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NUMERICAL MODELS

MODELS FOR THE EVOLUTION OF THE MWG

- The numerical models solve directly the equations systems: all useful inputs may be included.
- There is a large number of models with different hypotheses about the ingredients, IMF, SFR, stellar yields, or scenario.

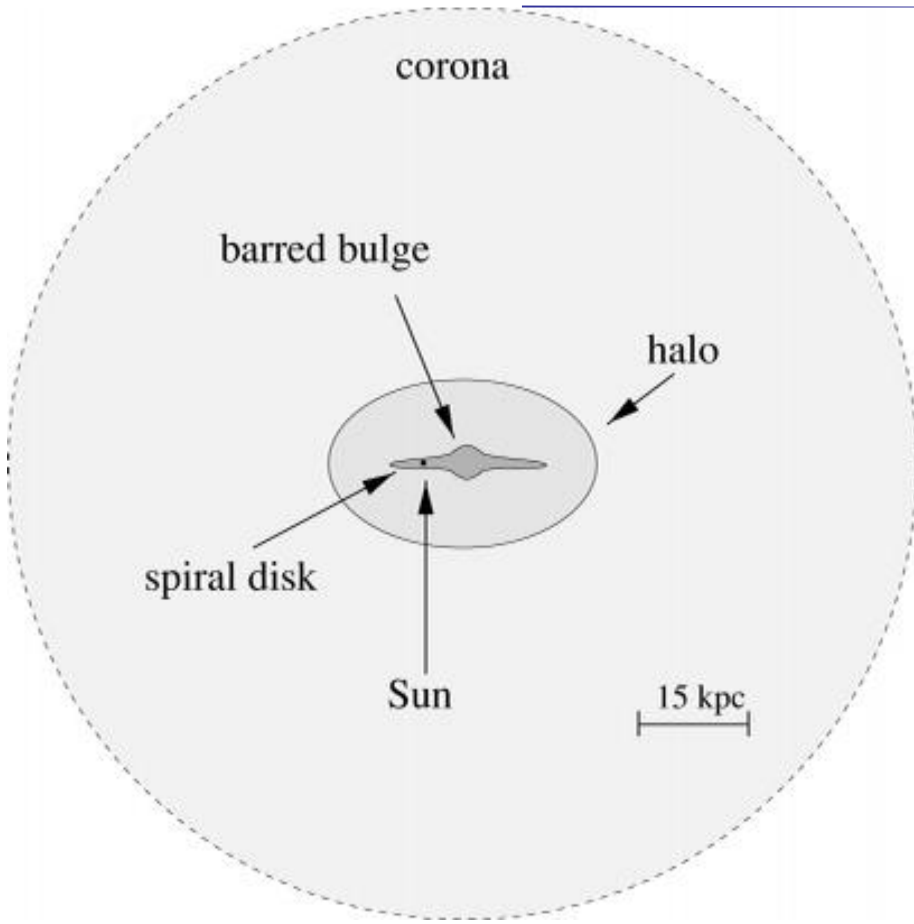
Early numerical chemical evolution models

- Algunos de estos modelos son la base de los siguientes:
  - Lacey & Fall (1983, 1985):
    - Disc-halo connection
    - Radial dependendent infall
  - Wyse & Silk (1989)
    - Star formation rate depending on galaxy total mass
    - Star formation rate dependent on galactic radius
  - Matteucci (1989)
    - Disc-halo connection
    - Radial dependendent infall
    - Star formation rate depending on galactic radius and galaxy total mass Dependencia de la SFR con el radio y con la masa total
  - Díaz & Tosi (1984, 1985)
    - Multizonal modelo
    - Star formation rate depending exponentially decrasing with time
    - Gas infall rate constant over the disc (decreasing with galaxy radius)

The chemical evolution of The Galaxy

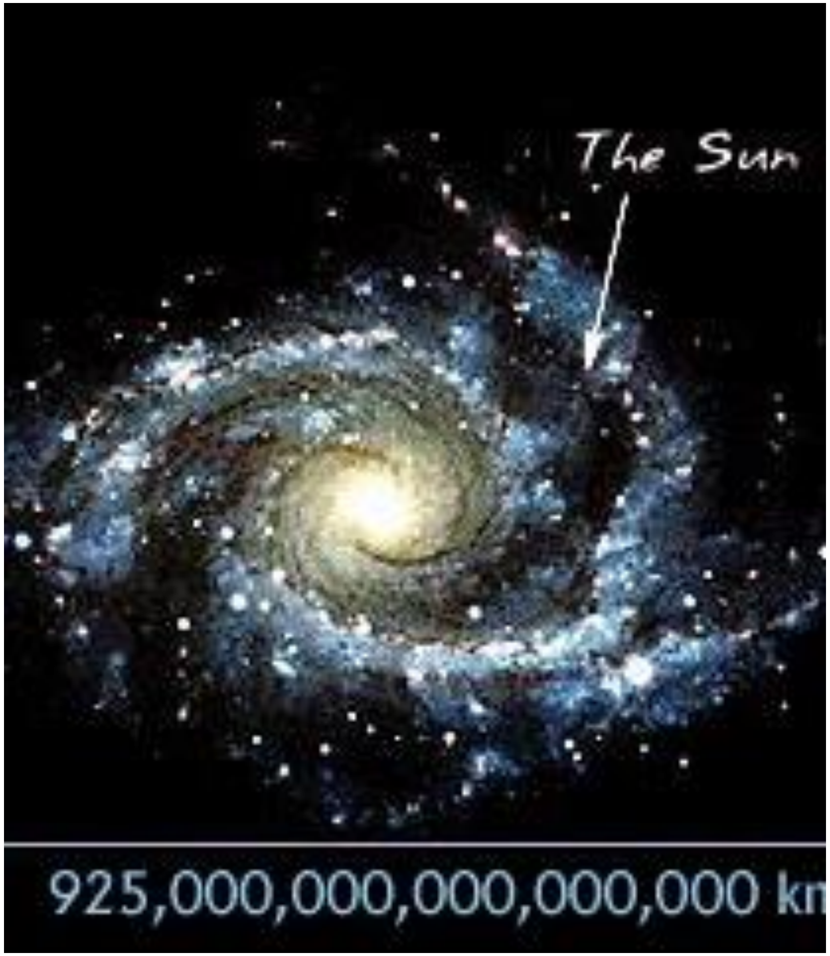
- Halo and corona (up to ~ 100 kpc)
- The thick disc (1 kpc)
- The thin disc (300 pc)
- The spiral arms (density waves)
- Substructures
  - Open clusters and OB associations (~1500 known)
  - Globular clusters (~ 170 known)
  - Dwarf galaxy remnants (Saggitarius ?)
  - Gaseous structures: diffuse gas, molecular clouds, gaseous shells, etc …

Structure components of The Galaxy



The formation of The Galaxy

- Eggen, Lynden-Bell & Sandage (1962) proposed a rapid collapse in about n x 10^8 yr.
- Searle & Zinn (1978) proposed a central collapse while the external halo would have formed by accretion of small neigbouring systems.



Different approaches to modelling The Galaxy

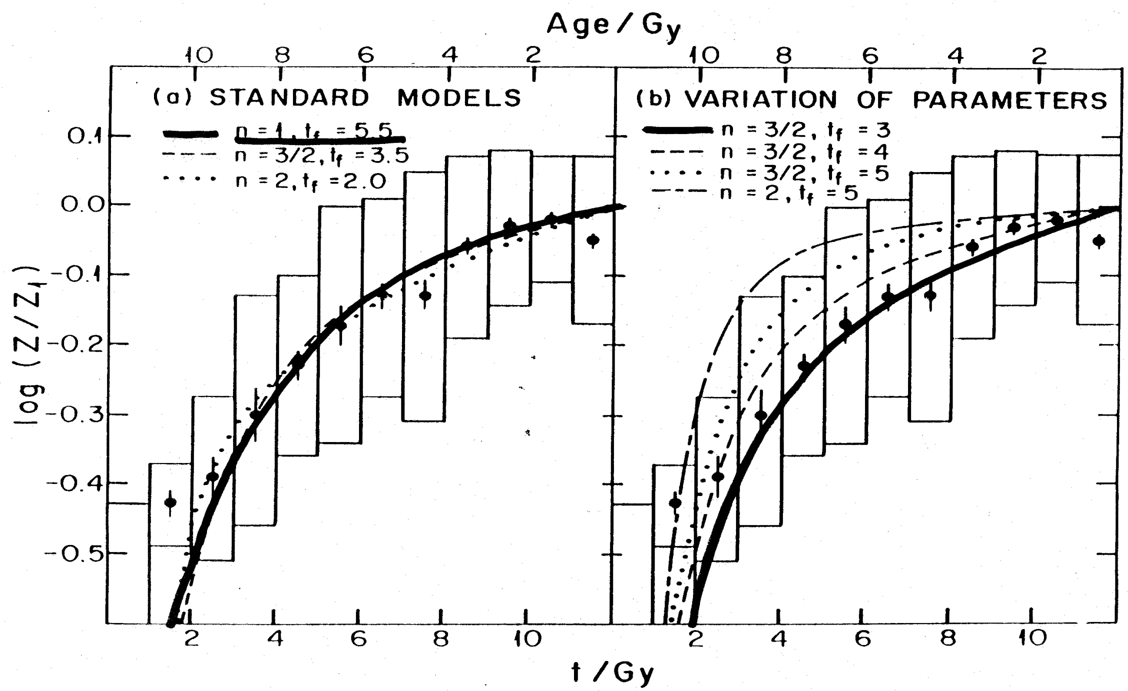
- ***Serial sequence:*** halo and disc (thick and thin) are formed in a continuous sequence (Lacey & Fall 1985; Matteucci & Francois 1989).
- ***Parallel Sequence:*** the different components of the Galaxy evolve at different rates but are interconnected (Ferrini et al. 1994; Pardi, Ferrini & Matteucci 1995).
- ***Different formations of disc and halo:*** they would form in two different infall episdodes (e.g. Chiappini, Matteucci & Gratton 1997; Alibes, Labay & Canal 2001).
- ***Stochastic processes:*** mixing would not be efficient, especially at the beginning of halo evolution (e.g. Tsujimoto et al. 1999; Argast et al. 2000; Oey 2000).

