The Formation of Disks in Galaxies

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ABSTRACT. Different chemo-dynamical models dealing with the formation of stellar disks in the course of galaxy evolution are presented. One-dimensional models concerning the vertical stratification of disks are in strikingly good agreement with the solar vicinity. Two-dimensional investigations of the global evolution of disk galaxies show from preliminary results that the disk formation is delayed by means of an equatorial outflow of hot metal-enriched gas that stems from supernova ejecta in the star-forming central region.

1 General remarks on dissipative galaxy evolution

In order to understand central concentrations in galaxies, disky isophotes and metallicity gradients in giant ellipticals (gEs) as well as the mere existence of gas in all morphological types of galaxies, and most evidently the gaseous disks in spirals, **dissipation** must have played a dominant rôle during galactic evolution.

The stars formed during the galactic collapse decouple from the dissipative dynamical evolution of the gas, by this leading to the initial spheroidal stellar population, the halo. Its shape (and that of gEs) is supported by an anisoptropic velocity dispersion of the stars. A disk can only be formed if the remaining gas is enabled to settle down towards the equatorial plane according to its angular momentum. The amount of stellar matter that can be formed within this disk depends then only on the pre-history of star formation, in particular, on its dependence on the gas properties in the collapsing proto-galaxy and, by this, on the ratio of dissipative and collapse timescale to the star-formation timescale τ_{SF}.

2 Hydrodynamical models of disk galaxies

First simple hydrodynamical models of the evolution of disk galaxies had been calculated by *Larson (1975, Mon. Not. R. astr. Soc.* **173**, *671, 1976; Mon. Not. R. astr. Soc.* **176**, *31).* He obtained stellar systems that are comparable to disk galaxies even including a central bulge component, but he had to vary star-formation rate (SFR) and viscosity artificially. Nevertheless, kinematics, density, and metallicity of the stars in his models are showing too smooth gradients, not in agreement with the almost distinct stellar components like the observed disk and halo populations.

B. Barbuy and A. Renzini (eds.), The Stellar Populations of Galaxies, 119–122.

Burkert and Hensler (1987, Mon. Not. R. astr. Soc. **225**, *21p, 1988; Astr. Astrophys.* **199**, *131*: hereafter *BH88)* improved *Larson's* models by allowing for an anisotropic velocity dispersion of the stellar component. Although this improvement led to two distinct stellar populations because stars formed in the halo are prevented by their anisotropy to settle into the equatorial plane (like the gaseous component does) due to its isotropic pressure, they failed to produce a central bulge. This problem, however, can be avoided if the proto-galaxy is centrally condensed and non-rigidly rotating *(Dünhuber, 1990, Dipl. thesis, University of Munich).*

All these above-mentioned models achieved a fast formation of the disk after already three free-fall times (τ_{ff}) and in most cases a too rapid consumption of gas due to a high SFR in contradiction to observationally derived SFRs within the disk *(Sandage, 1986, Astr. Astrophys.* **161**, *89).* Although such a rapid collapse agrees with the first naive picture for our Galaxy proposed by *Eggen, Lynden-Bell, and Sandage (1962, Astrophys. J.* **136**, *748)*, it disagrees to that by *Yoshii and Saio (1979, Publ. Astr. Soc. Pac.* **31**, *339).*

Detailed observations of the stellar disk population provide strong constraints on evolutionary models of the galactic disk and presumably on the proto-galactic conditions. In the solar vicinity the lack of metal-poor G-dwarfs, the age-metallicity relation, the metallicity-scaleheight-relation, the step-wise distributions of stellar kinematics and metallicity from halo to thin disk with the transition phase of a thick disk, age differences between halo and disk stars, and hints of a radial propagation of the onset of star formation within the disk itself serve as a challenge for our understanding of galactic evolution and as a sensitive probe for the quality of models. Several explanations have been proposed to solve some of these problems, however, applying non-dynamical studies only.

