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# THE MILKY WAY AND THE EVOLUTION OF DISK GALAXIES

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RESUMEN

Presentamos un enfoque fenomenológico al estudio de la evolución de discos galácticos basado en (i) un modelo detallado de la Vía Láctea (que se usa como prototipo de las galaxias de disco), y (ii) la extensión del modelo a otros discos mediante relaciones de escala sencillas, obtenidas dentro del marco de los modelos de materia oscura fría. La conclusión principal es que, en promedio, los discos masivos han formado la mayor parte de sus estrellas antes que sus contrapartes menos masivas. La razón por la cual la "jerarquía de la formación estelar" ocurre a la inversa que el "ensamblaje de la materia oscura" aún no queda clara.

ABSTRACT

We present a phenomenological approach to the study of disk galaxy evolution, based on i) a detailed modelling of the Milky Way (used as a prototype disk galaxy) and ii) an extension of the model to other disks through some simple scaling relations, obtained in the framework of Cold Dark matter models. The main conclusion is that, on average, massive disks have formed the bulk of their stars earlier than their lower mass counterparts. It is not yet clear why the "star formation hierarchy" has been apparently opposite to the "dark matter assembly" hierarchy.

*Key Words:* **GALAXIES: EVOLUTION, FORMATION, MILKY WAY, SPIRALS**

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## 1. INTRODUCTION

According to the currently popular scenario for galaxy formation (pioneered by White and Rees 1978) the dark haloes of galaxies form hierarchically by the gravitational clustering of non-dissipative dark matter, while the luminous parts form through a combination of gravitational clustering and dissipative collapse (which may be affected by feedback). The major uncertainty in this scenario concerns the baryonic component, since the physics of star formation and feedback are very poorly understood at present, thus requiring a parametric approach to the problem. Semi-analytic models of galaxy formation help to explore large regions of the relevant parameter space and have produced quite encouraging results (e.g. Cole et al. 2000); still, they have not yet managed to reproduce succesfully some key observed properties of disks (van den Bosch 2002) or ellipticals (Thomas et al. 2002).

Simple (i.e. not dynamical) models of (chemical and/or photometric) galaxy evolution use, in general, fewer free parameters than semi-analytical models. If the number of observables that are successfully reproduced is (much) larger than the number of free parameters, it is reasonable to assume that the galaxian histories produced by such models may indeed match the real ones. In that spirit, we have developed a simple approach to disk galaxy evolution, based on (i) a detailed model of the Milky Way (used as a prototype, Sec. 2) and (ii) an extension to other disks through some simple scaling relations (Sec. 3). The main conclusion (Sec. 4) is that massive disks have formed the bulk of their stars earlier than low mass ones. Whether this "star formation hierarcy" is compatible with the "dark matter assembly" hierarchy remains to be demonstrated.

## 2. A SIMPLE MODEL FOR THE MILKY WAY DISK

Several simple models have been developed in the past few years for the chemical evolution of the Milky Way disk (e.g. Prantzos and Aubert 1995, Chiappini et al. 1997, Boissier and Prantzos 1999, Chang et al. 1999, Portinari and Chiosi 2000). Although they may differ considerably in their ingredients (radial dependence of star formation rate and/or infall rate, inclusion or not of radial inflows, etc.) these models converge in the following points (see e.g. discussion in Tosi 2000): (i) infall (of primordial or low metallicity gas) on a long timescale ($\sim$7 Gyr) is required locally, in order to reproduce the observed G-dwarf metallicity distribution in the solar neighborhood; (ii) strong radial dependence of the star formation rate and/or the infall rate is needed in order to reproduce the observed radial profiles of gas, SFR and metal abundances[1].

[1] In recent cosmological hydro-simulations of galaxy formation Sommer-Larsen et al. (2002) find that gas accretion in regions 8 kpc distant from the centers of Milky Way type spirals takes place on timescales of $\sim$6 Gyr, in reasonable agreement with the requirements of simple models.