Gas infall depending on galactrocentric radius

- Halo-disc connection with t constant with R
- Infall depending on R
- SFR proportional a Σ_g^n with n =1 o n =1.5

$$f(r,t) = m_0 e^{-ar} F(t)$$

$$F(t) = \frac{e^{-t/t_f}}{t_f(1-e^{-T/t_f})}$$



Results for MWG:

1) n =1 , t_f=5.5 Ga, or

2) n=1.5, t_f=3.5 Ga

Lacey & Fall, 1985

Model results

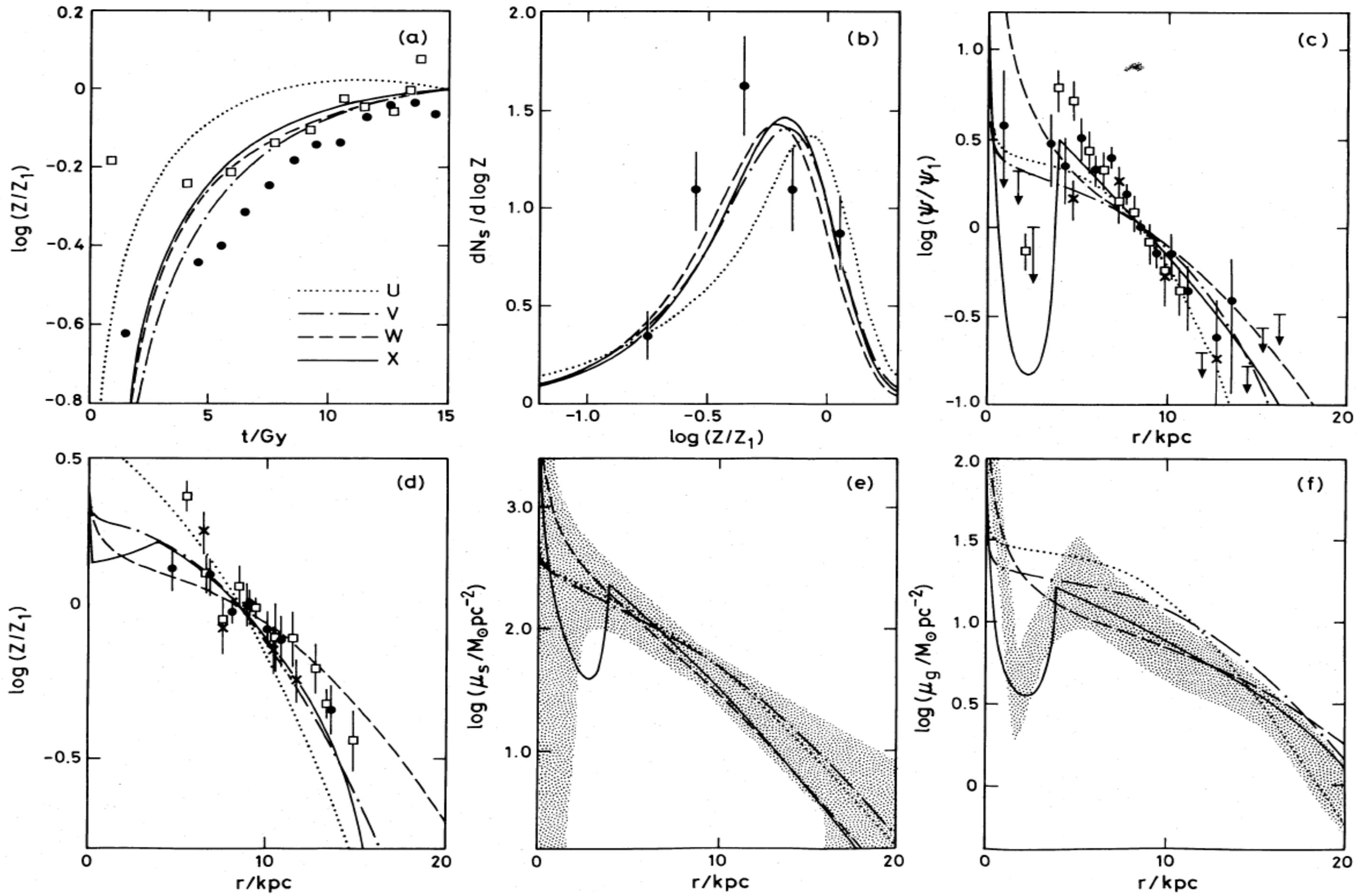


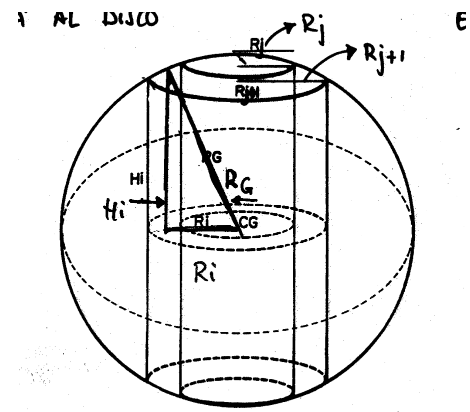
FIG. 8.—Same as Fig. 3, but for models U, V, W, X

The multi-phase chemical evolution mode MULCHEM *Ferrini, Mollá, Pardi & Díaz 1995*

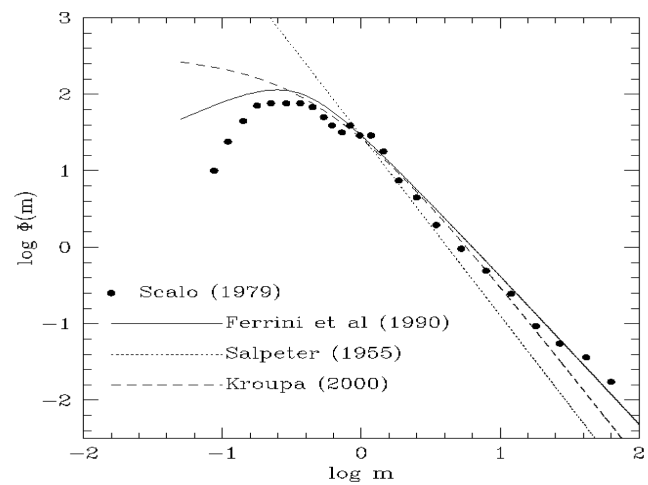
- Disc-halo connection: gas infall from the halo forms the disc as a secondary structure.
- Different matter phases are treted separately:
  - Diffuse gas
  - Moldecular gas
  - Massive stars
  - Low mass stars
  - Stellar remnants
- Exchange of matter among different phases according to diverse conversion processes.
  - Diffuse gas forms molecular clouds
  - Molecular clouds form stars by collisions
  - Massive stars interact with surrounding molecular clouds
  - Gast return to the ISM by the different processes above

MULCHEM modelling

- The Galaxy is modelled as concentrical cylindres
- The IMF is determined from the molecular cloud fragmentation:



$$F(m) = 2.01 m^{-0.52} 10^{\left(2.01+\left(\log m\right)^{2}+1.92 \log m+0.73\right)^{1/2}}$$