The above-mentioned purely dynamical models can also not account for all these problems, because they assume too unrealistic simplifications like a one-phase interstellar medium (ISM), instantaneous recycling, a dependence of the SFR on the total gas density, and the neglection of star-gas interactions. In particular, the G-dwarf problem, the thick-disk formation, and a time delay of the disk formation as well as the influence of superbubbles, galactic winds, and starburst epochs on the evolution of galaxies and their disks cannot be investigated by such a simple single-phase ISM description.

Supernovae (SNe) are violently acting upon the ISM by means of thermal (formation of hot bubbles, evaporation, condensation) and dynamical processes (sweep-up of surrounding material, formation of hot bubbles) and by metal enrichment due to stellar nucleosynthesis yields. In addition, the different gas phases need not show strongly coupled dynamics, but the SN-heated gas expands and can even be expelled from the galaxy, by this, carrying a non-negligible amount of metals away. While τ_{ff} and τ_{SF} determine the dynamical evolution of galaxies in the purely hydrodynamical one-phase description, in reality, the stellar lifetimes of massive stars inherently involve a heating timescale due to SN explosions. On the other hand, this requires to account for the cooling timescale from the hot to the cool star-forming phase. The latter one can exceedingly influence the collapse and galaxy evolution.

As demonstrated elsewhere *(Hensler and Burkert, 1990, in "Windows on Galaxies", eds. P. Fabbiano et al., Kluwer, p. 321)*, only the most sophisticated chemo-dynamical investigations taking a multi-phase ISM and the star-gas interactions with the metal dependence of processes into account are suitable for those problems. Tests have convincingly demonstrated that the neglection of a particular process has in most cases much stronger consequences for the evolution of the ISM than the acceptance of an uncertainty in its parametrization *(Hensler, 1988, Habil. thesis, University of Munich; Theis, 1990, Dipl.*

thesis, University of Munich; Hensler and Burkert, 1991, Astr. Astrophys. , submitted). The main features of the chemo-dynamical treatment are reviewed e.g. by *Hensler (1987, Mitt. Astron. Ges.* **70**, *141).*

3 Chemo-dynamical evolution of disk galaxies

Although, several observers have invoked the existence of different step-wise disk stratifications from halo to thick and thin disk populations, one of the major uncertainties at present and one of the most basically addressed questions of this conference concerns with the relative ages of these structures.

Two strategies for chemo-dynamical calculations of the galactic disk formation can now be followed:
1) A one-dimensional (1d) consideration of the vertical disk formation can study the disk stratification and the existence of different disk layers.
2) Two-dimensional (2d) global calculations of the evolution of disk galaxies can yield an insight in the evolutionary epochs of the different galactic components including the bulge and their interferences.

3.1 One-dimensional vertical formation of the galactic disk

As a first step towards getting an insight into the timescales of the disk settling 1d chemo-dynamical calculations have been performed by *Burkert, Truran, and Hensler (1991, Astrophys. J., in press*: hereafter *BTH)*. Starting with an initial stratification of a 10^6 K hot gaseous proto-disk with a typical column density for the solar vicinity of $\Sigma \approx 50 M_{\odot} pc^{-2}$, that is metal-enriched by population II stellar ejecta up to already 5% $Z_{\odot}$, the model is able to reproduce the different vertical disk layers in strikingly good agreement with observations.

The results of *BTH* are in particular briefly summarized here: After a cooling time of approximately 200 Myrs the star formation increases accordingly. Stars in the low metallicity range of $-1.5 \leq [Fe/H] \leq -0.5$ form only during the first 350 Myrs. In agreement with the thick disk values their vertical velocity dispersion amounts to $c_w \leq 40\ km\ sec^{-1}$, providing a scaleheight of $h_z = 1.3\ kpc$. While the star formation in the metal-poor gas ceases abruptly due to the gas consumption, metal-enriched SNII ejecta of the thick-disk stars provide a hot gas phase that starts after its cooling 250 Myrs after the onset of the thick-disk formation to form new stars, now with $-0.5 \leq [Fe/H] \leq 0.25$. This new stellar disk population represents the old thin disk and is shrinked within the next 4 Gyrs to only $h_z = 300\ pc$ with a smaller c_w of 20 $km\ sec^{-1}$. Meanwhile, the star formation decreases from $10^{-7.4}\ M_{\odot}\ pc^{-2}\ yr^{-1}$ by one order of magnitude.