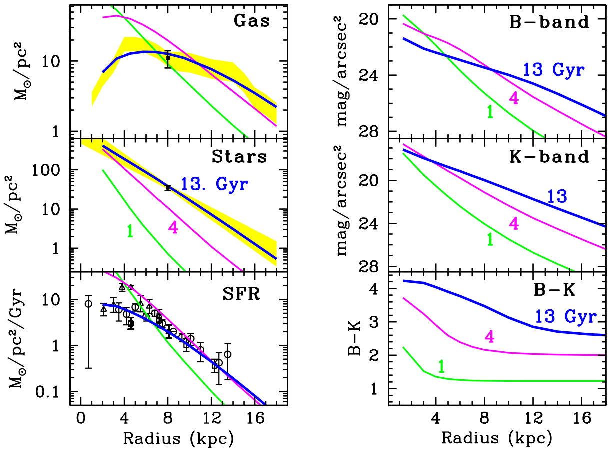


Fig. 1. Chemical (*left*) and photometric (*right*) evolution of the Milky Way disk, according to the model of Boissier and Prantzos (1999). In all panels the solid curves correspond to model results at galactic ages of 1, 4 and 13 Gyr, respectively; the latter (*heavy curves*) are compared to observations of the present day disk (in the left panels: *shaded* regions for the gaseous and stellar profiles and *data points* for the Star Formation Rate). The model leads naturally to different scalelengths for the B-band (4 kpc) and the K-band (2.6 kpc), in agreement with observations.

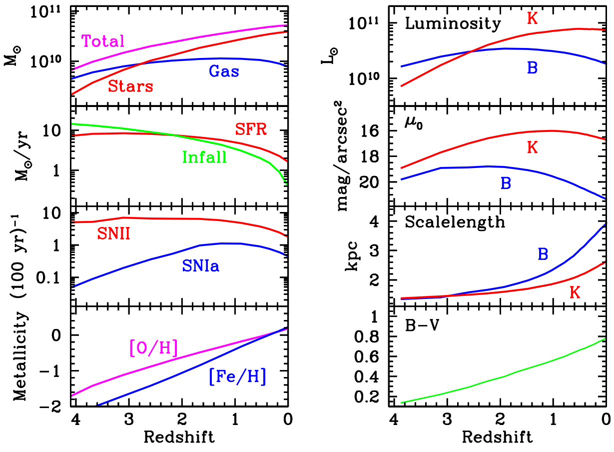


Fig. 2. Results of the Milky Way disk model of Boissier and Prantzos (1999) plotted as a function of the redshift (for a Universe with $\Omega_M$=0.30, $\Omega_\Lambda$=0.70 and $H_0$=65 km/s/Mpc). The model suggests that such disks are fainter in the K-band in the past, but slightly brighter in the B-band at intermediate redshifts; they are also more compact in the past, especially in the B-band.

Fig. 1 displays the results of a simple model, (from Boissier and Prantzos 1999) which also reproduces all the main observables in the solar neighborhood. The adopted SFR as a function of radius $R$ is of the form

$$\Psi(R) \;=\; A\ V(R)\ R^{-1}\ \Sigma_G^{1.5}(R) \qquad (1)$$

where $V(R)$ is the rotational velocity at $R$ and $\Sigma_G$ the gas surface density; this SFR is based on the assumption that large scale star formation in spirals is induced by the passage of the spiral waves (Wyse and Silk 1989).

The model reproduces satisfactorily the observed chemical and photometric radial profiles of the MW disk (Fig. 1) as well as those of oxygen and other metal abundances (Hou et al. 2000); in particular, the model predicts a flatenning of the abundance gradients with time (due to the assumed inside-out formation of the disk), in agreement with the recent observational results of Maciel and Da Costa(2002), based on O abundances of planetary nebulae of various age classes [Note: taking into account the uncertainties in evaluating ages of planetary nebulae, the importance of that agreement should not be overestimated; it is, however, encouraging].

Fig. 2 displays the evolution of several observables of a Milky Way disk as a function of redshift in a "standard" cosmology, according to the model. It appears that such disks evolved with quasi-constant amount of gas and were in the past substantially more compact in the B-band; they also were slightly brighter in the B-band (at least at redshifts $z \sim$ 1-2) and always fainter in the K-band.

Although the model reproduces successfully the present day profiles of the Milky Way disk, its "predictions" for the past history of such disks cannnot be considered very robust, since a degenerate solution (several different histories leading to the same final state) cannot be excluded. Still, it is tempting to explore the consequences of that model, after extending it to other disk galaxies.