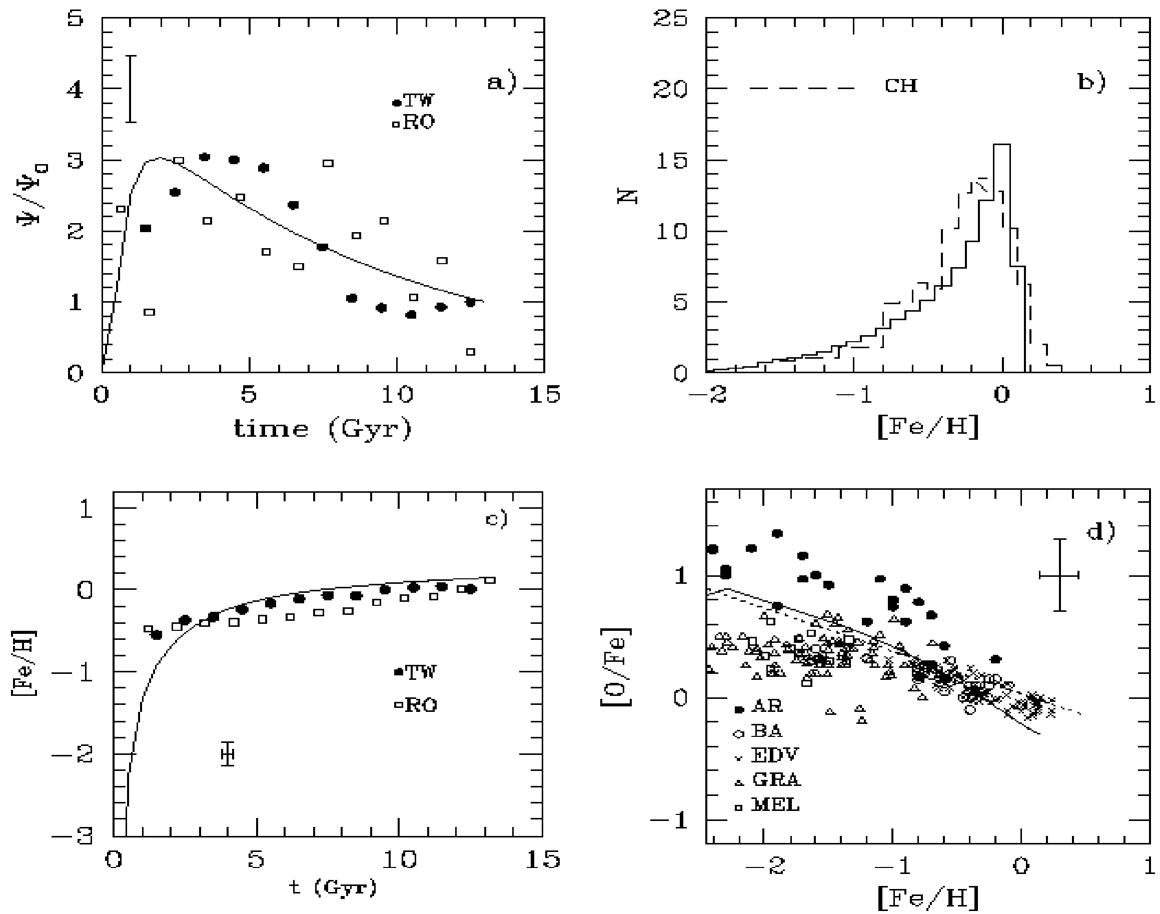
MULCHEM ingredients

- SFR
  - in two steps for the disc
  - a Schmidt Law for the halo
- Nucleosynthesis:
  1) Massive stars → Woosley & Weaver (1995)
  2) Low and intermediate mass stars → Renzini & Voli (1981)
  3) Type I SNe →Nomoto, Thielemann & Yokoi (1984)

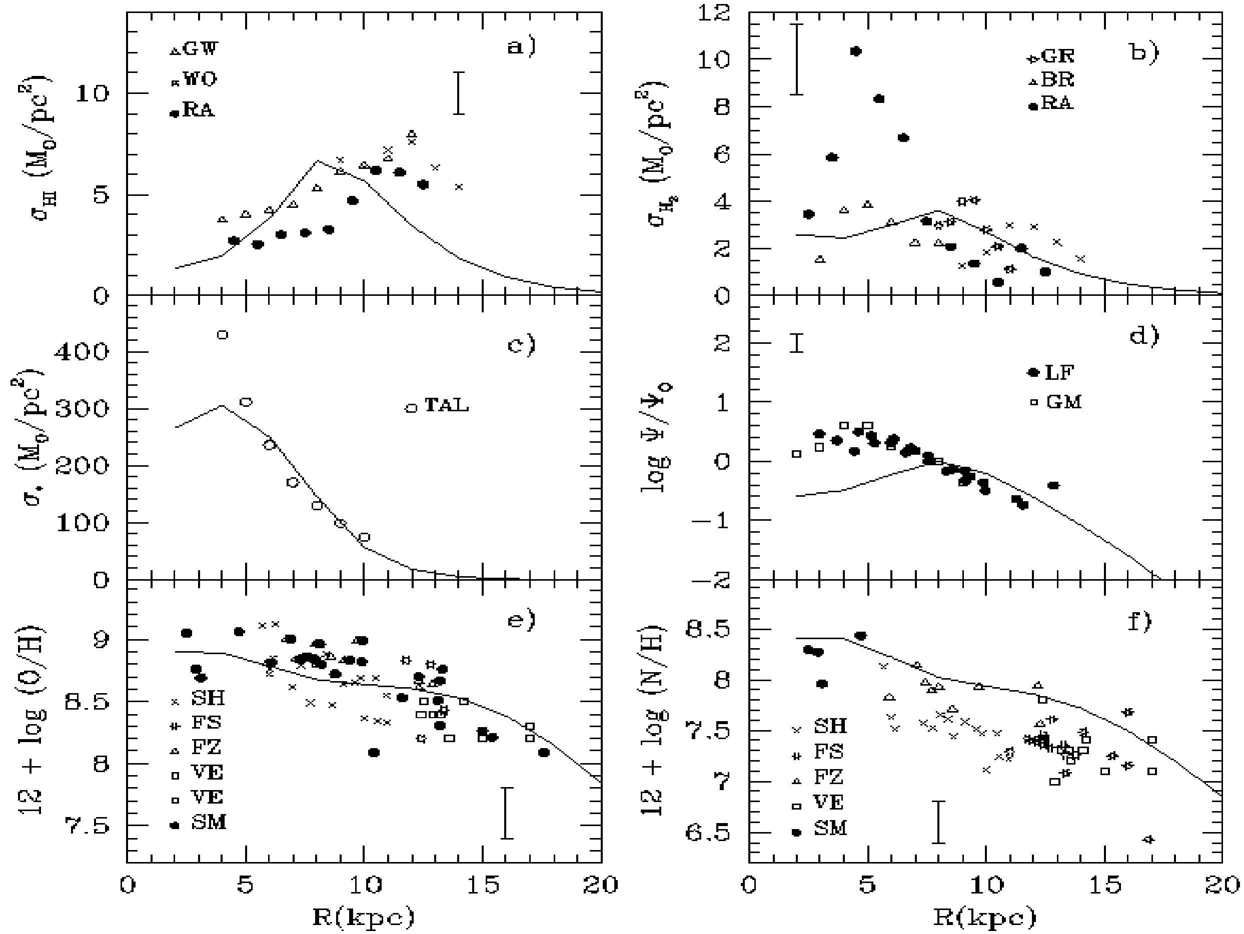
$$\Psi_D(t) = (H_1 + H_2) c_D{}^2(t) + (a_1 + a_2) S_{2,D}(t) c_D(t)$$