After 6 Gyrs 80 % of the gas is converted into stars and more metal-enriched gas of $[Fe/H] \geq 0.25$ can further concentrate to an accordingly young thin disk with $h_z \approx 50\ pc$.

The final vertical stellar stratification agrees well with the exponential law derived by Sandage *(1987, Astron. J.* **93**,*H 610)*, if a stellar halo component is added accordingly.

If Σ is larger the thin disk forms faster. A radial column density gradient in a galactic disk would thus lead to a radial propagation of the thin disk formation. Furthermore, the model predicts a sharp edge of galactic disks for $\Sigma \leq 10 M_{\odot} pc^{-2}$. Due to the strong self-regulation effects that balance heating and cooling a thin disk cannot form. For the same reason the collapse of low-density galaxies can sometimes be prevented *(Theis, Burkert, Hensler, 1991, Astr. Astrophys. , submitted).*

3.2 Two-dimensional models

In order to date the onset of the thick-disk formation as well as the timescale for the formation of the halo and bulge, i.e. in order to study the evolution of galactic disks in the context of the whole galaxy evolution, global, at least, two-dimensional investigations have to be carried out. We have commenced the calculations with the same initial conditions as a typical model galaxy of *Larson* and *BH88*: The total mass is $10^{11} M_\odot$, however, now devided into two gas phases in pressure equilibrium, a hot one of 10^6 K and a cool cloudy one with 10^3 K and a volume filling factor of 0.1; the radius amounts to 30 kpc; the rigid rotation leads to a spin parameter $\lambda \approx 0.15$. Although the calculations have not yet be performed to more than 10 τ_{ff}, what amounts to approximately 2.7 Gyrs, the preliminary results by *Dünhuber, Theis, Burkert, Hensler (1990, Astron. Ges. Abstract Series* 4, *61)* already reveal an impressing insight to the early stages of halo, bulge, and disk formation and will, therefore, be presented here.

The SFR drops from a high initial value caused by heating of the gas due to the collapse and in addition due to first stellar ejecta. Within the first 2 τ_{ff} the collapse of the proto-galactic cloud proceeds nearly spherical symmetric while it cools and the SFR increases again. However, because of the higher central gas condensation the SFR in the center exceeds that in the halo by far, i.e. more than 4 orders of magnitude. Then the still collapsing configuration flattens due to its angular momentum and the stellar distribution consists after $\approx 4\tau_{ff}$ of a prominent central dense almost spherical structure with an additional flat spheroid in the equatorial plane. Intimately coupled with the burst-like increase of the SFR in the center, a hot (several 10^6 K) central bubble of ejected stellar material forms and expands due to continuous feeding by SN explosions.

Differently from superbubble calculations *(Tomisaka and Ikeuchi, 1988, Astrophys. J.* **330**, *695)* but in agreement with investigations of the gas flow in gEs *(Yorke and Kunze, 1990, in "Physical Processes in Fragmentation and Star Formation", Capuzzo-Dolcetta et al. (eds.), p. 241)* this hot gas phase expands pressure-supported (due to further infalling cooler material) primarily in the galactic plane towards larger radii. By this it delays the formation of a stellar disk but forms a hot metal-enriched disky layer of a vertical height of 1-2 kpc. Because this global picture has not changed for at least almost three Gyrs, we suggest that the hot gas can produce a metal pre-enrichment of the disk material, by this providing the formation of a thick disk, an explanation of the G-dwarf problem, and the radial star-formation propagation. The star formation in the disk can further be fuelled by gas infalling from the halo, because at that time not more than 60% of the matter is transformed into stars. Further studies will clarify the evolutionary scenario and are in progress.

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Discussion

A. Serrano: *1) Can you form a bulge? 2) Can you explain galaxies without thick disks?*
G. Hensler: *to 1): The 2d chemo-dynamical evolutionary models show already after few τ_{ff} the formation of a clearly distinct central spheroid.*
to 2): No, not with our prescription of the star-formation. If such systems exist, specific processes have to be invoked that allow cooling of the gas but prevent star formation within the cool clouds.

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