## 3. SCALING RELATIONS FOR GALACTIC DISKS

Assuming that the MW is a typical spiral, one may try to extend the model to the case of other disk galaxies by means of simple scaling relations (in an analoguous way, the Sun is a typical star used to "calibrate" models of stellar evolution). The scaling relations derived by Mo et al. (1998) in the framework of Cold Dark Matter models of galaxy formation can be used (Boissier and Prantzos 2000, BP2000) to describe disks as a two-parameter family (scale length $R_d$ and central surface brightness

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$\Sigma_0$), in terms of the corresponding MW parameters (represented by subscript G below):

$$\frac{R_d}{R_{dG}} = \frac{\lambda}{\lambda_G} \frac{V_C}{V_{CG}} \tag{2}$$

and

$$\frac{\Sigma_0}{\Sigma_{0G}} = \frac{m_d}{m_{dG}} \left(\frac{\lambda}{\lambda_G}\right)^{-2} \frac{V_C}{V_{CG}} \tag{3}$$

The two fundamental parameters entering these relations are the circular velocity $V_C$ (a measure of the disk's mass) and the spin parameter $\lambda$ (a measure of the disk's angular momentum distribution); large $V_C$ values correspond to massive disks and large $\lambda$ values to extended ones. The baryonic fraction $m_d$ of the disks is taken to be 0.05 in our calculations. Finally, for the MW parameters we have: $R_{dG}$=2.6 kpc, $\Sigma_{0G}$=1150 $M_\odot$/pc$^2$, $V_{CG}$=220 km/s.

Note that these scaling relations apply to gaseous disks, assumed to be formed at the redshift of the corresponding dark halo formation; this formalism is adopted in semi-analytic models of galaxy evolution, where the baryon accretion history (the "infall" history, in our terminology) is determined essentially by the dark matter accretion history. A Schmidt type law for star formation (with an efficiency proportional to local dynamical timescale) is usually assumed in such models, along with some prescription for "feedback" (a term describing the way gas is affected by the energy input from stars); the interplay between the three effects (accretion, star formation, feedback) determines the effective star formation efficiency in semi-analytic models.

A different approach is adopted in BP2000: the star formation law and efficiency A (Eq. 1) are kept the same as in the MW model (with rotational velocity curves properly calculated), while the infall rate is adjusted in order to reproduce main properties of present-day spirals. This approach (i.e. using present-day properties of galaxies to infer their histories) has been characterised as "backwards" approach to galaxy evolution (e.g. Fereras and Silk 2001); our use of scaling relations borrowed from Cold Dark Matter ("forwards") models qualifies our approach rather as a "hybrid" one. In fact, the scaling relations allow to tie the geometric properties of disks to those of the Milky Way and nothing more; the overall disk evolution is really determined by the assumed infall (or mass accretion) history.

## 4. RESULTS

Our "hybrid" approach allows to reproduce successfully a large number of observables of galaxies in the local Universe (BP2000), including: disk sizes and central surface brightness, Tully-Fisher relations in various wavelength bands, colour-colour and colour-magnitude relations, gas fractions vs magnitude, abundances as a function of local and integrated properties etc; it also reproduces naturally detailed spectra from the Kennicut atlas of galaxies for various galaxy types.

We find that the crucial ingredient of that success is the assumption that gas is infalling more slowly in galaxies with smaller masses and/or surface densities. These two parameters are the main drivers of