$$\Psi_H(t) = (K_1 + K_2) g_H{}^n(t)$$

Results for the Solar Neigbourhood



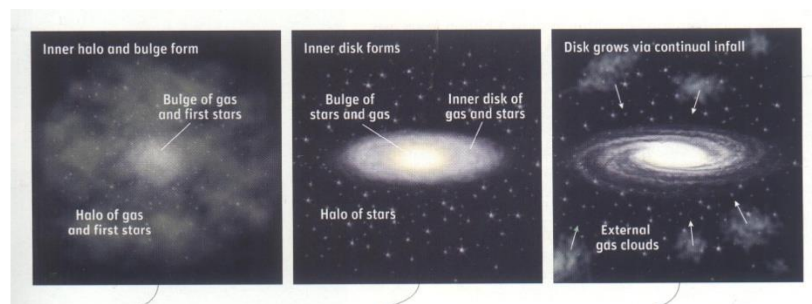
Results for the MWG



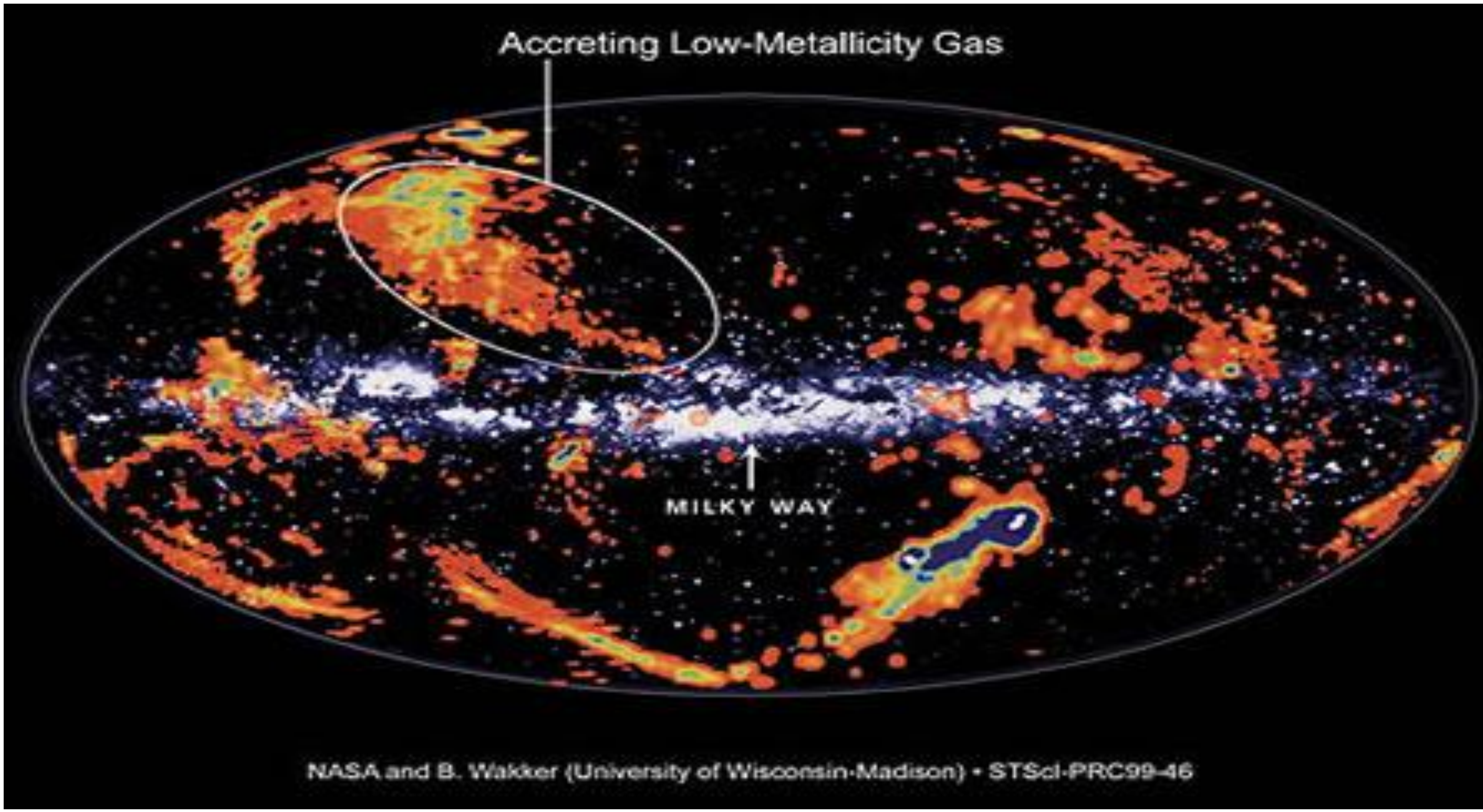
The two-infall model for The Galaxy

Chiappini, Matteucci & Gratton 1997

- This model proposes two main gas accretion episodes in the formation of The Galaxy.
- During the first one, halo and bulge would form. The second would give rise to the disc.
- In fact, the original model tried to reproduce the evolution of the two components of the disc: thin and thick.



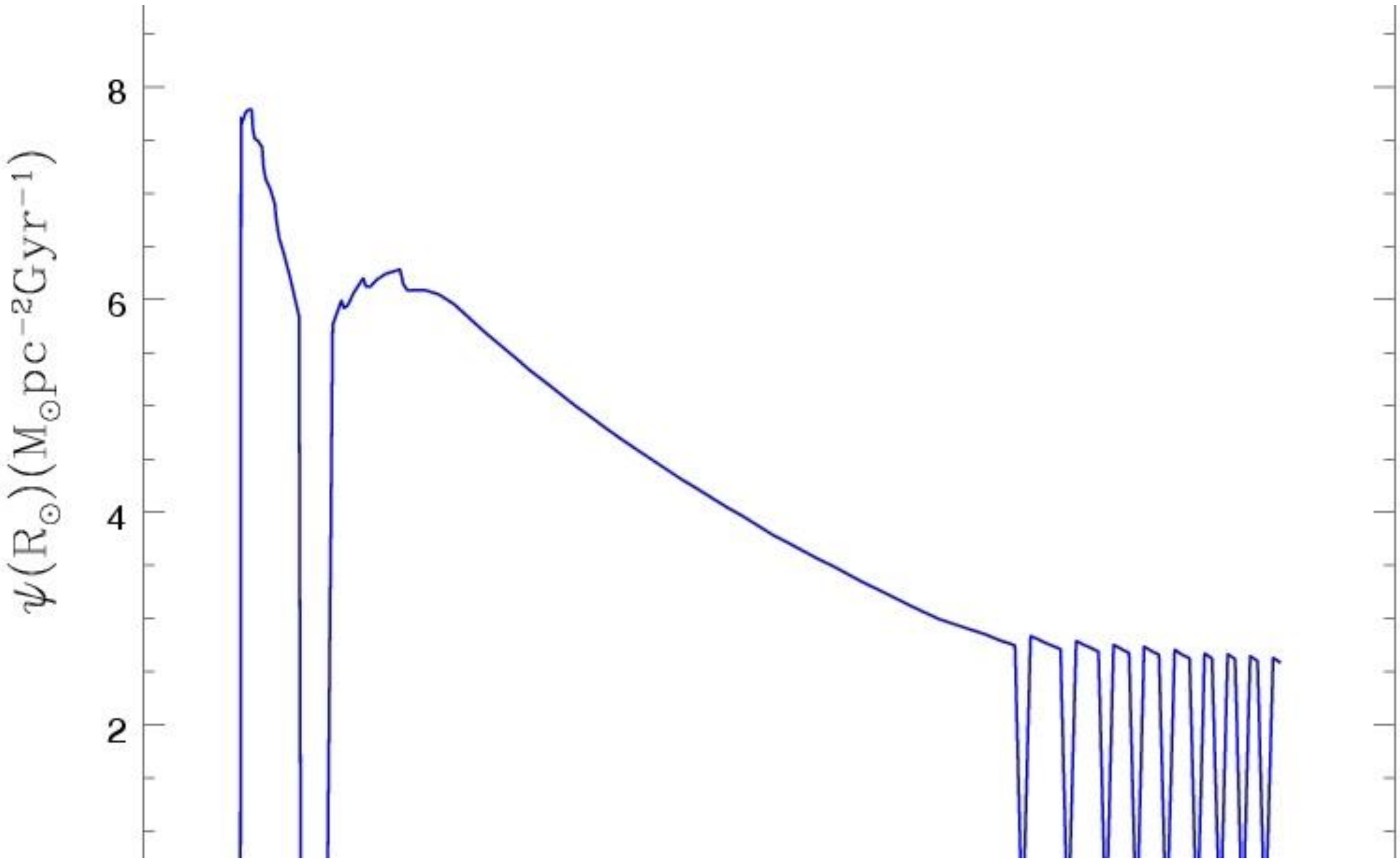
Gas accretion onto the MWG at present



Characteristics of the two-infall model

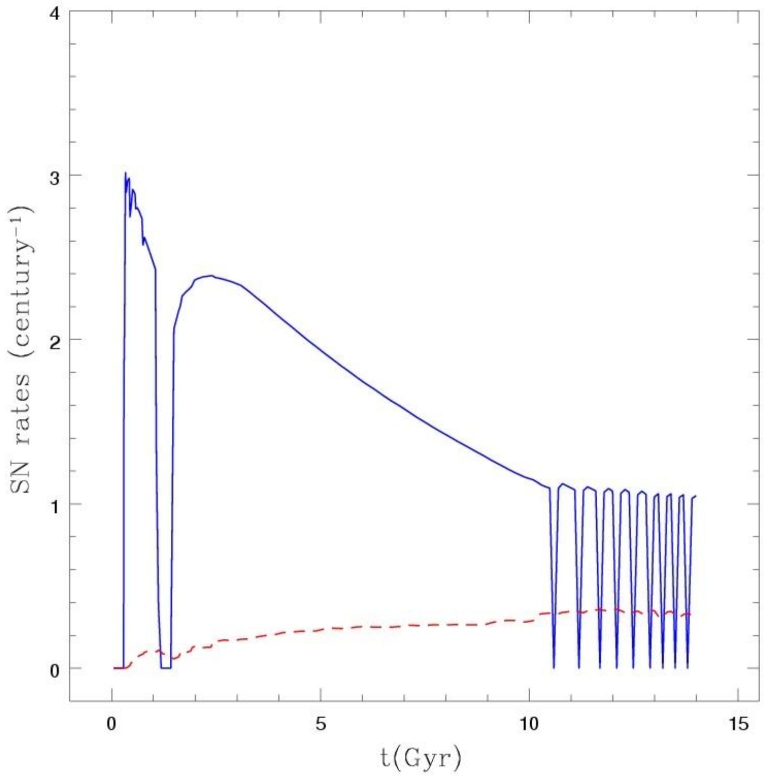
- The SFR follows a Kennicutt-Schmidt Law with k=1.5, plus a dependence on total mass surface density. There is a threshold for star formation of 7 $M_{\odot}$ pc^{-2}.
- IMF from Scalo (1986) normalised over a range 0.1-100 $M_{\odot}$
- Exponentially decreasing infall with different time-scales for the inner halo (1-2 Gyr) and the disc (inside-out formation with 7 Gyr in the Solar Neighbourhood).
- Type Ia SN (WD+RG or MS) (Greggio & Renzini 1983; Matteucci & Recchi 2001).
- Minimum time for explosion of 35 Myr (life-time of 8 $M_{\odot}$ stars).
- Return time for most of the Fe in the SN of 1Gyr depending on SFR.

