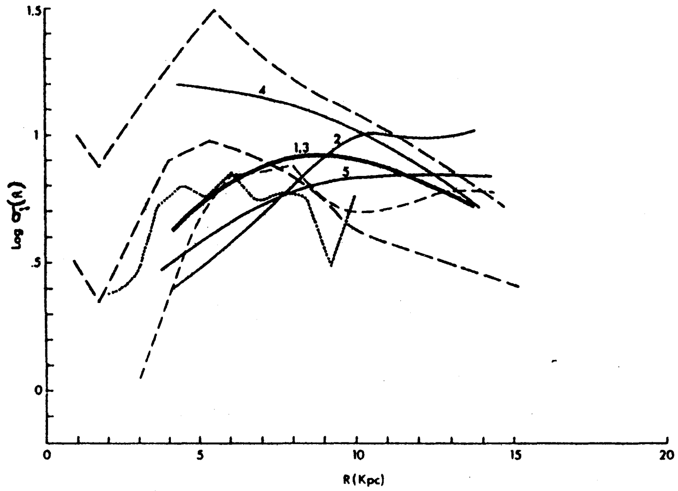

Fig. 9. The present day surface gas mass distribution.

IV. DISCUSSION

A self-consistent treatment of the disk structure and the star formation rate is an important ingredient in evolutionary models of disk galaxies. This approach requires the specification of the processes controlling the physical state of the gas and the star forming activity. As a first step in this direction, here we have used the feedback between gas and stars described by Franco and Shore (1984) to derive the chemical properties of the Galaxy in the isothermal disk case. This feedback results in a star formation rate that depends on both σ_{tot} and σ_g. The exponent on the gas density is 59/40 and no parameters were adjusted to achieve the properties of the solar neighborhood and the radial gradients.

The results are in fair agreement with the available data, and we have also compared them with the set of models recently discussed by Matteucci and François (1989). These other models were performed with the star formation rate described in Section 3, which has three free parameters selected to match the observational results. The best model of this set, model 1, has a star formation rate with an exponent $k_2 = 1.1$ and seems to reproduce better the trends observed in the present day gas distribution (see Fig. 9). However, the galactic evolution model presented here could be too simple and perhaps small amounts of radially inflowing gas could be required. A more refined model, including radial inflows, will be presented in a future communication.

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