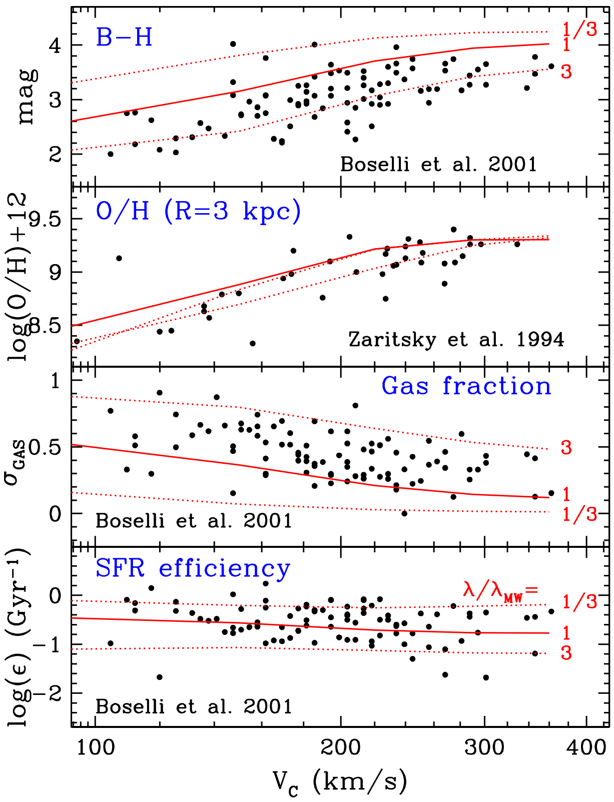


Fig. 3. From top to bottom: Colour, metallicity at 3 kpc from the center, gas fraction and star formation efficiency (defined as star formation rate divided by the total gas amount) as a function of rotational velocity for galactic disks. In general, more massive (rapidly rotating) disks are redder, more metal-rich and gas poor than less massive ones; however, the star formation efficiency does not seem to depend on the disk's mass. Put together, these observational data suggest that the more massive disks are chemically and photometrically older than less massive ones. The curves corrspond to model results of Boissier et al. (2001) for three values of the spin parameter $\lambda$: 1/3, 1 and 3 times the one of the Milky Way (the latter corresponds to the solid curves in all panels).

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disk evolution. We note that Bell and de Jong (2000) reach similar conclusions, but they attribute a more important role to local surface density while we find that galaxy mass plays an even more important role: on average, massive disks are older than lower mass ones. Disks with $V_C$ ~100 km/s have formed the first half of their stars within 4-9 Gyr, while disks with $V_C$ ~300 km/s have done so within 2-6 Gyr (depending on spin parameter, that is, surface density, see Boissier et al. 2001).

The main observational arguments on which our conclusion is based are presented in Fig. 3. One sees that, on average, massive disks are redder, poorer in gas and richer in metals than less massive ones. Each one of these observables, taken separately, could be easily explained (e.g. redder colours could be explained by larger amounts of dust, as invoked e.g. in Somerville and Primack 1999 or Avila-Reese and Firmani 2000). When all three observables are considered together, the idea of a star formation efficiency increasing with galaxy mass apears as a viable explanation. Such a possibility has been invoked in Ferreras and Silk (2001), but it requires huge amounts of (undetectable) gas to be present in small galaxies. However, when the fourth observable is taken into account, namely the absence of any dependence of the present-day of star formation efficiency on rotational velocity (or B-magnitude, see Boissier et al. 2001), the only viable explanation is the one invoked above: massive disks are older.

## 5. CONCLUSION

In the currently popular paradigm of hierarchical galaxy formation, low mass dark matter halos form first, while more massive ones are formed later through accretion and merging; in principle, baryons are supposed to follow the dark matter, but their fate is largely unknown at present, due to a lack of a reliable theory of star formation (and feedback).

In recent cosmological hydro-simulations by Nagamine et al. (2001) it is found that star formation in small galaxies has stopped many Gyr ago, in clear contradiction with observations of local galaxies. On the other hand, van den Bosch (2002) finds that semi-analytical models, even with feedback, produce massive disks that are systematically bluer than their lower mass counterparts, again in contradiction with observations; the reason of the failure is obviously related to the fact that the mass accretion histories of baryons are largely dictated by the hierarchical clustering of dark matter (e.g. Avila-Reese & Firmani 2000). Once gas becomes available it rapidly forms stars; feedback can only delay star formation for a short time (shorter than the several Gyr that are observationally required to obtain small disks bluer than massive ones).

Our simple, "hybrid" model for disk evolution, calibrated on the MW, suggests that on average massive disks have formed the bulk of their stars several Gyr earlier than low mass ones. Its predictions match successfully most currently available observables, including data from surveys at intermediate redshifts (Boissier and Prantzos 2001).

At present, and despite claims to the contrary, there is no satisfactory explanation (at least, no published one) for the observables presented in Fig. 3 in the framework of hierarchical galaxy formation. It remains to be shown why star formation in galaxies apparently followed an "inverted hierarchy" w.r.t the dark matter asembly. Feedback offers an obvious solution to that problem, but the required delay timescales appear unphysically large.

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