SFR threshold effects



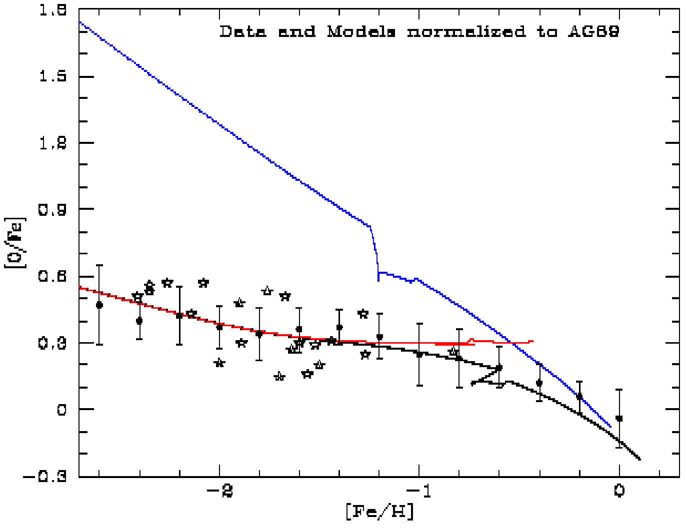
Predicted SN rate

- Type II SN (in blue) follow the SFR
- Type Ia (in red) increase gradually with a small maximum at 1Gyr.



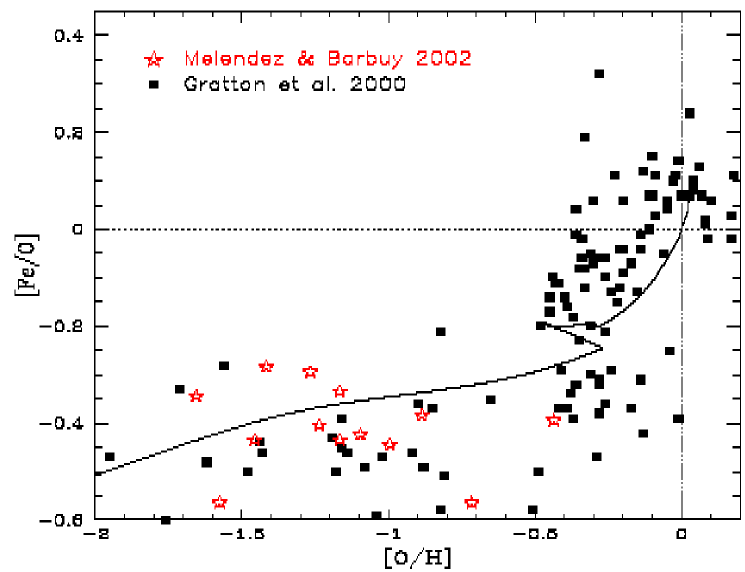
Delay effects

- Blue line : only SN II produce Fe.
- Red line: only sólo SN Ia produce Fe.
- Black line : SN II produce 1/3 of Fe and SN produce 2/3 of Fe.

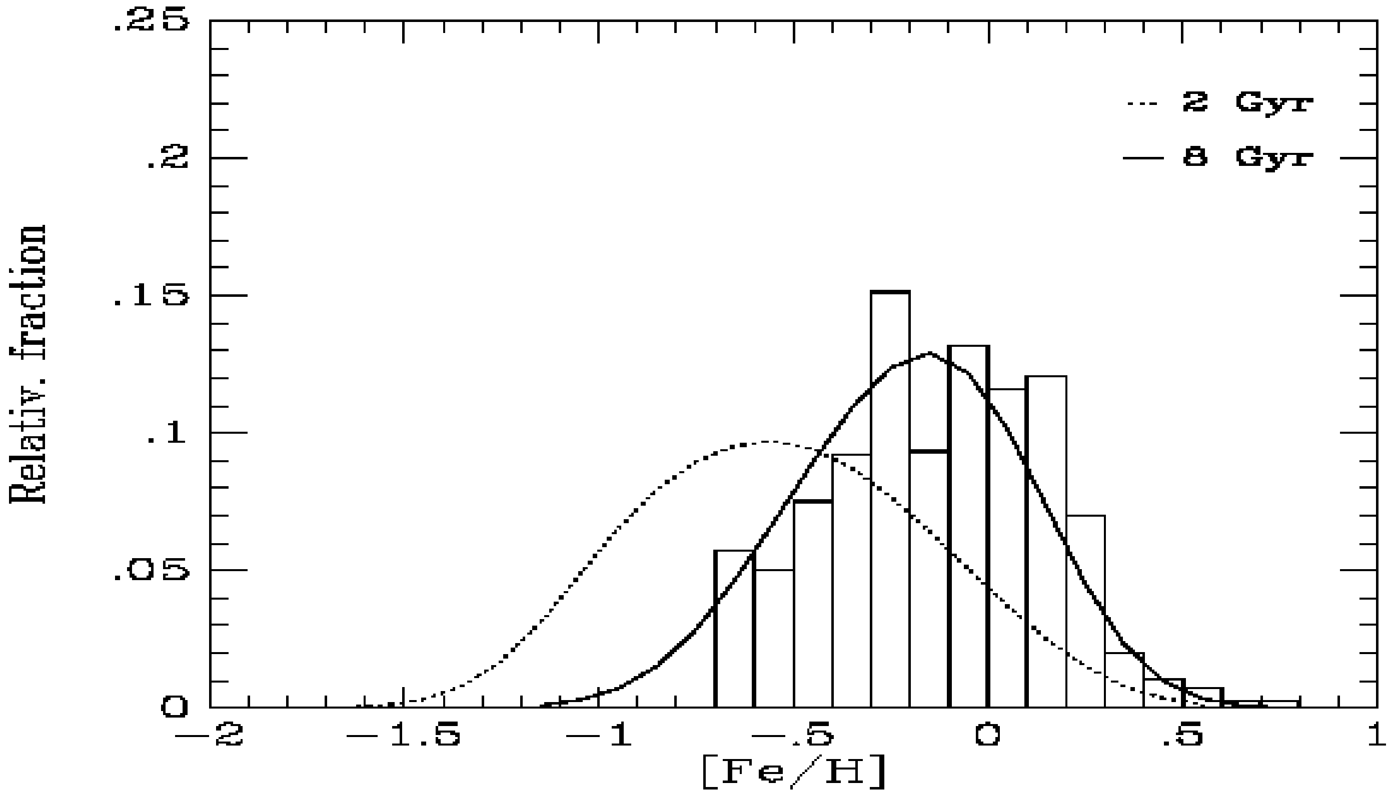


Specific predictions by the two-infall model

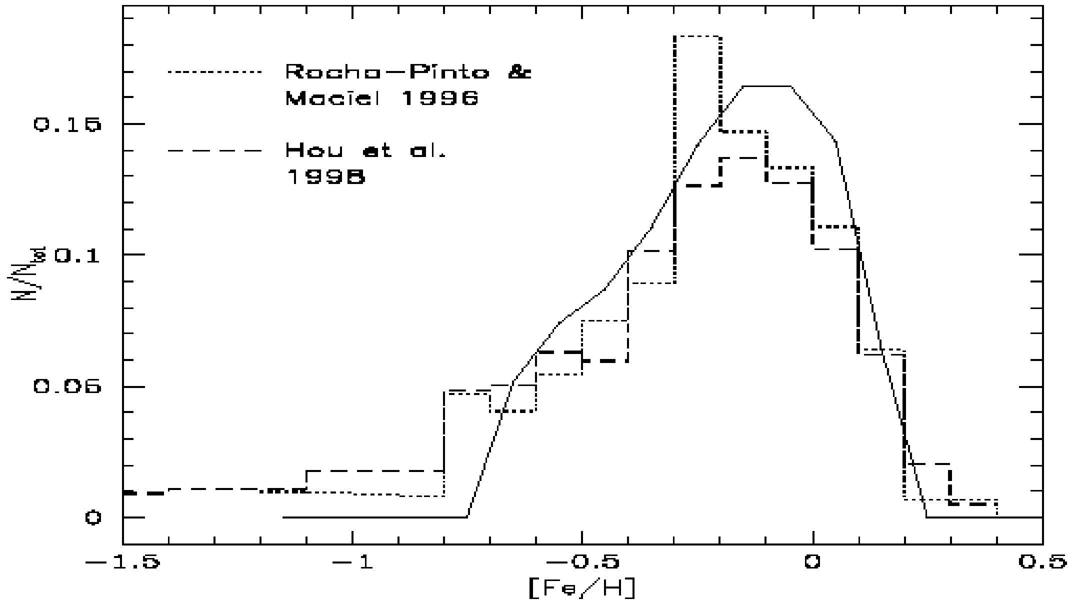
- Adopting a gas density threshold for the for SF to proceed creates gaps in the SFR
- These gaps take place between the formation of the halo and thick disc and the thin disc.



Different time scales for the disc formation



G-dwarf Distribution

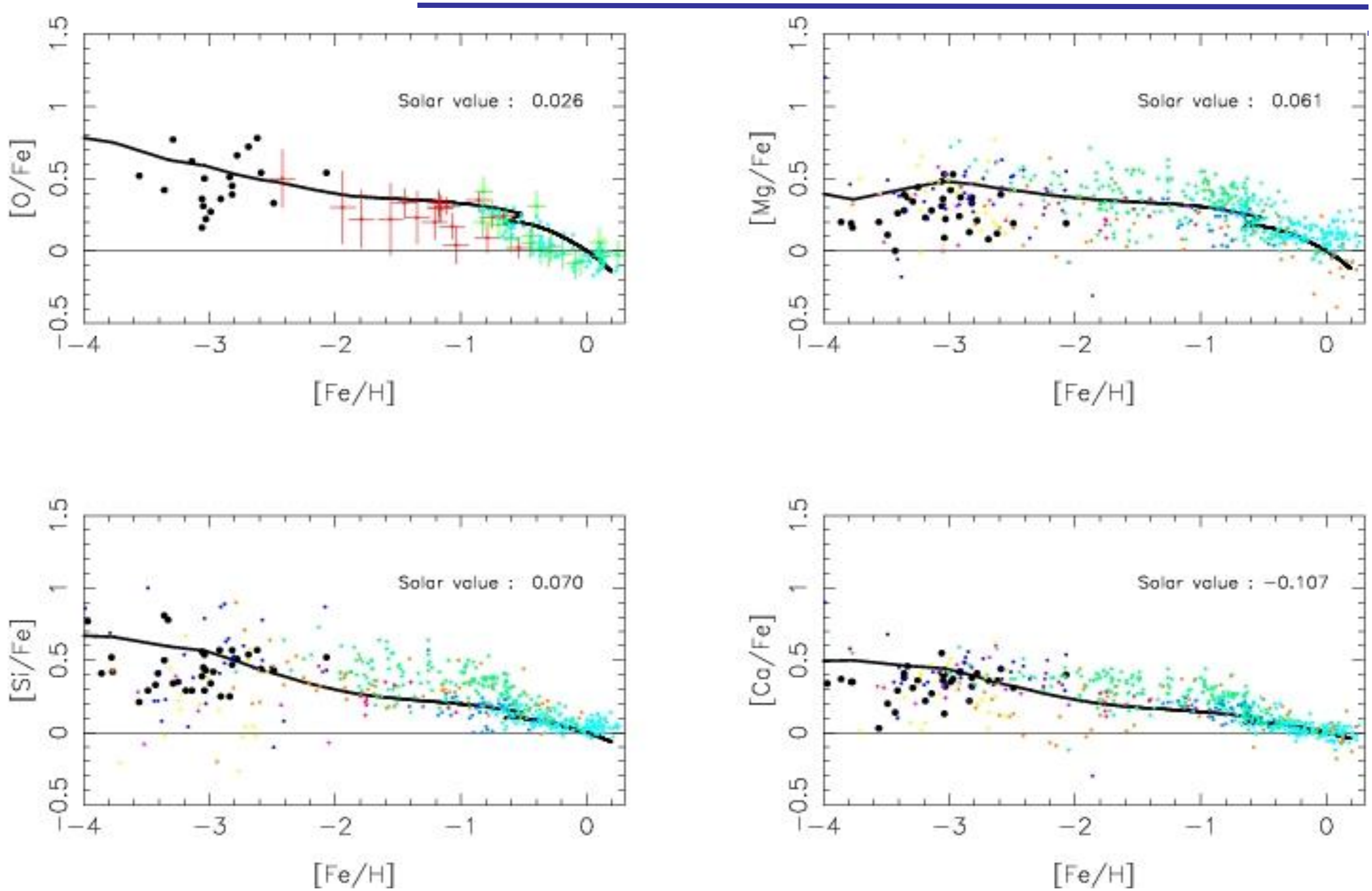


- Chiappini et al. (1997) , Alibes et al. (2001) y Kotoneva et al. (2002) concluded it is possible to obtain a good fit to the G-dwarf metallicity distribution only with a time scale of 7-8 Myr at the solar galactocentric radius.

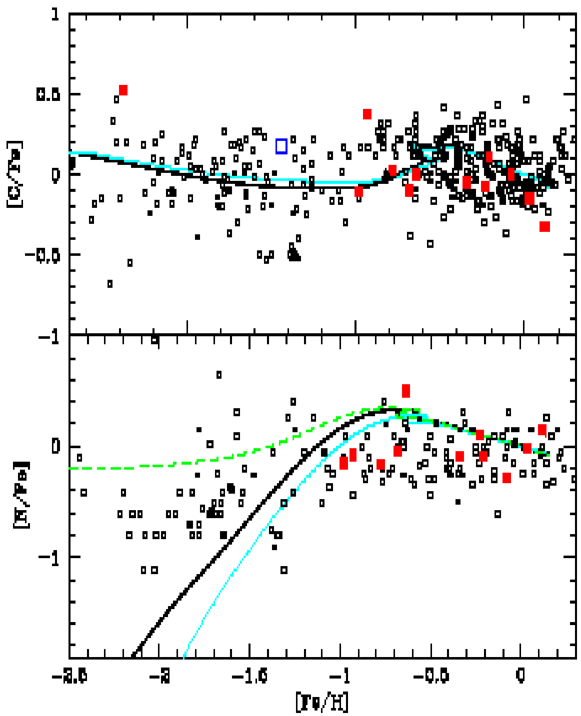
The evolution of chemical abundances

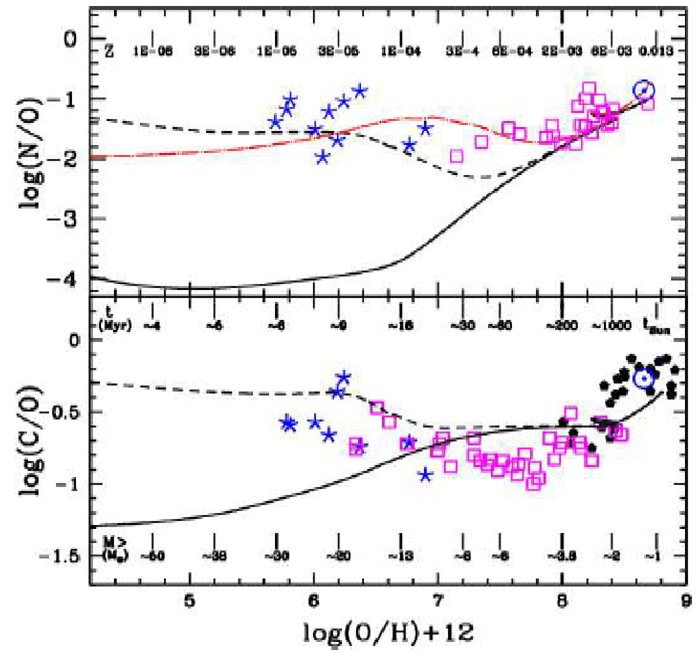
- In this model the space and time evolution of 35 chemical elements is calculated: H, D, He, Li, C, N, O, Ne, Mg, Si, S, Ca, Ti, K, Fe, Mn, Cr, Ni, Co, Sc, Zn, Cu, Ba, Eu, Y, La, Sr plus other isotopes (Francois, et al 2004).
- This implies the resolution of a system of 35 equations where SFR, IMF, nucleosynthesis and gas accretion are taken into account.
- The yields are those of : WW95 (massive stars), van den Hoeck & Groenewegen 1997, (low and intermediate mass stars) and Iwamoto et al. 1999, for type Ia SN.

Relative abundance relations



C and N evolution w.r.t. Fe

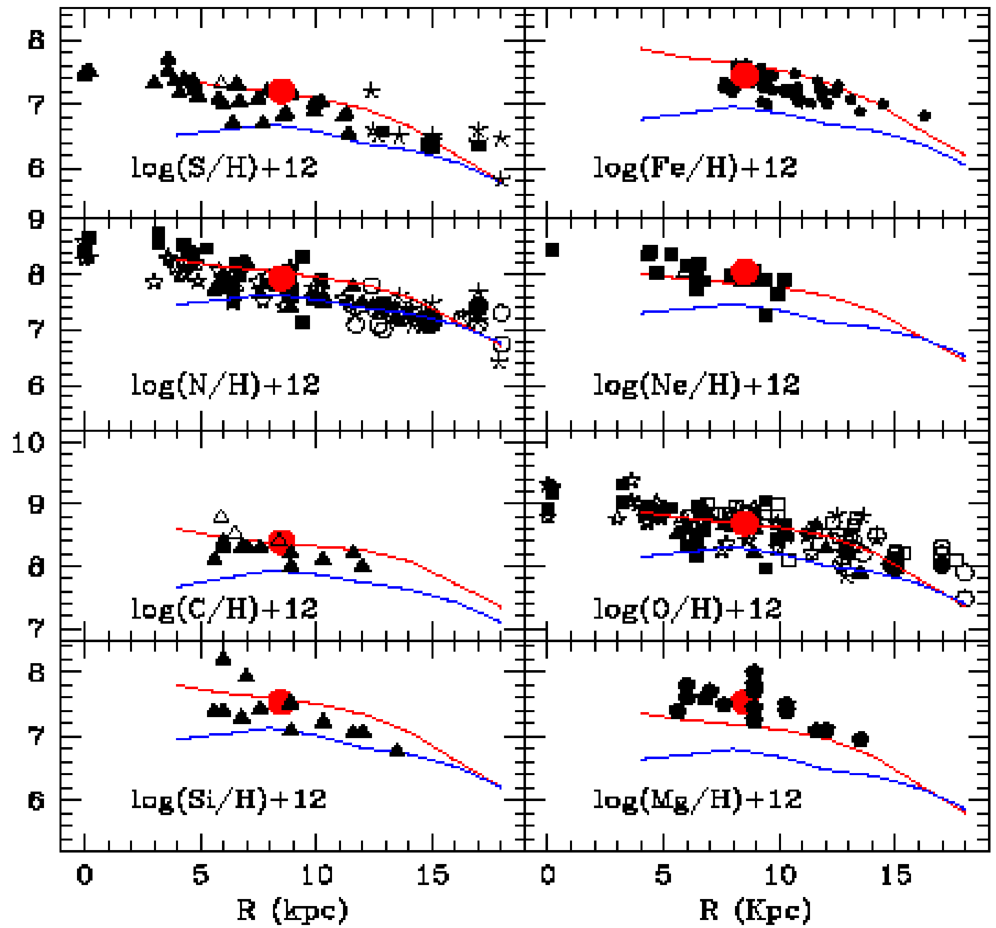




Models by Chiappini et al. 1997. The green line is a heuristic model in which all N is of primary origin.

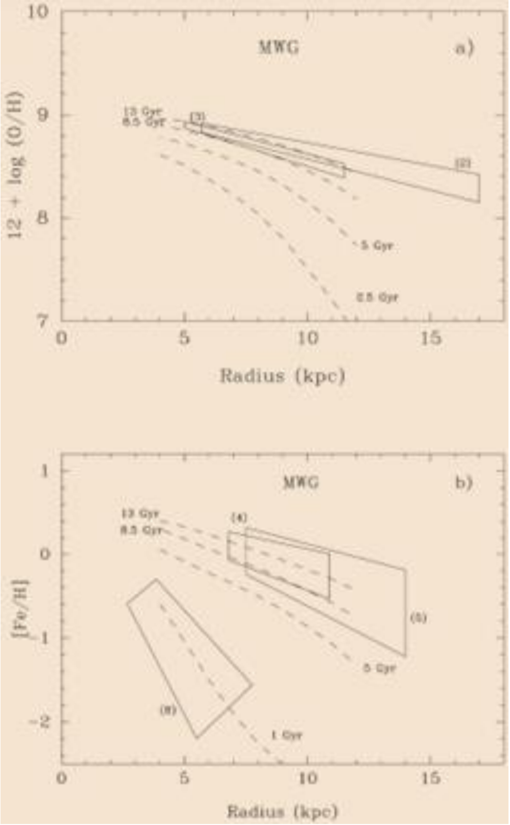
Dotted lines correspond to models by Chiappini et al. 2006 in which massive stars with rotation produce substantial amounts of N at low metallicities.

Abundance gradients



A characteristic of these models is that gradients steepen with time (from blue to red)

Time evolution of gradients in the multi-phase model



In multi-phase models the gradients get flatter with time, which is more compatible with observations.

Time evolution of gradients

The presence and the time evolution of radial abundance gradients may offer criteria to distinguish among chemical evolution models. Now, in the literature, there is a very large number of them; we suggest that it would be more interesting to study chemodynamical evolutionary models, rather than chemical evolution ones. Paraphrasing Larson (1976), it is important to investigate the factors that determine the SFR and the initial mass function, more than run a large amount of parametric models aimed at fitting observations. Perhaps this effort will help us make progress in the understanding of galactic evolution.

The time evolution of abundance gradients

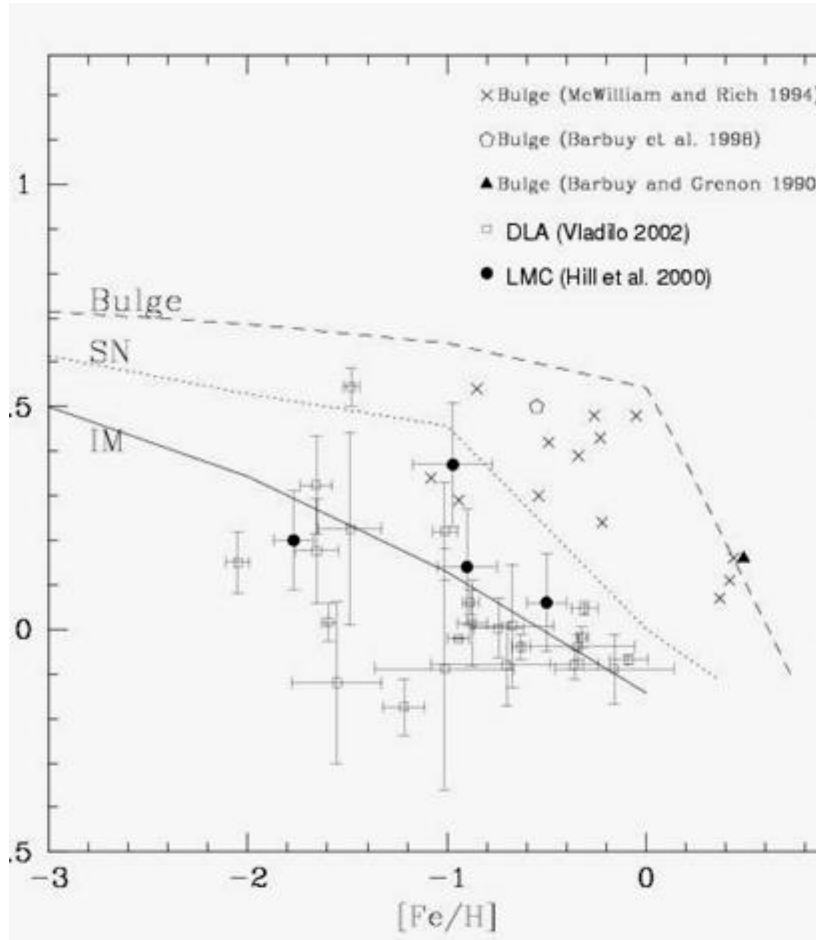
- The time evolution of abundance gradients has been studied in several works, and different predictions have been producedby different authors using chemical evolution models.
- Some authors predicted that the gradient steepens with time (Chiappini et al. 2001; Mott et al. 2013), whereas others suggested that the gradient flattens in time (Prantzos & Boissier 2000; Mollá and Díaz 2005; Vincenzo & Kobayashi 2018).
- The discrepancy between different model predictions is due to the fact that chemical evolution is very sensitive to the prescriptions of the physical processes that lead to the differential enrichment of inner and outer discs, hence and the flattening or steepening of gradients with time depends on the interplay between infall rate, SFR along the disc, and the presence of a threshold in the gas density for star formation.

The time evolution of abundance gradients

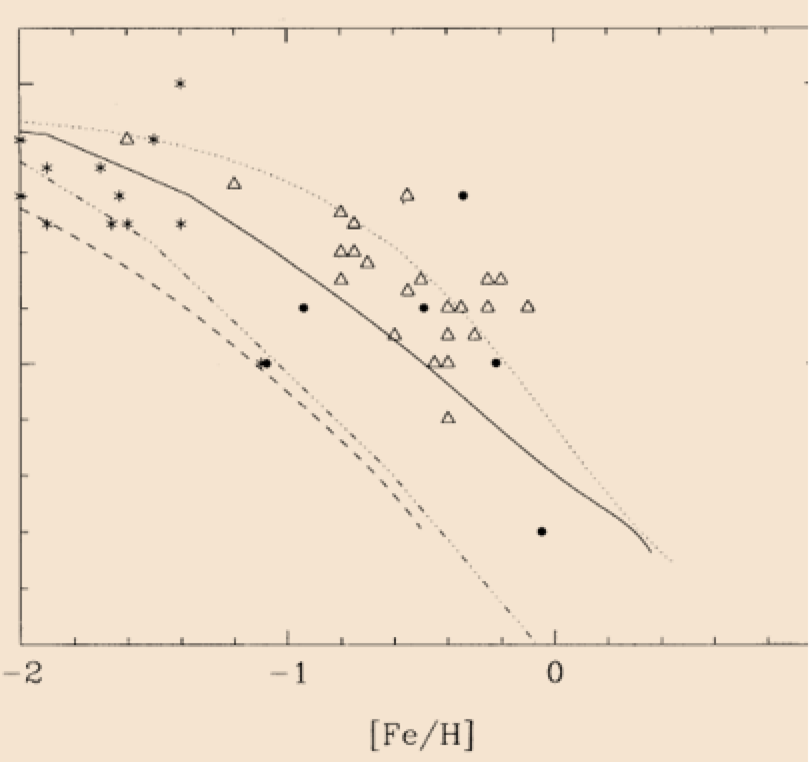
- It seems that the inside-out scenario is a key ingredient for the formation of Galactic discs but cannot constitute the only mechanism to explain abundance patterns at different galactocentric distances and **abundance gradients**.
- Other possible effects can be:
  - a variable star formation efficiency combined with radial gas flows
  - radial migration could have an effect, although this may not be very important in the case of the Milky Way.
  - different recipes for the star formation process or gas accretion mechanisms can provide very different predictions for the abundance gradients,

The formation of the galactic bulge

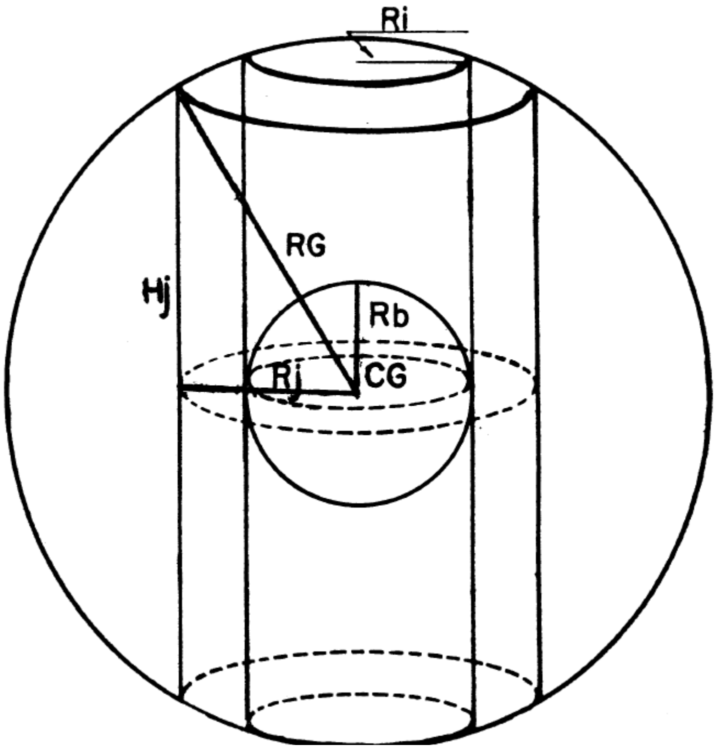
- Accretion of other minor systems formed earlier that finally will emerge in the galactic centre.
- Accumulation of the gas coming from the halo (or the disc) in the galactic centres, with its subsequent evolution.
- The first model for the chemical evolution of the bulge was made by Matteucci & Brocato (1990). It postulates a rapid formation (<1 Ga) from the gas coming from the halo that evolves rapidly with a high star formation efficiency.



The bulge evolution in the multi-phase model



8.—[O/Fe] vs. [Fe/H] for bulge (*solid line*), solar neighborh
line), halo (*long-dashed line*), and elliptical (*dot-dashed line*). Data
cWilliam & Rich (1994) (*filled circles*) for the bulge, from Barbuy (19
s) for the halo, and from Barbuy & Erdelyi-Mendes (1989) (*triang*
lisk.



Evolution of the gas content

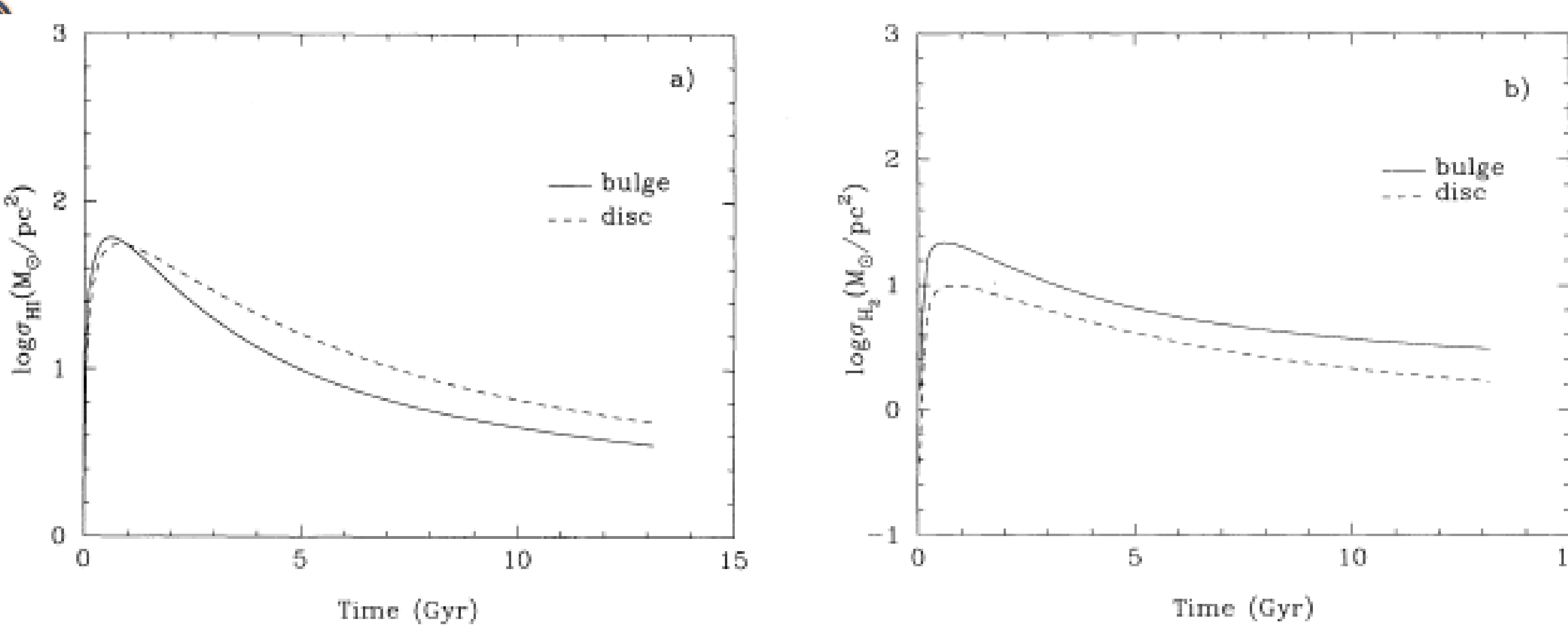


FIG. 2.—Time evolution of surface density for (*a*) diffuse gas and (*b*) molecular clouds

The stellar metallicity distribution

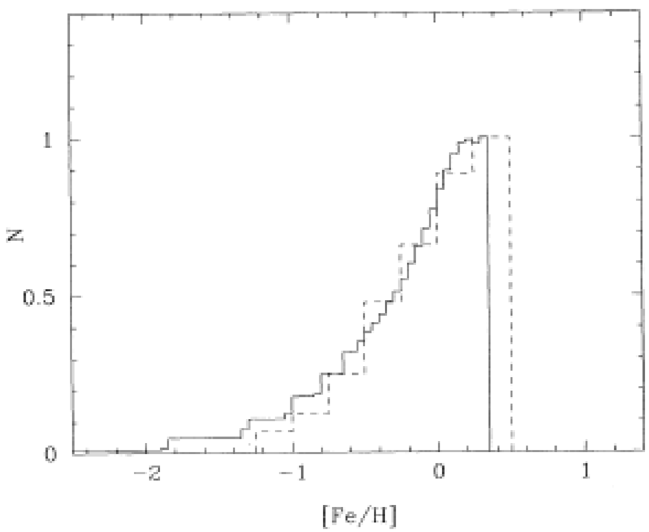


FIG. 6.—Cumulative K giant metallicity distribution compared with observations by McWilliam & Rich (1994) (*dashed line*).

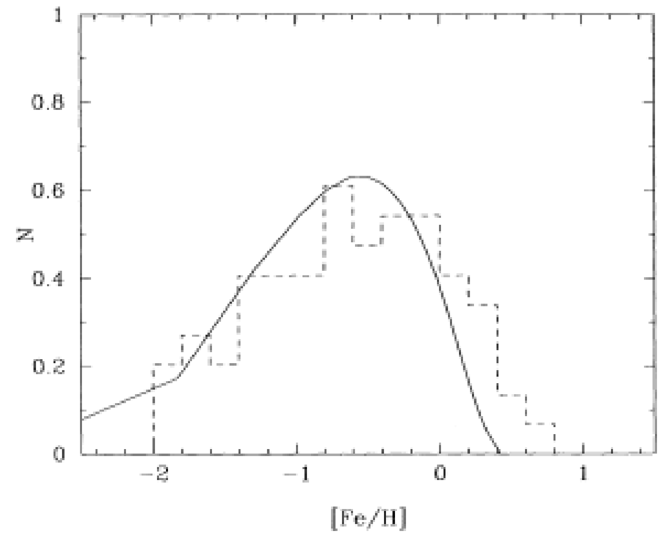


FIG. 7.—Metallicity distribution of K giants of the model compared with that obtained from Minniti (1994) for the M22 field.

Conclusions about the chemical evolution of The Galaxy

- The best models for the galactic bulge suggest this is rather old and was formed in a short time scale, with a high star formation efficiency
- The SN G-dwarf metallicity distribution can be reproduced only if the disc has formed by a process of slow accretion infall. The time scale for the formation of the disc in the SN is between 6 and 8 Ga.
- The relative abundances [X/Fe] vs [Fe/H] can be interpreted in the light of the delay existing between the appearance of SN II y SN Ia. These relations suggest a time scale for the thick disc formation between 1.5 and 2.0 Ga.
- The reproduction of the SFR, gas distributions and abundance gradients implies the inside-out formation of the disc, with a SF efficiency that reaches its maximum earlier in the inner disc zones and moves throughout the disc with time.